INTERNATIONAL MONETARY FUND

The Great Carbon Arbitrage

Tobias Adrian, Patrick Bolton, and Alissa M. Kleinnijenhuis

WP/22/107

2022
MAY

WORKING PAPER

 WP/22/107

IMF Working Paper
Monetary and Capital Market Department

The Great Carbon Arbitrage*

Prepared by Tobias Adrian[1], Patrick Bolton[2], and Alissa M. Kleinnijenhuis[3]

ABSTRACT: We measure the gains from phasing out coal as the average social cost of carbon times the quantity of avoided emissions. By comparing the present value of benefits from avoided emissions against the present value of costs of ending coal and replacing it with renewables, our conservative baseline estimate is that the world can realize a net gain of $85 trillion. This global net social benefit can be attained through an international agreement to phase out coal. We also explore how this net benefit is distributed across countries and find that most countries would benefit from a global coal phase-out even without any compensatory cross-country transfers. Finally, we estimate the size of public funds that must be committed under a blended finance arrangement to finance the cost of replacing coal with renewables.

JEL Classification Numbers:	Q20, Q48, Q50, Q51, Q54, G00
Keywords:	Climate, Carbon; Environment; Climate Policy; Valuation of Environmental Effects; Financial Economics
Author's E-Mail Address:	TAdrian@imf.org pb2208@columbia.edu amklein@stanford.edu

* The views expressed in this paper do not necessarily reflect the views of the International Monetary Fund, its Management, or its Executive Directors. The authors would like to thank Viral Acharya, Ananthakrishnan Prasad, Helge Berger, Darrell Duffie, Charles Goodhart, Robin Greenwood, Lawrence Goulder, Emmanuele Massetti, Robert Pindyck, Rick van der Ploeg, James Roaf, Suphachol Suphachalasai, Rupert Way, and Johannes Wiegand for helpful suggestions. Funding from the European Research Council (ERC) under the ERC Advanced Grant program (grant agreement No. 885552 Investors and Climate Change) for this research is gratefully acknowledged. We thank Asset Resolution for offering access to their data. We are thankful to the participants at the seminars of the Free University of Amsterdam, the University of Amsterdam, the Dutch Central Bank, the International Monetary Fund, the Institute for New Economic Thinking at the Oxford Martin School, Fidelity Investments, the Climate Policy Initiative, the World Resources Institute, and the Office of the Comptroller of the Currency for their feedback. We also thank the participants of the Sustainable Capital Conference, the Cornell University ESG Investing Conference, the Climate Finance Innovation and Challenges for Policy Conference at the Stanford Department of Economics, the Workshop on Fiscal Policy and Climate Change at the European Central Bank, and the Political Economy of Environmental Sustainability Conference of the Stanford Graduate School of Business and Stanford Doerr School of Sustainability for their comments. We would like to thank Moritz Baer, the Environmental Stress Testing and Scenarios Programme (ESTS) at the Oxford Sustainable Finance Group and 2° Investing Initiative for valuable research support. We further thank Liumin Chen, Yanzhe Xiao, and in particular, Rudy Tanin for their excellent research assistance. A computational tool and extra analysis can be found at https://greatcarbonarbitrage.com.

[1] International Monetary Fund
[2] Columbia Business School and Imperial College
[3] Institute for New Economic Thinking at University of Oxford

Contents

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 internalize the social externality (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 marginal social cost of carbon (SCC), defined as the incremental expected present discounted social harm from an additional ton of CO_2 emissions, relative to a benchmark global emissions scenario. This SCC is estimated based on an integrated assessment model (IAM) that maps economic activity into CO_2 emissions, and in turn CO_2 emissions into temperature rise, which negatively affects future growth. The logic behind the Pigouvian approach is that when carbon emissions are taxed at the marginal SCC then competitive market economies will achieve efficiency (the marginal unit of CO_2 emissions will be priced at the marginal SCC). There is by now a sizeable literature on IAMs providing quantitative estimates of the *marginal* SCC (see e.g., Nordhaus (1993), Hope et al. (1993), Stern and Stern (2007), Gollier (2012), Llavador et al. (2015), Heal (2017), and Daniel et al. (2019)). The marginal SCC, however, is only relevant to evaluate a marginal change in emissions relative to a baseline future emissions scenario (often this scenario is taken to be a business as usual (BAU) scenario).

In this paper we seek to evaluate the net social benefit from a large reduction in CO_2 emissions arising from the replacement of coal with renewable energy. Our approach is closer to a Coasian approach (Coase (1960)), as we seek to determine the total net benefit from a transaction and how this net benefit is split among the contracting parties. The main question we address is: how much would the world benefit from phasing out coal and replacing the energy from coal with energy from renewable sources such as wind power and solar radiation?

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.

Under a Coasian bargain coal companies would be compensated for losses they incur from ceasing their operations, and the social benefits from avoided emissions would be assessed net

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

of both opportunity costs of phasing out coal and capital expenditures required to install the replacement renewable energy capacity. We measure the gross social benefit from all avoided emissions resulting from the phase-out of coal by pricing each unit of avoided emissions at an average SCC. We take the estimate of the average SCC from the Pindyck (2019) survey study. If an efficient global emissions trading system (ETS) were in place, the equilibrium carbon price in this market would be equal to the applicable (and changing) marginal SCC. It would then be possible to reap a total gross revenue from phasing out coal equal to average carbon price (i.e., the average SCC) times total avoided emissions. Shorting coal and going long replacement renewables could then result in a net gain, or a carbon arbitrage.

Our estimate of the net gain to the world of phasing out coal is very large indeed. The baseline estimate of the global net social gain from beginning a phase-out in 2024 in line with the Net Zero 2050 scenario of the Network for Greening the Financial System (NGFS), always replacing coal with renewable energy, is 85 trillion US dollars. This represents an increase of around 1.3% of current world GDP every year until 2100. Per ton of coal this represents a net gain of around \$136, and per ton of avoided CO_2 emissions this represents a net gain of \$60.

This baseline estimate takes the *average* SCC to be \$80 per ton of CO_2 (tCO_2) – which is the lower-end estimate in Pindyck (2019). We also conduct a sensitivity analysis for all our main parameter values, including the mix of replacement energy sources and different values of the SCC, ranging from a minimum of \$61.4/tCO_2 to a maximum of \$268.4/tCO_2 as in Rennert et al. (2021). For the less conservative estimate of \$268.4/tCO_2, we find that the net social benefit rises from \$85 to \$211 trillion. Our baseline estimates are much closer to the minimum values than to the higher end values in our sensitivity analysis, indicating that we have not only chosen a conservative estimate for the average SCC in our baseline, but also conservative estimates for our other parameter values.

Our paper makes a simple but major 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, even when accounting for the investment costs in renewables and the opportunity costs of coal. 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 plausible explanation could be that the countries involved in working out a global agreement to phase out coal are not aware of the size of the benefits from such a phase-out, even taking into account the costs of replacing coal with renewables and the cost of compensating coal businesses and workers. How could policymakers know? The IAM literature has focused primarily on estimating the additional climate damage from adding one extra ton of CO_2 into the atmosphere. Indeed, to our knowledge no official study has asked the question before what the benefits might be of a large emission reduction (of around 1425 Gt) resulting from phasing out coal, as well as its costs. No earlier work has provided a quantitative answer to such a question with a granular data set (by Asset Resolution) of coal production and emissions aggregated from the plant level.

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 several major emerging market economies that heavily rely on coal for energy production did not sign on. The 197 parties of the convention could only agree on accelerating independent efforts towards the phase-down of unabated coal power.[2] A smaller group of forty countries, however, did agree to sign the Global Coal to Clean Power Transition accord. They noted that “coal power generation is the single biggest cause of global temperature increases”, and “recognized the imperative to urgently scale-up the deployment of clean power to accelerate the energy transition.”[3]

From a Coasian perspective it is sound economics to compensate losses incurred from phasing out coal, to account for capital expenditures needed to replace the energy from coal, and to link the social benefits of avoided emissions to these costs. Thus, if compensation was a more important part of global agreements, and if the yet to be fulfilled promise to finance 100 billion dollars a year in green finance (much more is needed) to developing countries had been made <u>conditional</u> on phasing out coal extraction and keeping coal underground, a global agreement could be reached more easily.

To gain further insight into the size of financing that may be required to pay for the replacement of coal with renewables, we break down where these costs would be incurred on a regional basis. We provide the first estimates of climate financing needed to replace coal with renewables in every country of the world, accounting for both the opportunity costs of coal and the investment costs in renewables. We find that the present value of financing needed to end coal globally is around 29 trillion dollars. This represents an annual global climate financing need between $\frac{1}{2}$ a trillion and 2 trillion dollars, with a front-loaded investment this decade, which we estimate reaches up to around 3 trillion. Of the global financing needs of around

[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.

$29 trillion, we estimate that 46% is in Asia, 18% in Europe, 13% in North America, 13% in Australia and New Zealand, 8% in Africa, and 2% in Latin America and the Caribbean.

Persuading countries to collectively provide annual climate financing of between $\$\frac{1}{2}$ trillion and $2 trillion dollars (up to $3 trillion) to concurrently *phase out coal* and phase in renewables across the world clearly represents a major challenge. At the COP26 it was emphasized that no government in the world has enough money to make such sizeable investments, pointing to the difficulties in gaining sufficient political support for public funding of such a large investment program, and calling on the private sector to steer the required funding to renewable energy investments. Yet, more support could be obtained by highlighting the enormous benefits in terms of avoided loss in future GDP from these investments and by not focusing only on costs.

The climate financing needs are indeed large (around $29 trillion), but our first point is that they are small relative to the social benefits (conservatively estimated over $104 trillion). The financial transfers promised to poor countries for their energy transition are not a handout, they are an investment with an enormous benefit that far exceeds the cost. As André de Ruyter, chief executive of Eskom, South Africa's state power utility recently observed: "Mitigating a tonne of carbon in South Africa is a tenth the cost of mitigating a tonne of carbon in Europe. So the value proposition for the German taxpayer is, because carbon is a global phenomenon, let's give our money to a country where you get more tonnes of decarbonisation per euro than anywhere else."[4] Our second point is that most of the financing for replacement renewable energy can come from the private sector (as we discuss in the policy section), once these investments are de-risked through public co-investments via blended finance (see Arezki et al. (2016) and Bolton et al. (2020)). Accounting for such private financing would bring governments' total fiscal commitments for renewables to replace coal down to between roughly $50 billion and $200 billion per year.

To better understand the extent to which governments stand to benefit from a phase out of coal and replacement with renewables, we break our global cost-benefit analysis down to country-level benefits and costs. We find that it is in most countries' economic interest to participate in a global deal to end coal, even in the absence of cross-country compensatory transfers. Some (mostly developing) countries require small compensatory transfers to benefit from a global coal phase-out. We show that it is in rich countries' self interest to make these transfers, as they are main beneficiaries from eliminating coal. Considerations of fairness, a country's fiscal position, or both, may of course call for rich countries' contributions to finance these investments.

[4] David Pilling, The cost of getting South Africa to stop using coal, Financial Times, 2 November 2022. See: https://www.ft.com/content/3c64950c-2154-4757-bf25-d93c7850be8f.

In sum, the key conclusion from this paper is that the net social gains from phasing out coal are huge. It is therefore in everyone's interest to double down on efforts to overcome the current obstacles to striking a global agreement to phase out coal. We show that even in the absence of a global deal, substantial net benefits from regional or even country-level coal phase-outs are available. Indeed, the paper shows that to make global progress on tackling climate change, you do not need a global agreement, you can work by *blocks*. This is especially salient as COP(27) turns out to be an ill-functioning mechanism for tackling climate change at the scale that is required. "By the standards of COP agreements, which require unanimous consensus among nearly 200 countries, this was a creditable result. Set against the worsening tragedy of the climate crisis, it was a colossal failure."[5] Coasian bargaining at a global scale is likely to break down (as it will rely on the lowest common denominator), whereas Coasian bargaining to strike a sequence of country deals, adding up to the global deal, is much more feasible. Our paper offers an alternative (incentive-compatible) model for cross-country cooperation to timely tackle climate change.

The outline of the remainder of the paper is as follows. Section 2 discusses our contributions to literature. Section 4 describes our data. Section 3 describes our methodology. Section 5 reports our results. Section 6 discusses climate finance implications of a Coasean bargain to replace coal with renewables. Section 8 provides concluding comments.

2 Literature

We undertake the first global cost-benefit analysis of phasing out coal and replacing its energy with renewable energy. The closest earlier related study is by Rauner et al. (2020). They undertake an analysis of local environmental and health benefits from phasing out coal and argue that these benefits outweigh the costs of eliminating coal. Unlike our study, they do not estimate the net present value of costs and benefits over a decarbonization horizon. Their study focuses on local externalities whereas our analysis estimates the global climate change mitigation benefits from phasing out coal.

The Coasian approach that underlies our analysis is related to the early contribution by Harstad (2012). He suggests that countries seeking to mitigate climate change could buy out fossil reserves from existing owners producers who plan to extract them and then keep the reserves unexploited. This suggestion is similar to a Coasian bargain. However, Harstad (2012)

[5]See: "The Good, The Bad and The Ugly in the COP27 agreement", Financial Times (November 21, 2022). See: https://www.ft.com/content/344ec421-510d-4099-a903-a818b8fb8f90?shareType=nongift.

does not undertake a cost-benefit analysis of such a transaction.

Our paper belongs to a larger literature on supply-side climate policy (e.g., Harstad (2012) and Collier and Venables (2014)). This literature advocates the closure of coal mines on the basis of the high emission intensity of coal, low rents per unit value, and the local environmental costs of coal. However, it does not conduct a quantitative analysis of the economic benefits and costs of replacing coal with renewables.

For simplicity we have not taken into account any general equilibrium effects, which might be linked to the phase-out of coal. The main likely general equilibrium effect is that the price of coal could increase as a result of the sharp reduction in coal supply. This effect could raise the opportunity cost of shutting coal operations for the coal companies that are due to close their operations at a later stage in the transition. This effect could reduce the size of the carbon arbitrage but is unlikely to significantly erode the net social benefit from phasing out coal. Liu and Lu (2015) undertake a general equilibrium analysis of the effects of carbon taxation under different assumptions on how tax revenues are redistributed for the Chinese economy. They show that the net impact of carbon taxation on economic activity depends on how tax revenues are spent.

Big picture, the conceptual contribution of the paper is that paying the polluter — via climate finance — to stop polluting (as is, for example, happening now in South-Africa and Indonesia) results in a Coasian bargain. Coase won the Nobel prize for his insight that paying the polluter to stop polluting may make you better off. But, as far as we are aware, no earlier work has linked his theory to the idea that the provision of climate finance could result in a Coasian bargain. No earlier work has quantified whether such a bargain exists. The empirical contribution of the paper is to provide the first quantification of the costs of climate finance to end coal and net benefits this brings to different countries.

3 The Great Carbon Arbitrage

The size of the carbon arbitrage is given by the difference between the present value of benefits from avoided carbon emissions minus the present value of costs of replacing coal with renewable energy, taking into account both the opportunity costs of shutting down coal operations and the investment costs of setting up renewable energy operations. Formally, the global carbon arbitrage $A_{t,T}^{s_1,s_2,s_r,\theta}$, our focus in this study,[6] is thus defined as the present value at time t of

[6]These formulae can be adapted to estimate the size of the carbon arbitrage for individual nations or individual regions. This can be done under the assumption that damages from carbon emissions are homogeneously distributed across the world. In practice this is not true, as impacts from climate change around the world are

benefits $B_{t,T}^{s_1,s_2,\theta}$ minus the costs $C_{t,T}^{s_1,s_2,s_r,\theta}$ of avoiding coal emissions and replacing coal with renewable energy:

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

We estimate 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 by pricing avoided emissions at the average social cost of carbon θ (Pindyck (2019)).

The present value of costs $C_{t,T}^{s_1,s_2,s_r}$ of depends on the coal-phase-out scenario s_2 relative to a business-as-usual scenario s_1, the time horizon $[t+2,T]$ over which the coal phase out takes place, and on the replacement scenario s_r specifying with what mix of renewables phased-out coal is substituted.

We take the size of avoided emissions to be 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 avoided emissions, we also examine a scenario s_2 in which coal production is halted completely starting from $t+2$ and replaced with renewables.

We calculate the net social gain associated with a gradual phaseout of coal starting in 2024 and ending in 2100. 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.[7] The year 2070, or earlier, e.g., 2060, is the net zero target for various emerging and developing economies, such as China, Saudi Arabia, and India. In practical terms, a shorter T means a shorter cost horizon.

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

3.1 Benefits of Avoiding Coal Emissions

The present value of global benefits $B_{t,T}^{s_1,s_2,\theta}$ from each coal company $i \in \mathcal{C}$ (where $\mathcal{C}$ is the set of coal companies) were to reducing its CO_2 emissions by an amount $\Delta E_{i,\tau}^{s_1,s_2}$ each year

uneven (IPCC (2021)). To estimate the carbon arbitrage for individual regions or countries, a regional SCC could be used (Nordhaus (2017)). We estimate the country-level net gain from phasing out coal based on country-level estimates of the SCC by Ricke et al. (2018); see Section 7.

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

$\tau \in [t+2, T]$ is given by

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

where avoided emissions are priced at the mean SCC 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: $\Delta E_{i,\tau}^{s_1,s_2} = E_{i,\tau}^{s_1} - E_{i,\tau}^{s_2}$. 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 multiplied with the emission intensity $\epsilon_{i,l}$ of the plant

$$E_{i,\tau}^{s} = \sum_{l \in \mathcal{L}_i} P_{i,l,\tau}^{s} \epsilon_{i,l}.\text{[8][9]} \tag{3}$$

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

The marginal SCC is expected to change (in particular, grow) over time as more CO_2 emissions accumulate in the atmosphere, causing more rapid and extreme temperature rise with all attendant physical and economic damages (Daniel et al. (2016), Dietz and Stern (2015)).[10] Hence, using the marginal SCC to estimate benefits from avoiding multitudinous tonnes of emissions (by reducing coal production from a business-as-usual pathway s_1 to a pathway s_2 compatible with net zero 2050) is not suitable, since the marginal SCC is only applicable to a one-tonne deviation from a business-as-usual pathway s_1. For a two-tonne deviation from business as usual the marginal SCC is given by the extra damage generated by putting an extra tonne of CO_2 in the atmosphere relative to the tonnes of emissions under "business-as-usual + 1", and so on. *Vice versa*, the reduction in climate damages by not putting a tonne of CO_2 into the atmosphere is also assessed relative to the applicable business-as-usual scenario s_1. So to capture that the applicable marginal SCC at a given time depends on the cumulative emissions up to that date, we use the average SCC. In particular, we'd like to use average SCC

[8] As noted in Section 4, we define a coal company's plant to be any unique combination of energy use, coal technology, coal sub-technology and plant country of a coal company. So in practice, we sum the product of coal production and associated emission intensity for each unique combination of these.

[9] In so far as coal companies decide to invest in abating emissions from coal production so as to lower their plants' emission intensities at future dates $\tau \in (t, T]$, we may slightly overestimate global benefits of reducing coal production, since we assume that the future emission intensity of coal production at the plant level will remain equal to what it is today. Abatement of coal emissions remains as of yet cost ineffective (see Section 5), even under optimistic technological advance assumptions. This is in part due to high costs of early-demonstration projects hindering large-scale deployment (Lu et al. (2022)). Abatement of coal emissions is especially problematic in emerging and developing economies, where regulatory uncertainties, lack of public financial support, and risks around long-term ownership and liability of stored CO_2, as well as complex chains of capture-transport-storage, hinder the cost-effective deployment (IEA (2021e)).

[10] Nordhaus (2017) estimates that the SCC is likely to grow in real terms at 3% every year up to 2050. In fact, the SCC is likely to grow non-linearly as we get closer to climate tipping points.

corresponding to the average marginal SCC that applies over the course of emission reductions to move from a business-as-usual pathway s_1 to a net-zero-2050 pathway s_2.

Pindyck (2019) defines the average SCC θ as the ratio of the present value of lost GDP due to direct or indirect climate damages from an extreme climate outcome (causing GDP reductions of at least 20%) to the total emission reduction needed to avert that outcome. Put differently, Pindyck's average SCC corresponds to the average SCC that applies when moving from a business-as-usual pathway s_1 to a pathway where catastrophic climate outcomes causing a GDP reduction of at least 20% are avoided. We can use Pindyck's average SCC θ, since the emission reduction needed to avoid a climate catastrophe (for the lower bound estimate of the mean SCC of \$80/tCO_2 in Pindyck (2019)) is similar to the 1425.55 GtCO_2 emission reduction from phasing out coal along the pathway of the NGFS Net Zero 2050 scenario s_2 relative to business as usual s_1.[11] The average SCC already embeds a discount rate R to obtain the present value of avoided GDP losses and emission cuts, which is why there is no explicit discount rate in the formula in equation 2.

To be precise, the average social cost of carbon S in Pindyck (2019) is given by the present value of future benefits B_0 from emission reductions divided by the size of emission reductions ΔE (Pindyck (2019)). The average SCC is given by $S = \frac{B_0}{\Delta E}$, where $B_0 = \frac{\beta[\mathbb{E}_0(z_1)-\mathbb{E}_1(z_1)]}{(R-g)(R+\beta-g)(1-\exp^{-\beta T_1})}$ and $\Delta E = \frac{(m_0-m_1)E_0}{(R-m_0)(R-m_1)}$. Here $\mathbb{E}_0(z_1)$ represents expected future damages to GDP under a business as usual scenario, and $\mathbb{E}_1(z_1)$ represents future expected damages to GDP once emissions are reduced sufficiently to avoid the worst climate catastrophes (taken to be those that cause reductions to GDP greater than 20%). E_0 gives the current emissions and $m_0 - m_1$ gives the reduction in the growth rate of emissions to avoid the worst climate catastrophes. R is the discount rate and g the projected growth rate of GDP. β captures how climate damages change over time. Essentially, the denumerators in the equations of B_0 and E_0 discount future climate damages and emissions back to today. The parameter values for R, g, β, m_0 and m_1 are elicited by surveying a broad panel surveying experts (climate scientists and environmental economists).

Pindyck's approach thus boils down to a combination of quantitative modelling and expert elicitation. Rather than estimating an IAM to back out a quantitative estimate of the marginal SCC, Pindyck (2019) surveys a broad panel of climate scientists and economists to elicit median and lower-bound estimates of total and average SCC.[12] Relying on expert opinion

[11] We derive the size of avoided emissions from micro data about carbon emissions from coal, taking as our benchmark scenario for future emissions from coal under a business-as-usual scenario, s_1, and as our alternative scenario, s_2, the future emissions from coal under the NGFS net zero 2050 scenario, under which coal production is gradually phased out.

[12] Pindyck's main justification for taking this alternative approach is the admission that estimates of marginal and infra-marginal SCCs based on an IAM are not robust given our current state of knowledge in economics:

or on IAM modelers' best judgments, in the end is not a fundamental difference. Arguably, the advantage of an SCC estimate based on an IAM is that the approach taken to the estimation is more structured. But the advantage of Pindyck's more reduced-form approach, surveying experts with varied backgrounds, is that there is less risk of leaving something crucial out of the analysis.

Indeed, a comparative advantage of Pindyck (2019) is that key input parameters are estimated by many experts rather than by the judgement of one integrated assessment modeller alone. Pindyck's approach allows for the integration of expert opinions from economists as well as non-economists. Pindyck (2019) approached 6833 authors and around 1000 took part in the survey. "Respondents largely agreed about the growth rate of emissions under BAU (m_0) and the growth rate needed to avert a GDP impact of 20% or greater.... But opinions regarding the probabilities of alternative outcomes, and the most likely impact in 2150, varied widely." [page 150]. The wide difference in opinions regarding probabilities is altogether not too surprising given that damage functions in IAMs are notoriously difficult to pin down (Nordhaus (2013), and Llavador et al. (2015)). Pindyck (2019) found that the lowest average SCC estimates are from economists: "But even for economists, the mean SCC is large (\$153 to \$203, depending on the distribution). The mean SCCs are much higher for climate scientists (from \$291 to \$326).... . If one gives more weight to the views of economists (who perhaps better understand GDP impacts), gives more weight to respondents who express greater confidence in the probabilities they report, and also trims outliers, then the right number is around \$80/tCO_2. But if one takes a more democratic view of "expertise" and treats all respondents equally, the right number is closer to \$200/tCO_2." [pages 150, 154-155] Accordingly, consistent with our general approach which is to err on the side of caution, we take our baseline estimate for the mean SCC to be θ=\$80/tCO_2. In comparison, central estimates of Rennert et al. (2021) suggest a range for the

"The use of a complex model throws a curtain over our lack of knowledge, and suggests we know more than we do. The use of a survey is more transparent and summarizes the views (however obtained) of researchers who have studied climate change and its impact. This approach acknowledges that currently the best we can do —especially with regard to extreme outcomes — is rely on the opinions of experts" [page 141, Pindyck (2019)]. As Greenstone et al. (2013) explain, efforts by the Interagency Working Group on Social Cost of Carbon 2010 to obtain a range of values for a marginal SCC based on estimated IAMs involved "making many assumptions: it is necessary to make assumptions concerning the four main steps in the estimation process: (1) the future emissions of GHGs; (2) the effects of past and future emissions on the climate system; (3) the impact of changes in climate on the physical and biological environment; and (4) the translation of these environmental impacts into economic damages... the interagency group conducted an extensive review of the literature and identified three key input parameters—socioeconomic and emissions trajectories, climate sensitivity, and discount rates—that were made consistent across the three models. All other model features were left unchanged, thus relying on the modelers' best estimates and judgments" [pages 25 and 28, Greenstone et al. (2013)]. The difficulties in estimating a total social cost of carbon from a large, non-marginal, change in emissions, using an IAM are compounded, as this also involves estimating inframarginal SCCs and computing an integral under a social welfare function. Some of these difficulties are illustrated by a first analysis in this direction attempted by Greenstone et al. (2013).

marginal SCC as high as \$168.4 and as low as \$61.4 per tonne of carbon.[13] We use this range for our sensitivity analysis.

An important observation for our analysis is that social benefits of building renewable capacity over [t+2,T] extend beyond time T, the final year phase-out costs are accounted for. The reason is that a renewable plant with a lifetime of l years will still be operational beyond year T as long as it is built after time $T-l$. It can thus help avoid coal emissions after year T, since renewable energy, which compared to coal generates insignificant emissions over its life cycle (see e.g., Hertwich et al. (2016)),[14] 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 Coal Emissions

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 $I_{t,T}^{s_1,s_2,s_r}$:[15]

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

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

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

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

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

[15] For simplicity, we ignore the variable costs of renewables, as these are small compared to the large upfront costs in renewables.

The missed free cash flow $O^{s_1,s_2}_{i,\tau}$ of coal company i in year τ is given by the multiplication of its reduction in coal production $\Delta P^{s_1,s_2}_{i,\tau}$ 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.

$$O^{s_1,s_2}_{i,\tau} = \Delta P^{s_1,s_2}_{i,\tau} \times \pi_{i,\tau}. \tag{6}$$

The difference in i's coal production between scenario s_1 and s_2 is given by $\Delta P^{s_1,s_2}_{i,\tau} = P^{s_1}_{i,\tau} - P^{s_2}_{i,\tau}$, where its coal production $P^{s}_{i,\tau}$ in year τ under scenario s given by the sum of its coal production of each of its plants; i.e. $P^{s}_{i,\tau} = \sum_{l\in\mathcal{L}_i} P^{s}_{i,l,\tau}$. 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 $O^{s_1,s_2}_{i,\tau}$ 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 $\mathbb{E}[R^M]$.[16] 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 $\rho = 5\%$.

We can break down the global cost into the a cost per country, i.e. $O^{s_1,s_2}_{t,T} = \sum_{y\in\mathcal{Y}} O^{s_1,s_2}_{y,t,T}$, where $\mathcal{Y}$ is the set of countries.[17] Here we assume that opportunity costs accrue to the country

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

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

where the coal plant is located, since local coal production supports income and taxes in the local economy (Clark and Zhang (2022)).[18]

A broader interpretation of the opportunity costs of coal, would not only consider missed revenues to coal owners, but also lost wages of coal workers who lose their job because coal mines are shut down early and retraining costs they may face to find employment in other industries (such as the renewable industry). Under this broader interpretation, the opportunity costs of coal capture the main adverse impacts of shutting down coal mines on each local economy. To estimate the opportunity costs of coal under this broader definition, we also calculate the present value of compensation for lost wages and retraining costs (see Appendix A). 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 the sum of investments that must be made in each country y to replace phased-out coal in scenario s_2 relative to the business-as-usual scenario s_1:

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

The investment costs in country y in turn are 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 $\tau \in [t+2, T]$:

$$I_{y,t,T}^{s_1,s_2,s_r} = \sum_{\tau=t+2}^{T} \frac{I_{y,\tau}^{s_1,s_2,s_r}}{(1+\rho)^{(\tau-t)}}.^{19} \tag{9}$$

The production loss $\Delta P_{i,y,\tau}^{s_1,s_2}$ in country y is a function of the production loss of each plant in country y.

We compute annual investment costs $I_{y,\tau}^{s_1,s_2,s_r}$ in renewable energy per country y rather than per coal plant in country y, because it seems most reasonable to assume that replacing lost coal production with renewable energy does not happen at the level of the coal plant but at the level of the country. Coal companies do not necessarily have the right skills to

$P_{i,y,\tau}^{s} = \sum_{l \in \mathcal{L}_i^y} P_{i,y,l,\tau}^{s}$. 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 $\Delta P_{i,y,\tau}^{s_1,s_2} = P_{i,y,\tau}^{s_1} - P_{i,y,\tau}^{s_2}$.

[18] 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.

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

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 10 to 16. 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 (this concern is especially salient following the energy shock brought about by the Russian-Ukraine war), 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.

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

Intermittent renewable energy will typically also require complementary investments into energy storage and systems providing flexibility to the grid to manage supply and demand fluctuations (see e.g., Creutzig et al. (2017)) – even more so as the share of renewables on the power grid increases. We estimate these complementary investment costs in Appendix A. The renewable capacity $G_{y,\tau}^{s_1,s_2,s_r,q}$ (see equation 10) 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; see Table 8 in Appendix A). 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

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

We explain the interpretation of equation 11 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[20] – produces in year τ, i.e.

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

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.,

$$R_{y,\tau}^{s_1,s_2,s_r} = \sum_{q \in \mathcal{R}} R_{y,\tau}^{s_1,s_2,s_r,q}. \tag{13}$$

This is given by the renewable stock $S_{y,\tau}^{s_1,s_2,s_r,q}$ of type q in country y converted with function h into the annual energy that stock can produce. This number is then multiplied with the capacity factor $f^q \in [0,1]$ applicable to type renewable q. The capacity factor f^q captures the fact that the renewable energy stock typically does not 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

$$R_{y,\tau}^{s_1,s_2,s_r,q} = h(S_{y,\tau}^{s_1,s_2,s_r,q}) \times f^q. \tag{14}$$

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, because there is no systematic data available that would allow us to make these adjustments. Nor do we account for any time variation in the average capacity factors, as wind and solar capacity are built out in new regions with potentially different wind and sun exposure. The stock of renewable energy capacity of type q in country y at time τ is given by

$$S_{y,\tau}^{s_1,s_2,s_r,q} = \sum_{\tau_d=t+2}^{\tau-1} G_{y,\tau_d}^{s_1,s_2,s_r,q} \times (1-d_q)^{(\tau-\tau_d)} \mathbb{I}_{\{\tau-\tau_d \leq l_q\}}. \tag{15}$$

Equation 15 says that the stock of renewable energy capacity of type q at time τ is given by the renewable energy capacity $G_{y,\tau_d}^{s_1,s_2,s_r,q}$ of type q that has been built in each historical year τ_d from starting date $t+2$ when the coal phase out started up to the year before τ. The built

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

renewable capacity experiences a degradation rate (henceforth referred to as depreciation rate) of $d_q\%$ per year and has a lifetime of l_q years.

Most of the literature takes the lifetime of solar and wind farms to be $l_q = 30$ years, since empirical data on longer lifespans is not widely available (as most wind and solar farms are built in the recent two decades). Jordan and Kurtz (2013) find that the 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 farms could have a lifespan much longer than 30 years, albeit at reduced capacity (e.g., after 30 years a solar farm on average runs at 86% of original capacity). Therefore, we will also consider a life time of wind and solar farms of $l_q = 50$ years, while taking into account depreciation, as well as a lifespan dictated only by the degradation rate (i.e., l_q large).

We are now in a position to interpret equation 11. 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 this by the capacity factor f^q of renewable type q to reflect that more capacity must be built, because the capacity factor of renewable energy is less than a 100%. The lower the capacity factor of renewables is the more renewable capacity must be built to create enough renewable energy.

In our baseline analysis, we take the set of renewables to replace phased-out coal given by $\mathcal{R} = \{\text{Solar PV, Wind Onshore, Wind Offshore}\}$. 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 $\omega_\tau^{wind-offshore,s_r} = 25\%$. 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 (2021g)). 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 (2021e)). As a robustness check – and to use a phase-in scenario for renewables that is fully consistent with our Net-Zero-2050 phase-out scenario for coal – 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 replacement energy set $\mathcal{R}$ and renewable mix s_r, which we explore in our sensitivity analysis.

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

$$i_{\tau}^{s_1,s_2,s_r,q} = \alpha_q \left(\sum_{y \in \mathcal{Y}} \left(\sum_{\tau_d \leq t-1} G_{y,\tau_d}^q + \sum_{\tau_b = t+2}^{\tau-1} G_{y,\tau_d}^{s_1,s_2,s_r,q} \right) \right)^{-\gamma_q}. \tag{16}$$

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 $\sum_{\tau_d \leq t-1} G_{y,\tau_d}^q$ is the cumulative installed renewable energy capacity of type q in country y up to time $t-1$ and the second component $\sum_{\tau_d=t}^{\tau-1} = G_{\tau_d}^{s_1,s_2,s_r,q}$ 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.,

$$\Theta_q = 1 - 2^{-\gamma_q}. \tag{17}$$

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 16 with these values.

Equation 16 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 1. Figure 1 exhibits the average investment costs in complementary short-term and long-term electricity storage to make up for intermittent renewable energy as a function of the cumulative build up of installed capacity in the same scenario.[21][22] 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.[23]

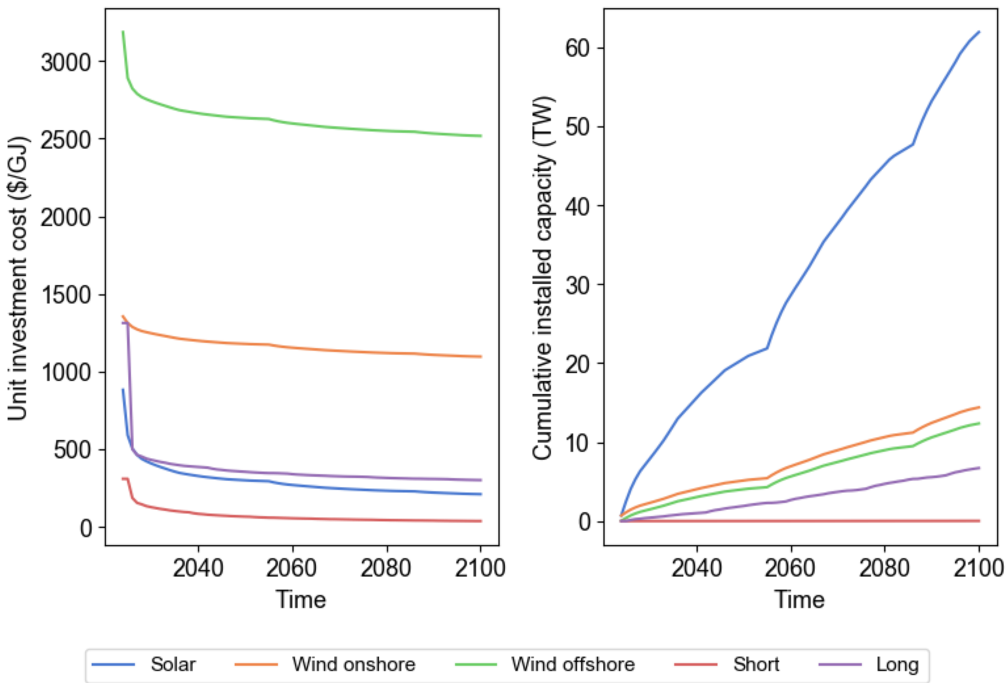


Figure 1: Drop in investment costs of each renewable (in dollars per KW) and storage type as a function of cumulative installed capacity (in TW).

[21]The projected drop in investment costs for short- and long-duration storage is somewhat conservative, because we only capture learning-by-doing effects from building sufficient storage to create a reliable grid to replace coal; while in reality, in a Net Zero 2050 scenario, experience is also gained in building storage to electrify the economy with renewables more generally (e.g., to build electric vehicles, and phase out gas and oil).

[22]The investment costs in long-term storage are projected under Wright's law (calibrated to historical cost declines) to fall fast initially since the cumulative capacity built to date is small; see Appendix A for details.

[23]A drop in investment costs resulting from learning-by-doing effects is not expected to shrink the profitable life time of renewable plants compared to a scenario of no drop in investment costs. The reason is that maintenance costs are insignificant in comparison with capex costs. So once capex costs are made, it makes sense to keep renewable plants in operation for as long as possible.

3.3 Climate Finance to Phase Out Coal

We now turn to the estimation of the aggregate amount needed to finance the coal phase-out. The financing needed to phase out coal production according to phase-out scenario s_2 relative to a business-as-usual scenario s_1, and to replace coal 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 global climate financing can be broken down into the sum of that of individual countries. The climate financing of country y is in turn given by the sum of the present value of opportunity costs of coal $O_{y,t,T}^{s_1,s_2}$ in country y and the present value of investment costs in renewables $I_{y,t,T}^{s_1,s_2,s_r}$ in country y. Hence, the present value of the global climate financing can be expressed as $C_{t,T}^{s_1,s_2,s_r} = \sum_{y \in \mathcal{Y}} O_{y,t,T}^{s_1,s_2} + I_{y,t,T}^{s_1,s_2,s_r}$ and the present value of country y's climate financing as $C_{y,t,T}^{s_1,s_2} = O_{y,t,T}^{s_1,s_2} + I_{y,t,T}^{s_1,s_2,s_r}$.[24]

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 Data

We make use of a unique granular data set from Asset Resolution (AR) on historical and projected coal production around the world. For each coal company, AR's company data capture the underlying plant-level characteristics for each unique combination of energy use (i.e. power or non-power sector), coal technology (e.g. lignite, sub-bituminous, bituminous, anthracite), coal technology sub-type (e.g. surface, underground), plant country, and geolocation. The data includes information on the ownership structure of plants, from its direct owner to any of its parents or ultimate parents.[25] 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 underlying data that feed into the company-level data specify its emission intensity (in tonnes of CO_2 per tonnes of coal) as of 2020, as well as its historical production from 2013-2021 (in tonnes of coal) and the projected production from 2022 to 2026. The emission intensity of each coal-mining plant captures its scope 1 and 3 CO_2e

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

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

emissions.[26] The scope I emission intensity captures methane emissions from coal mining, which are converted into CO_2 emission equivalent (CO_2e).

These data cover at least 85% of global coal production according to AR. Based on this AR data our estimate of global coal production in 2020 is 6.41 Giga tonnes (Gt). In combination with the AR emission intensity data, our estimate of global scope I and III emissions from coal in 2020 is 14.53 Giga tonnes of CO_2e. Both the AR coal production and emission estimates are in line with estimates of the Network for Greening the Financial System (NGFS (2021)), the BP Statistical Energy Review (BP (2021)), the International Energy Agency (IEA (2021g)), and the Global Enery Monitor[27]; see Table 1.[28]

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

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

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

The Asset Resolution data carves out how much of global coal mining is deployed in the power sector. The total capacity in the coal power sector is 1938 GW in 2020, which again is consistent with 2020 estimates of NGFS, BP Statistical Energy Review, the IEA and the Global Energy Monitor. Since the coal mining emission intensities already capture scope III emissions, we should not separately count the amount of emissions that can be avoided by phasing out coal in the power sector, as this would result in double counting.[29]

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

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

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

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

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 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) representing a business-as-usual scenario.

In our baseline analysis 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.[30][31] 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 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 $t + 2$ onward.[32] We add a two-year lag to allow for sufficient time to implement the carbon arbitrage. We also consider a scenario where coal production is completely phased out from $t+2$ onwards,

[30] The NGFS projections are consistent with the shared socioeconomic pathways (SSPs) and the Representative Concentration Pathways (RCPs) used by the Intergovernmental Panel on Climate Change (IPCC). The NGFS Current Policy scenario and NGFS Net Zero 2050 scenario take the SSP2 "middle of road" scenario which projects forward the historical trend output growth of coal in the absence of any mitigation actions (NGFS (2021)). The NGFS Net Zero 2050 scenario is in line with the RCP1.9 scenario and the NGFS Current Policy scenario is in line with the RCP6.5 scenario. The GCAM, Message-Globiom and Magpie models are three integrated assesment models employed by the IPCC to generate economic and climate outcomes for a given SSP-RCP combination.

[31] As a scenario sensitivity analysis, we apply the regional NGFS projections (based on the GCAM5.3-NGFS model) of annual coal production under the Current Policy and Net Zero 2050 scenario. The regional scenarios capture regional differences in projected coal production under a Current Policy scenario, as well as a realistic rate at which coal can be phased out in different regions under a Net Zero 2050 scenario. As another scenario sensitivity analysis, we apply the MESSAGEix-GLOBIOM 1.1 and REMIND-MAgPIE 2.1-4.2 models of the NGFS rather than the GCAM5.3-NGFS model as in our baseline.

[32] The advantage of having granular data aggregated from the plant level – despite applying the same rate of projected coal production across coal plants (within a given region) beyond $t + 2$ or 2027 – is that these data allow us to estimate costs of replacing coal with renewables at the country level (or at an even more granular level), which is needed to estimate country-level net benefits and climate financing needs.

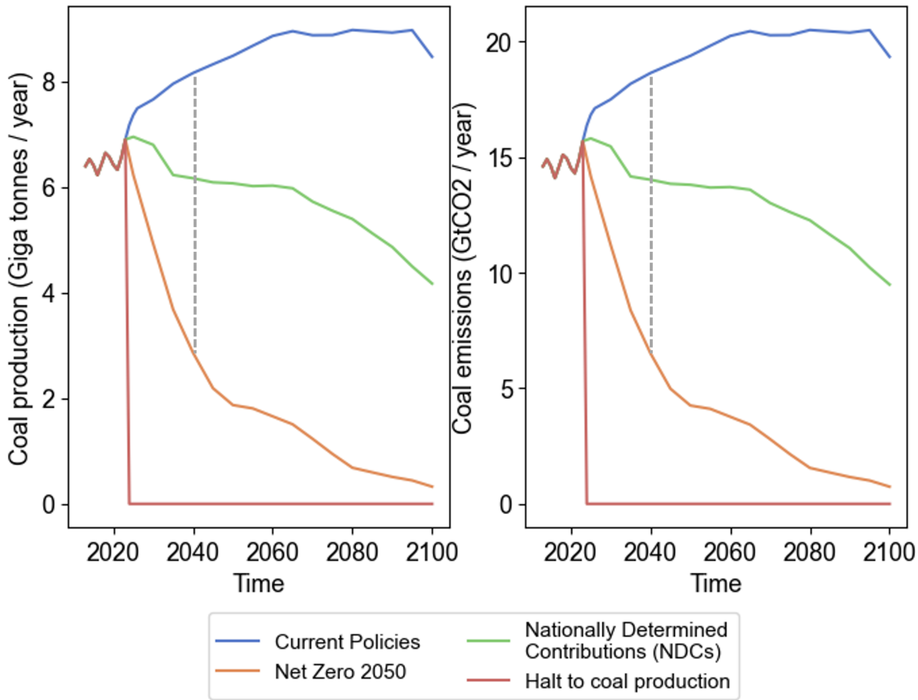


Figure 2: Global coal production under different scenarios (left plot) and associated annual global emissions (right plot).

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 the left plot of Figure 2. We also plot the Nationally Determined Contributions (NDC) scenario as a benchmark compared to the Net Zero 2050 scenario. NDCs reflect promises made by each Party of the Paris Agreement (Article 4, paragraph 2) to reduce emissions, and is shown to fall far short of what is required to reach net zero by 2050. The right plot of Figure 2 shows how the various scenarios affect global coal emissions assuming – as we do – that the emission intensity of each coal plant remains equal to its 2020 value. The difference in coal production in a given year between the Current Policy scenario and the Net Zero 2050 scenario in the left plot of Figure 2 represents the annual amount of coal that is phased out to align with the Net Zero 2050 pathway. This difference is illustrated with dotted grey lines for the year 2040. The same difference in the right plot of Figure 2 represents the amount of coal emissions that can be avoided annually by phasing out coal at this pace.

While we include the Halt to Coal Production scenario in Figure 2 as a theoretical case, it is unlikely that such scenario is feasible in practice. Instead the Net Zero 2050 scenario of the authoritative NGFS – our baseline – represents a feasible pace to phase out coal, as is widely acknowledged. Ending coal in the power sector, which our phase out scenario encompasses, is the lowest hanging fruit, and must be largely realized this decade (IEA (2021e)). 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.[33]

Opportunity Costs of Coal

To calculate the opportunity cost of phasing out coal, we obtain the operating revenue, profit margin, taxes, interest payments, and depreciation allowances for each coal 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.[34] The unit coal profit of a coal company in a given year is taken to be its free cash flow divided by its coal production that year. This gives a median free cash flow of 0.34 dollars per tonne of coal production. To obtain the median, we focus only on pure coal companies to avoid mixing our estimate of free cash flows with cash flows generated by other segments of business outside of coal. We also apply the median free cash flow of 0.34 to state-owned coal companies in our AR data for which Orbis financial data is not available. As a robustness check, we in addition compute the opportunity costs under the assumption that the unit coal profit of each coal company is equal to the median of the top 100 pure coal companies, giving a free cash flow of 0.58 dollars per tonne of coal. We take the median as a robust proxy for the unit coal profit of individual coal companies, since individual coal company estimates by Orbis revealed unrealistically large outliers.

We discount expected free cash flows of each coal company with the weighted-average cost

[33] In the AR data, over a fifth of global coal use in 2020 is in the power sector, using a capacity factor for coal power of around 50%, in line with IEA (2021a). The power sector can be made entirely coal free by switching to renewables (IEA (2021e)). 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 (2021e)). Jacobson et al. (2017) provide a road map to power energy infrastructures (i.e., electricity, transportation, heating/cooling, industry, agriculture/forestry/fishing) on renewable energy. Implementation challenges in the timely phase out of coal and replacement with renewable energy could include a lack of suitable locations, long implementation cycles, and bottlenecks in the supply of inputs and raw materials.

[34] While our assumption that future coal profits remain equal to what they are today is admittedly strong, our results in Section 5 reveal that the opportunity cost of coal is roughly three magnitudes smaller than the benefits of phasing out coal and the investment costs in renewables. Hence, even if coal profits fluctuate somewhat in the future it is implausible that our central estimate of the carbon arbitrage would be much affected.

of capital (WACC), assuming a constant beta, constant risk premium and a constant risk-free rate. We take the risk-free rate to be the nominal 30Y US treasury yield, 2.08%, and the global risk premium to be the average excess CAPE yield over the last decade of around 3% minus 1% to account for the greater diversification benefits that an investor can obtain by being globally diversified.[35] Historically the risk premium on a global index has been around one percentage point lower than the risk premium on the S&P 500 (see e.g., Dimson et al. (2003)). To obtain a robust estimate of coal company betas, we regress the MSCI World/Metal & Mining Index against the MCSI World Index using time series data from January 1 2017 until January 1 2022, giving a beta of 0.91. We assume that target leverage of each coal company is equal to the the 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%.[36] As a robustness check, we use the average global risk premium over the last 100 years, which we take to be the excess CAPE yield of Shiller averaged over 1922-2022 minus 1%, giving 3.87%.[37] We obtain a discount rate of 2.8% (and 3.6% with the average risk premium).[38]

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.

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

[36]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/.

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

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

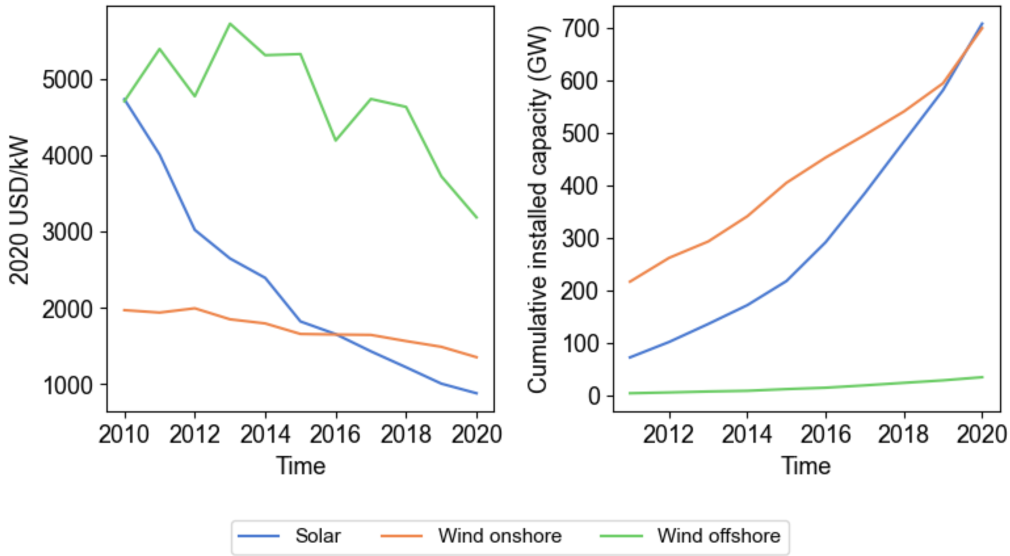


Figure 3: Investment costs in renewables (USD/KW) in the left plot and cumulative installed capacity in renewables (GW) in right plot, over 2010-2020.

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 8 in the Appendix.

5 Results

5.1 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 2.

In our baseline, we use Pindyck (2019)'s estimate for the SSC of \$80/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 2: Baseline settings of results.

Social cost of carbon	• $\theta_{pindyck} = \$80/tCO_2$
Time horizon [t+2,T] of carbon arbitrage	• $t = 2022$, $T = 2100$
Coal BAU scenario, s_1	• Stated policy scenario (GCAM5.3-NGFS)
Coal phaseout scenario, s_2	• Net zero 2050 scenario (GCAM5.3-NGFS)
Coal replacement scenario, s_r	• 50% solar, 50% wind (of which 50% onshore and 50% offshore)
Investment costs, I	• 30Y lifetime of renewable plants with depreciation and investment-cost experience curve
Opportunity costs, O	• Median unit coal profit of top 10 pure coal companies ($0.34 per tonne of coal)
Discount rate, ρ	• WACC ($\rho = 2.8\%$)

Table 3 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 $114.04 trillion, in 2022 dollars, while the present value of costs is only $29.03 trillion. This is a very large number for net present value of phasing out coal. As we will show below, the large size of this benefit is also robust to changes in our parameters. It would take an artificially low SCC to shrink this benefit to below a few billion. Clearly, the cost pales in comparison to the benefit. The value of preserving the planet, and limiting global warming by achieving a containment of coal emissions is highly valuable is naturally multiple times more than the cost of doing so.

The cost of phasing out coal can further be broken down into the investment cost, which at $28.98 trillion we estimate to be the lion share of the cost of phasing out coal, and an opportunity cost of only $50 billion. That is, by and large, the cost of phasing out coal consists in the additional investment required to shift to green sources of energy.[39] Netting costs out of benefits, we obtain a net carbon arbitrage of $114.04 - $29.03 = $85.01 trillion, or, as a fraction of current world GDP every year until 2100 a net benefit of 1.3%.[40][41][42]

[39] We have not accounted for the investments needed to keep coal mines and plants running should there be no phase out (see, Way et al. (2022)). As a result our opportunity cost number of $50 billion may be somewhat overestimated.

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

[41] 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.

[42] We report our headline results by rounding up to trillions of dollars. There is not much loss in information

Table 3: The Great Carbon Arbitrage.

Present value of benefits of phasing out coal (in trillion dollars)		114.04
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)		85.01
Carbon arbitrage relative to world GDP (%)*		1.3
Carbon arbitrage (in dollars) per tonne of coal production		136
Carbon arbitrage (in dollars) per tCO_2		60
Total coal production prevented (Giga Tonnes)		623.62
Total emissions prevented ($GtCO_2$)		1425.55
Further temperature increase – on top of 1.1 $°C$ already observed – prevented **		2.14

* The world GDP in 2020 is 84.705 trillion US Dollars according to the World Bank.** The best estimate of Matthews et al. (2009) for the temperature increase per trillion tonnes of carbon emitted is 1.5 $°C$. The 5th to 95th percentiles estimates are 1.0 $°C$ and 2.1 $°C$ per trillion tonnes of carbon emitted, associated with a further temperature increase prevented of 1.43 $°C$ and 2.99 $°C$, respectively.

We estimate that the total stranded coal production from the phase out is 623.62 gigatonnes, and total emissions avoided are $GtCO_2$ of 1425.55. We can also express our estimate of the total net social benefit from the coal phase out of 85 trillion dollars, as both the net social value per tonne of avoided coal production and per tonne of avoided carbon emissions. Our per unit estimates are by approximately \$136/tonne of coal and \$60/tCO_2, respectively. The further temperature increase – on top of the 1.1 degrees already observed – that would be prevented by executing the coal phase out is estimated to be 2.14 degrees Celcius, which would obviously have a major impact on slowing down climate change.

5.1.1 Sensitivity Analysis on the Carbon Arbitrage

In our baseline analysis, we use the Pindyck (2019)'s estimate of the social cost of carbon of \$80/tCO_2, see Figure 4.

in doing so given that the estimate for the average SCC is not tied down precisely.

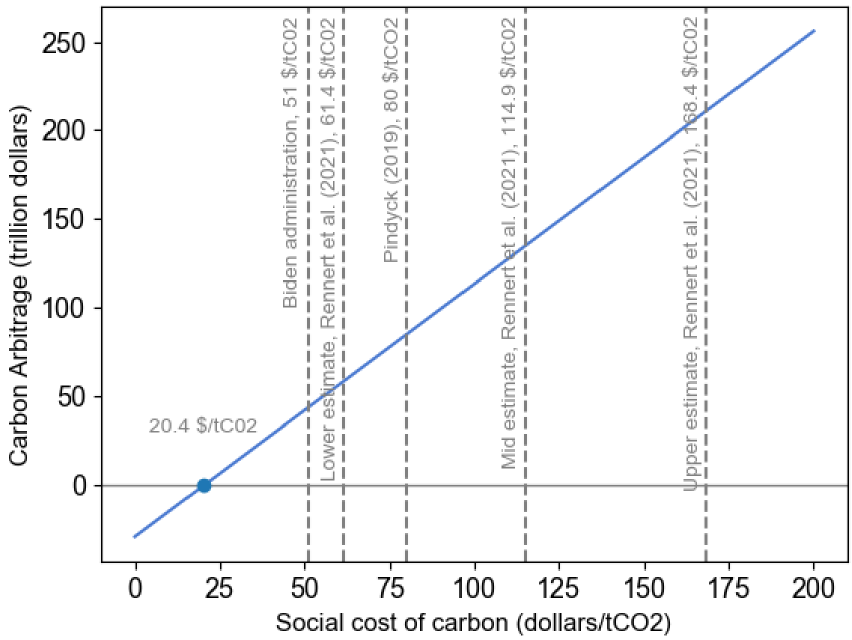


Figure 4: The carbon arbitrage as a function of the social cost of carbon.

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 $\$51/tCO_2$. 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 $\$168.4/tCO_2$, with a mid-point estimate of $\$114.9/tCO_2$.[43] The carbon arbitrage would disappear only if the social cost of carbon were to be less than or equal to $\$20.4/\mathrm{tCO}_2$. Hence, even under exceptionally conservative estimates of the social cost of carbon, a carbon arbitrage gain can be reaped from phasing out coal.

We proceed by presenting robustness analysis in Table 4 with the midpoint estimate of $\theta_{pindyck}$ =$\$80/\mathrm{tCO}_2$, the lower estimate of θ_{lower} =$\$61.4/\mathrm{tC0}_2$, and the higher estimate of θ_{higher} =$\$168.4/\mathrm{tC0}_2$. Clearly, the net benefit will be that much larger the higher the social value of the cost of carbon is assumed to be. In Table 4, we also show results for a time horizon of 2050 and 2070, in addition to the time horizon of 2100 which is our baseline. (Table 4 highlights parameters associated with our baseline with an asterisk.) The longer the time horizon, the larger the present discounted value of the carbon arbitrage.

Table 4 shows that the great carbon arbitrage through 2100 could be as large as \$211

[43] Note that the lower and upper bound for the SCC that we use for our sensitivity analysis are estimates for a marginal SCC. Based on Pindyck (2019)'s survey results the lower bound may be far too conservative, whereas the upper bound is in the middle of the range of average SCC estimates by climate scientists.

trillion if the higher estimate for the social cost of carbon of \$168.4/t$C0_2$ is assumed. On the other hand, if we use the lower estimate of a social cost of carbon of \$61.4/t$C0_2$, we obtain a net carbon arbitrage of \$59 trillion, which is of comparable magnitude. The net carbon arbitrage for shorter time horizons is mechanically smaller, but that is not surprising.[44][45]

Table 4 highlights how our carbon arbitrage estimates depend on the projection of coal production under a business-as-usual (BAU) scenario s_1. We use the global stated policy scenario generated using the GCAM5.3-NGFS model as our baseline, which has become an industry standard. To understand the sensitivity of our results to different projections, we alternatively use the MESSAGEix-GLOBIOM 1.1 and REMIND-MAgPIE 2.1-4.2 models employed by the NGFS. The MESSAGEix-GLOBIOM 1.1 and REMIND-MAgPIE model only make BAU projections of coal production up to $T = 2050$, however, rather than up to $T = 2100$, which is used in our baseline. Taking a different BAU scenario does not substantially alter our main estimate for the net social gain from phasing out coal. For a SCC of $\theta_{pindyck}$ =\$80/tCO_2 and a time horizon up to $T = 2050$, our estimate of the carbon arbitrage is \$18 trillion using the GCAM5.3-NGFS model (see Table 4), while the estimate of the carbon arbitrage is \$20 trillion using the MESSAGEix-GLOBIOM 1.1 model, and \$21 trillion using the REMIND-MAgPIE model (not shown in Table 4).

Table 4 further shows the alternative phase-out scenario where coal production is halted immediately, as of 2022. Of course, such a scenario is not very realistic as it is not obvious how coal can be replaced with renewables suddenly, especially for products such as steel. For an immediate phase out, the baseline estimate of the net carbon arbitrage benefit is slightly higher, at \$96 trillion.

Table 4 furthermore shows that the relative mixture of solar, wind onshore, and wind offshore to replace phased-out coal does not significantly alter the carbon arbitrage. Our baseline setting to replace coal with 50% solar and 50% wind (of which 50% onshore and 50% offshore) results in a slightly lower carbon arbitrage, at \$85 trillion, than that obtained under the Net

[44] 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.

[45] The average SCC captures benefits of avoided emissions related to reduced air pollution only in so far as it affects GDP. To gain some insight into how large the stand-alone health benefits from reduced air pollution might be, we conduct a back-of-the-envelope calculation using the estimates of Rauner et al. (2020) for a coal-exit scenario. We find that the present value of benefits from reduced air pollution is around \$52 trillion over the period 2022-2050. This number is obtained from Figure 2 of Rauner et al. (2020), which estimates that healthcare benefits are: \$3.8 trillion in 2050; around \$2.4 trillion in 2040; and around \$2 trillion in 2030. By assuming that the healthcare benefit of \$2 trillion applies not only in 2030 but applies each year in the period 2022-2030, the healthcare benefit of \$2.4 applies not only in 2040 but applies each year in the period 2031-2040 and the healthcare benefit of \$3.8 trillion applies not only in 2050 but each year in the period 2041-2050, and discounting these future benefits at $\rho = 2.8\%$ (our baseline discount rate), we obtain a present value of avoided damages from air pollution of \$52 trillion. The co-benefit of avoiding coal emissions in terms of lower air pollution is thus substantial.

Table 4: Sensitivity analysis of the great carbon arbitrage (in trillion dollars) around our baseline settings (see Table 2), shown for different estimates of the social cost of carbon θ.

		Carbon Arbitrage		
		θ_{lower}	$\theta_{pindyck}$	θ_{higher}
Time horizon [t+2,T] of carbon arbitrage	• $T = 2050$	9	18	59
	• $T = 2070$	28	44	121
	• $T = 2100$	59	85*	211
Coal BAU scenario, s_1	• s_1 = Stated policies (GCAM5.3-NGFS)	59	85*	211
Coal phase out scenario, s_2	• s_2 = Net zero 2050	59	85*	211
	• s_2 = Halt to coal production	62	96	260
Coal replacement scenario, s_r	• 50% solar, 50% wind	59	85*	211
	• Net zero 2050 scenario (56% solar, 44% wind)	66	92	218
	• 100% natural gas	-68	-62	-32
	• 33% solar, 33% wind, 33% natural gas	-14	6	100
	• 45% solar, 45% wind, 10% natural gas	5	29	146
	• 100% nuclear	-1	26	152
	• 33% solar, 33% wind, 33% nuclear	8	35	161
Opportunity costs, O	• Median unit coal profit of top 10 pure coal companies	59	85*	211
	• Median unit coal profit of top 100 pure coal companies	58	85	211
	• Median unit coal profit of top 10 pure coal companies, including broader opportunity costs (compensation for lost wages)	58	85	211
	• Median unit coal profit of top 10 pure coal companies, including broader opportunity costs (compensation retraining costs)	58	85	211
	• Median unit coal profit of top 10 pure coal companies, including broader opportunity costs (compensation for lost wages + retraining costs)	58	85	211

Table 5: Continuation of our sensitivity analysis of the great carbon arbitrage (in trillion dollars) around our baseline settings (see Table 2), shown for different estimates of the social cost of carbon θ.

		Carbon Arbitrage		
		θ_{lower}	$\theta_{pindyck}$	θ_{higher}
Investment Costs, I	• 30Y lifetime of renewable plants with depreciation (experience curve)	59	85*	211
	• 50Y lifetime of renewable plants with depreciation (experience curve)	76	106	250
	• Lifetime of renewable plants dictated by depreciation (experience curve)	165	222	492
	• 30Y lifetime of renewable plants with depreciation (no experience curve)	43	70	196
	• LCOE as proxy for investment costs (experience curve)	27	48	151
	• 30Y lifetime of renewable plants with depreciation, including short-term storage (experience curve)	53	80	206
	• 30Y lifetime of renewable plants with depreciation, including long-term storage (experience curve)	57	83	209
	• 30Y lifetime of renewable plants with depreciation, including short-term storage + long-term storage (experience curve)	51	78	204
	• 30Y lifetime of renewable plants with depreciation, including short-term storage + long-term storage + grid extension (experience curve)	34	61	187
	• 30Y lifetime of renewable plants with depreciation, including short-term storage (no experience curve)	24	51	177
	• 30Y lifetime of renewable plants with depreciation, including long-term storage (no experience curve)	39	65	191
	• 30Y lifetime of renewable plants with depreciation, including short-term storage + long-term storage (no experience curve)	20	46	172
Discount rate, ρ	• WACC ($\rho = 2.8\%$)	59	85*	211
	• WACC with climate-risk premium coal companies ($\rho = \rho + 0.5\% = 3.3\%$, $\rho = 2.8\%$)	59	85	211
	• WACC with average risk premium over 1922-2022 ($\rho = 3.6\%$)	63	90	216
	• Benchmark ($\rho = 5\%$)	68	95	221

Zero 2050 scenario of the NGFS, at \$92 trillion, in which phased-out fossil fuels are on average replaced with a relative mixture of 56% solar and 44% wind (of which 42% onshore and 2% offshore). Our estimate is somewhat lower because investment costs in wind, especially offshore wind, are higher than those in solar (recall Figure 3 and 1). A replacement scenario s_r in which solar and wind are the dominant forms of energy to replace coal is the central scenario in most Net Zero 2050 pathways (see e.g. IEA (2021d)).

In the interim period during which the switch from coal to renewables is implemented, coal could in part be replaced with a less polluting fossil fuel, such as natural gas.[46] If coal would be replaced with 33% solar, 33% wind (of which 50% onshore and 50% offshore), and 33% natural gas, the carbon arbitrage for a SCC of \$80/tCO_2 sharply drops from our baseline estimate of \$85 trillion to \$6 trillion (see Table 4). If instead gas would fulfill a comparatively smaller role as an transition fuel and be replaced with 45% solar, 45% wind (of which 50% onshore and 50% offshore), and 10% natural gas, the carbon arbitrage for a SCC of \$80/tCO_2 shrinks to \$29 trillion. Clearly, replacing coal with gas results in a smaller net gain than doing so with renewables such as solar and wind. The reason is twofold. First, the present value of benefits of phasing out coal is smaller as benefits of reduced emissions from coal are partly offset by emissions from natural gas. Second, the median LCOE globally of gas is higher than that of solar PV and wind onshore, while being lower than that of wind offshore; this holds, for instance, in the United States, Europe and China (IEA (2020a)). Therefore, it is efficient to rely as little as possible on natural gas.

Of course, coal can also be replaced with other types of transition fuels, or renewables (once they become viable), as well as with nuclear energy. It is straightforward to redo our calculations with alternative assumptions on the replacement scenario s_r, as our methodology does not depend on a specific replacement energy mix. For instance, if coal were to be replaced fully with nuclear energy, we estimate that the net gain would drop from our baseline estimate of \$85 trillion to around \$26 trillion (see Table 4). One reason is that nuclear plants are much more expensive to build than solar PV and wind onshore – the time to build (around 15 years) is nearly four times longer than for solar and wind energy. Unlike renewables, nuclear energy has not witnessed sharp cost declines from learning-by-doing effects in the past, so is not projected to experience cost declines in the future.[47] Replacing coal with nuclear energy

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

[47] In our model, we proxy the investment costs in nuclear energy with its global average LCOE (see Appendix A), capturing also operation and financing costs related with building and maintaining nuclear plants. Because we capture these extra cost components, our estimate of the net gain from replacing coal with nuclear energy (\$26 trillion) is somewhat suppressed and can best be compared against our estimate of the net gain from

(\$26 trillion) remains more beneficial than replacing it with natural gas (at \$-62 trillion) – even though the global median LCOE of nuclear and natural gas are estimated to be nearly the same (IEA (2020a)) –[48] because nuclear energy does not emit carbon. Our calculation of the costs of replacing coal with nuclear, reliant on the LCOE of nuclear, neither takes into account costs of nuclear waste nor the risks of nuclear energy. Once that is taken into account, the net gain of replacing coal with nuclear becomes even smaller (below \$26 trillion) compared to the net gain of replacing coal with renewables (at \$85 trillion).

Coal emissions could alternatively be abated by means of carbon capture, utilisation and storage (CCUS) once it becomes cost effective to do so. CCUS involves the capture of CO_2 from large emission sources or directly from the atmosphere. In 2021, the world's largest direct air carbon dioxide capture and storage system to date opened in Iceland and is called Orca. It can capture up to 4,000 tCO_2 a year and costs around \$1200/tCO_2 to be removed. We estimate the net gain from capturing emissions from coal production using direct air capture with a cost of \$1200/tCO_2 is \$-372 trillion (i.e., it gives a net loss).[49] Based on current levelized costs, CCUS based on direct air capture is thus not an attractive alternative to replacing coal with renewables. Of course, CCUS levelized costs may fall further in the future (IEA (2022)) and also vary significantly by CO_2 source (IEA (2021c)). Under our baseline settings, we estimate that only once the levelized cost of CCUS from coal sources drop on average below \$266/tCO_2 a positive net gain from capturing coal emissions can be reaped.[50]

Table 4 shows changing assumptions on future profits of coal companies does not alter the carbon arbitrage much, since opportunity costs of coal pale by comparison to the social gain of phasing out coal, and the investment costs in renewables. This is true even when we consider a broader definition of opportunity costs that includes compensation for missed wages of coal workers losing their jobs in the coal phase out (for the duration of five years while they seek employment in other industries or retire early) and compensation for retraining costs to qualify

replacing coal with renewables when also for renewables the LCOE is used as a proxy (\$48 trillion; see Table 5).

[48]The 2020 median LCOE estimate by IEA (2020a) (around \$70/MWh) we use seems to be on the low side compared to the low LCOE estimate (around \$110/MWh) and high LCOE estimate (around \$195/MWh) for nuclear plants estimated by Lazard (Way et al. (2021)). Given the large cost overruns to build a nuclear power plants, replacing coal with nuclear could thus result in a smaller net benefit (at \$-119 trillion, if we take Lazards' high estimate of \$195/MWh) than replacing it with natural gas (at \$-62 trillion).

[49]The present value of costs of removing $\Delta E_{i,\tau}^{s_1,s_2}$ amount of CO_2 from the atmosphere per year over $[t+2,\bar{T}]$ is given by $C_{t,T}^{s_1,s_2,s_r} = \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{\bar{T}} \frac{\Delta E_{i,\tau}^{s_1,s_2} \times c}{(1+\rho_i)^{(\tau-t)}}$, where c=\$1200/tCO_2 in this case, and $\bar{T}$ is the last year in which renewable plants built up to T can help reduce emissions. The present value of benefits $B_{t,T}^{s_1,s_2,\theta}$ of capturing emissions from coal is the same as the present value of benefits of reducing emissions by replacing coal with renewables (i.e., $B_{t,T}^{s_1,s_2,\theta}$=\$114 trillion).

[50]No practicable technologies or methods to capture fugitive methane emissions from operating open-cut coal mines exist so far. So replacing such coal mines with renewables (or other low-carbon options) is currently the only way to avoid emissions from open-cut coal mines. See: https://www.ft.com/content/387accfa-03ec-4103-9623-98ad174abb38.

for employment in other industries (e.g., the renewable industry). These broader opportunity costs bring our baseline estimate of the global opportunity costs of coal from $50 billion up to $331 billion (of which $275 billion for lost wages and $7 billion for retraining).[51] As the opportunity costs of coal are in the order of billions and the benefits from avoiding coal emissions are in the order of trillions, including compensation of workers (see details Appendix A) does not significantly change our baseline estimate of the net gain from replacing coal with renewables (at $85 trillion).

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 $85 to $106 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 $222 trillion.

Even if we assume that future investment costs in renewables will not fall further because of an (unrealistic) absence of "learning", or because of increasing scarcity of raw materials used as inputs for renewables, we still obtain a significant carbon arbitrage of $70 trillion. As a robustness check, we proxy investment costs in renewable energy to replace coal energy by means of the levelized cost of energy (LCOE); see details in Appendix A. The LCOE not only captures investment costs, but also captures other costs including financing and operational costs, which explains why our estimate for the carbon arbitrage is then reduced to $48 trillion (see Appendix A). The LCOE proxy is nonetheless useful to benchmark our results.[52]

It is often thought that the costs of energy storage and grid extension make the switch from coal to renewables prohibitively expensive. To the contrary. Table 5 shows that including investment costs in short-term and long-term storage (and associated systems to manage increased demand and supply fluctuations when electricity is generated with renewables) does not significantly shrink our headline result: a net gain of a $78 trillion dollars remains to be reaped. Even if we further include a very conservative estimate of grid extension costs, by assuming grid extensions will have to be made every time coal is replaced with renewables (see details Appendix A), the net gain from replacing coal with renewables is $61 trillion.[53] Hence, the global

[51] The min-max estimates of the retraining costs are estimated at $1.8-$19 billion dollars globally based on a study by Louie and Pearce (2016) (see details Appendix A).

[52] The LCOE proxy is a useful proxy for estimating the net gain of replacing coal with renewables if not only the investment costs in renewables would be compensated, but also the financing costs and operational costs. Compensation for such variable costs will not be necessary in practice, as renewable plants generate profits to cover these.

[53] Investments in energy storage and the grid are to some extent substitutes. The more storage exist the better demand and supply imbalances can be smoothed, which is a reason fewer capacity expansions in the grid will

price tag (under a conservative estimate) on the investments in storage and that would have to be made when replacing coal with renewables is around $7 trillion. This estimate assumes that 20% of daily electricity generated is stored in short-term Li-ion batteries and one month worth of electricity generation is stored long-term in green hydgrogen generated by electrolyzers that are powered by renewables (see Appendix A for details). Way et al. (2021) discuss that such storage will be *more than sufficient* to cover daily and long-term fluctuations in demand and supply.[54]

The last row of Table 5 shows the great carbon arbitrage with alternative discount rate assumptions. In the baseline, we are using a WACC of coal production of 2.8% based on a 2022 risk premium of 1.99%. When the average risk premium over the last 100 years is used of 3.87%, the discount rate rises from 2.8% to 3.6%, with an associated carbon arbitrage increase from $85 to $90 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 $80/tCO2$, we find 70 to 132 trillion dollars, around the 85 that is our preferred estimate. Clearly, alternative assumption lead to different results, but as a fraction of GDP this 70 - 132 range reduces to a range of 1.1 - 2.0 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 to 310 trillion, which is fairly wide (it corresponds to a range as a percent of GDP from 0.7 to 4.6 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

have to take place.

[54] In fact, for a renewable energy share on the grid of less than 85%, as is typically the case in our scenario where only coal is replaced with renewables and overall renewable electrification of the economy is not considered, estimate that short-term storage alone is sufficient to create a reliable grid. In such case, the global price tag (for short-term storage) is $5 trillion, reducing the net gain from replacing coal with renewables to only $80 trillion. We likely underestimate learning-by-doing effects driving down investment costs in short-term storage as we only capture learning that happens from building storage to phase out coal, whereas in reality storage would be expanded as the economy more generally decarbonizes, so the global price tag for energy storage could be smaller still. In case raw materials for building batteries get so scarce that no further drops in investment costs take place, which is unlikely in the next 50 years unless major geopolitical conflict occurs, the net gain from replacing coal would drop from $85 trillion (under our baseline) to $51 trillion (including short-term storage costs; no experience curve).

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 4.[55]

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

		Carbon arbitrage			
		θ_{lower}	$\theta_{pindyck}$	θ_{higher}	
Time horizon [t+2,T] of carbon arbitrage	$T = 2050$	(2, 36)	(11, 66)	(51, 148)	**(2, 148)**
	$T = 2070$	(16, 44)	(32, 66)	(109, 170)	**(16, 170)**
	$T = 2100$	(43, 94)	(70, 132)	(196, 310)	**(43, 310)**

5.2 Climate Finance to Phase Out Coal

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 financing 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 climate financing by geography, and state of development. Figure 5 shows the present value of all future conditional climate financing needs for developed countries, developing countries, and emerging markets.[56] We also report a breakdown by continent: 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.[57] Importantly, Figure 5 shows there are important financial needs to fund the investments in renewables

[55] We do not report the 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 do not report the estimate under the assumption that the lifetime of a renewable plant is dictated only by its depreciation rate, as this assumption gives implausibly long lifetimes (i.e., greater than a hundred years). We deem neither of these benchmarks plausible. We have also performed sensitivity analyses where coal is in part replaced with gas or nuclear energy, but we do not report the results of this analysis, since our focus is on replacing coal with renewables. Finally, we exclude estimates based on a broader definition of the opportunity costs of coal and based on estimates of investment costs capturing complementary investments in energy storage and the grid, but we do not report the results of this analysis in Table 6, as the data available for this analysis is more patchy.

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

[57] Quantitative estimates of climate financing needs to replace coal with renewables across the world, and over time, can be downloaded (for a variety of parameters) from: https://greatcarbonarbitrage.com.

to replace coal not just in developing and emerging market economies, as is commonly thought, but across all levels of development.[58]

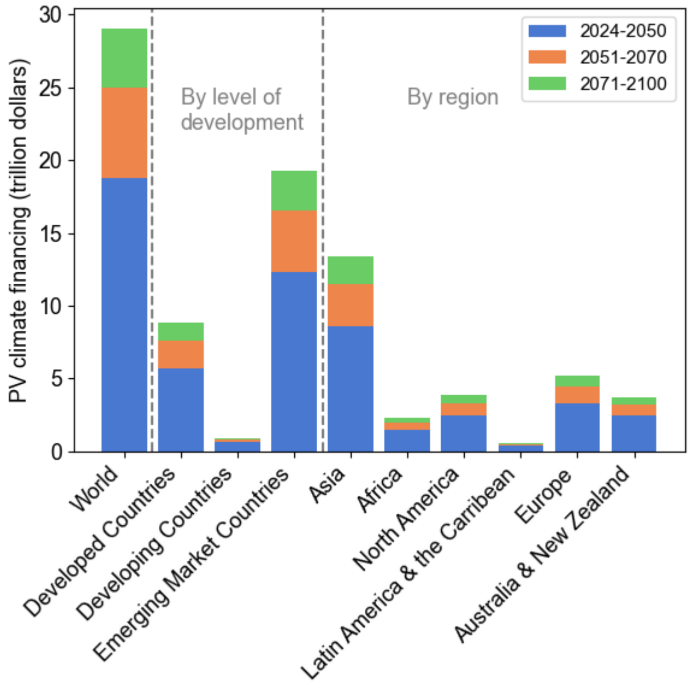


Figure 5: Present value of all future conditional climate financing needs.

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 6 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

[58] In our paper, when we speak of "climate finance" we thus either refer to domestic investments to replace coal with renewables in the home country (which could be a developed country) or foreign transfers to help replace coal with renewables abroad.

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.

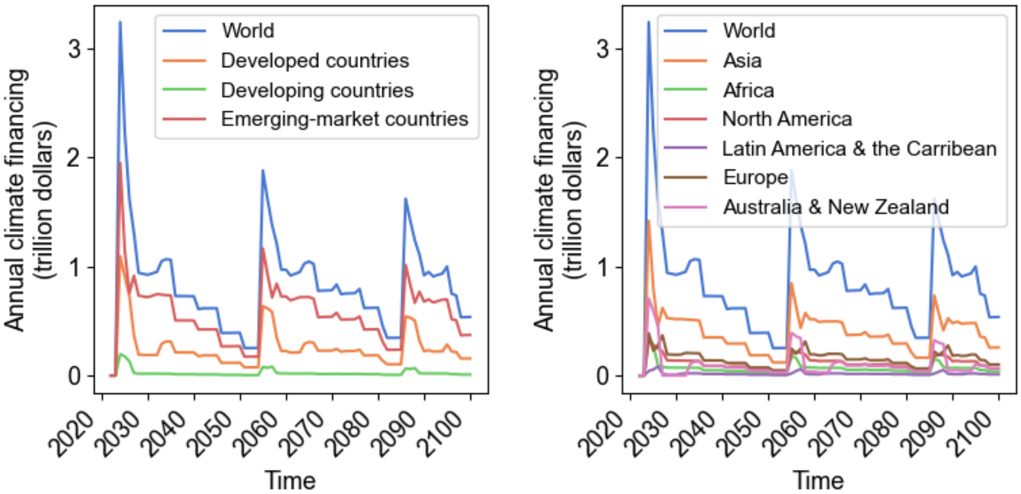


Figure 6: Annual conditional climate financing needs (in trillion dollars; non-discounted) broken down by level of development (left plot) and region (right plot).

Figure 7 shows the present value of the climate financing over 2024-2100 (relative to cumulative GDP) plotted against GDP per capita.[59]

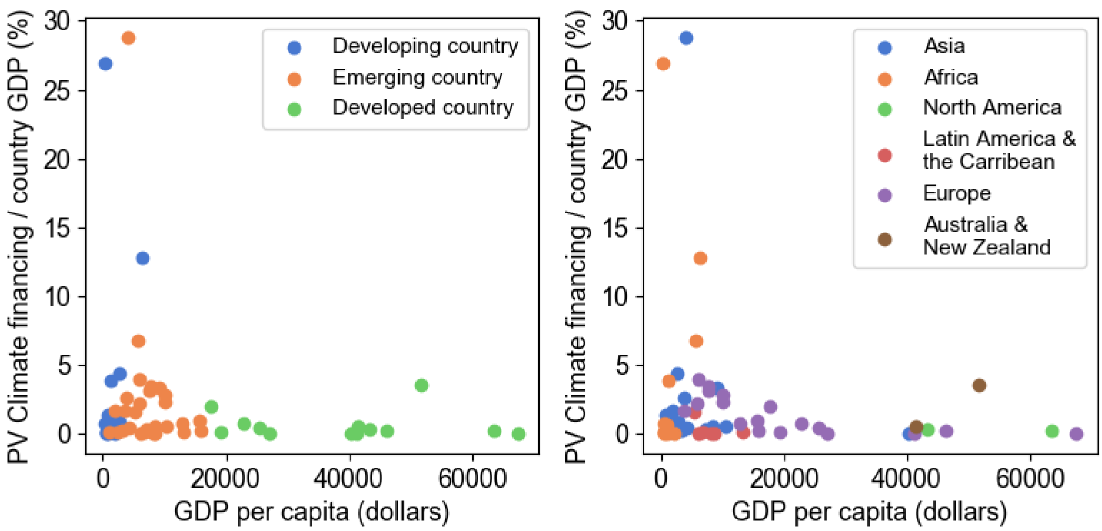


Figure 7: Present value of conditional climate financing need of each country relative to its GDP over 2024-2100. Countries are coloured either by level of development (in left plot) or by region (in right plot).

Financing needs per GDP tend to be higher for countries with lower GDP per capita, with

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

some notable outliers for emerging and developing countries. The right chart of Figure 7 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.[60] Hence, climate finance mechanisms to ensure a green transition appear as a first order policy goal.

5.2.1 Sensitivity Analysis of Climate Financing

Figure 8 presents sensitivity analysis of the global climate financing. We focus first on the top left and bottom plots. The top left plot shows the required annual financing (in trillion dollars) and the bottom plot shows its the present value. Each plot is based on 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 8 reveals that the investment cycle lengthens to 50 years if we lengthen the assumed lifetime of renewables from 30 to 50 years (compare blue and red line). 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 (see purple line). Two immediate observations emerge from Figure 8. First, if we allow for experience (i.e., learning by doing) effects later investment cycles come with lower capex costs (compare blue and orange line). Second, LCOE is a misleading proxy for investment costs as it does not capture the front loading of capex investments (see purple line).

The assumption on the lifetime of renewables does not matter much for the present value of the global climate financing, as seen by comparing the left panel (our baseline) with the middle panel of the bottom plot of Figure 8. What does matter is the degree of learning (E/no E) and the resulting fall in future investment costs. By construction, the present value will be higher with the LCOE proxy, since the LCOE also captures operational and financing costs.

In the right top plot of Figure 8, we show how our baseline estimate of global annual climate financing (see blue line) would change if we take into account complementary investment needs in short-term storage (S), long-term storage (L), and compensation for lost wages and retraining. As can be seen, including these costs does not significantly our alter our annual climate finance estimates; costs increase by around 200 billion annually at most. The right panel of the bottom plot confirms that in present value terms including a broader definition of investment costs and opportunity costs of coal barely changes our estimates of the present value of global climate financing needs to replace coal with renewables.

[60] Quantitative estimates of climate financing needs to replace coal with renewables for each country in the world, and over time, can be downloaded (for a variety of parameters) from: https://greatcarbonarbitrage.com.

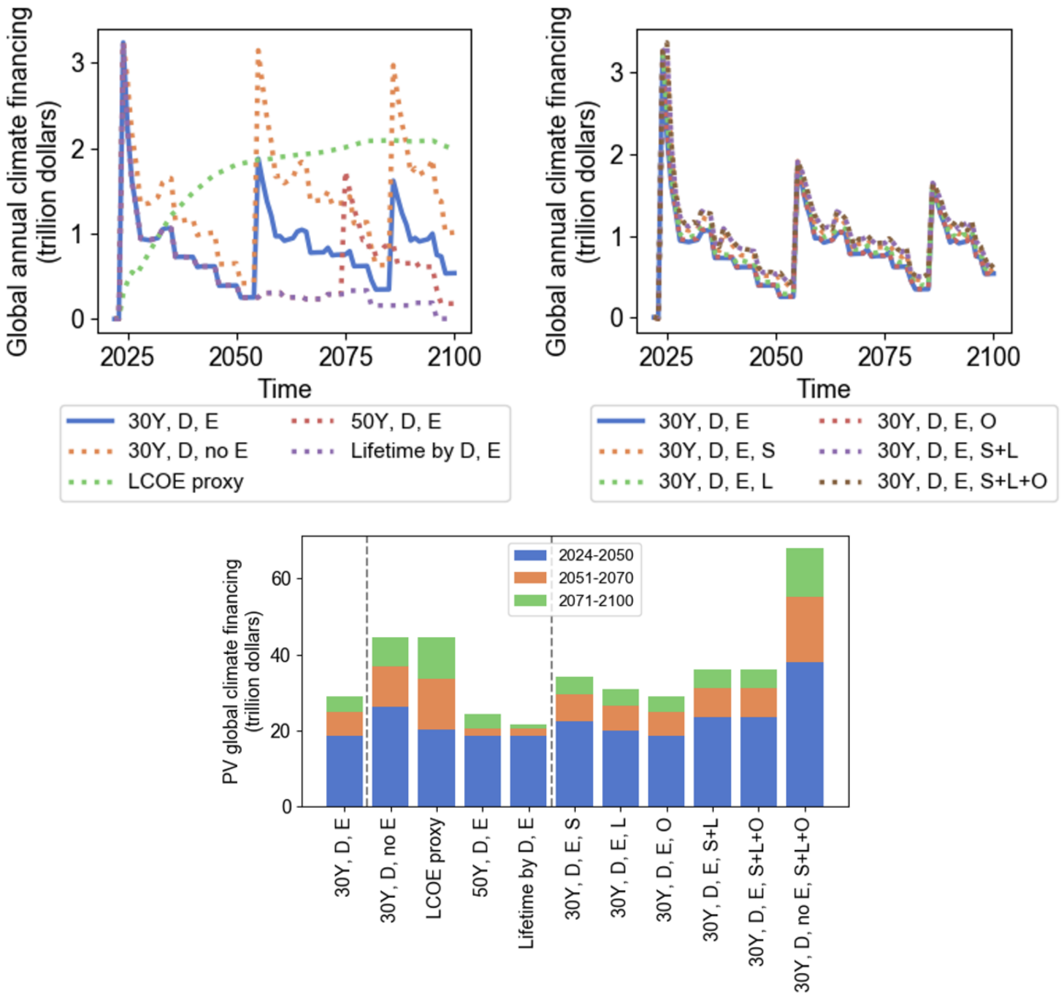


Figure 8: Annual global climate financing need (in trillion dollars; non-discounted) on the left plot and its the present value on the right plot, for different assumptions on the effective lifetime of renewables and investment costs.

Figure 9, we conduct additional sensitivity analysis of the required financing, this time by comparing the estimates of the global against the regional scenarios of the NGFS. The global NGFS scenario assumes that the coal production trajectories under the Current Policy scenario and Net Zero 2050 scenario are homogeneous across countries in the world, whereas the regional NGFS scenarios (also using the GCAM5.3-NGFS model) capture that certain regions, such as Africa and Asia, will have a faster growth of energy demand, and therefore coal demand, over the course of this century under the current policy scenario. The regional NGFS scenarios furthermore capture that certain regions, such as the developed world, are expected to phase out coal faster than others. While we find that the annual climate financing in certain regions is higher (e.g., in emerging countries, developing countries; in particular Asia) and in other regions is lower (e.g., in developed countries; in particular America and Europe) in the regional than in the global NGFS scenario, the present value of climate financing does not drastically differ. This is evident from the fact that the estimated present value of climate financing in the regional and global scenario sit close to the diagonal in Figure 9.

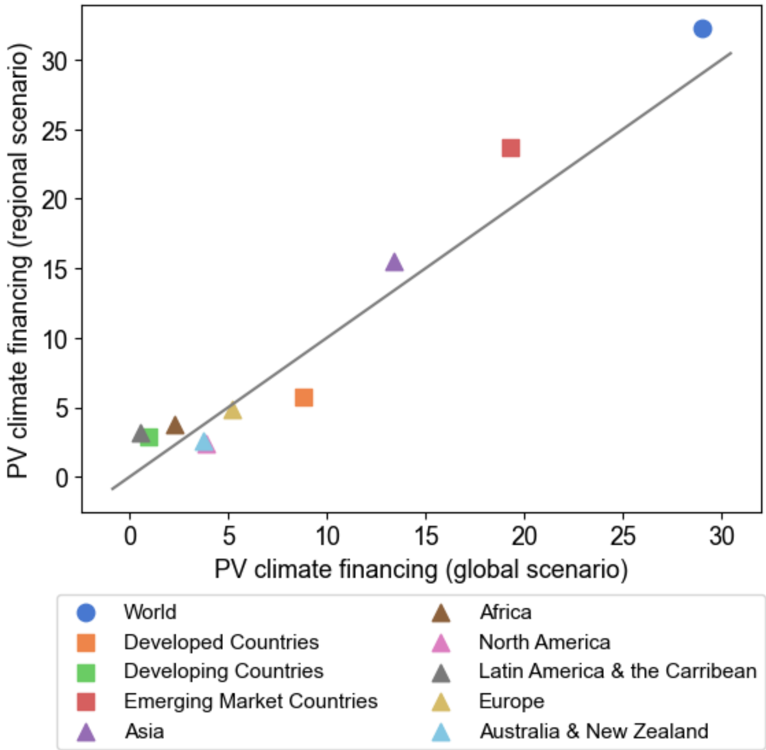


Figure 9: The present value of climate financing under the global vs. regional NGFS scenarios. Regions are shown with a square and countries with a triangle.

6 Coasian Bargain and Climate Finance

In light of the sizable gains from phasing out coal we identify in this paper it is all the more important to keep alive any negotiations on an agreement to stop burning coal, and to pursue policies that help accelerate the replacement of coal with renewable energy. Under a Coasian bargain it is sound economic logic to pay polluters for the costs of replacing coal with renewables, and to pay for the investment costs in renewables to attain the benefits from avoided emissions.

Blended Climate Finance

We estimate that the total funding costs to globally phase out coal is around 29 trillion dollars. It is not desirable, and often not possible to pay for all these investments through public funds alone. We propose that climate finance for countries be operationalized with blended finance, which leverages public funds to catalyze investments from capital markets. But much of the funding can come from capital markets through via blended finance (Arezki et al. (2016) and

Bolton et al. (2020)).

There are several advantages in structuring the climate financing in the form of blended finance. First, it reduces the reliance on public funds that have a higher marginal cost (Browning (1976)). Public funds would likely have to be obtained partially by raising taxes, which have a distortionary effect.[61] Second, it limits increases in public-debt-to-GDP. This is especially relevant for countries with pre-existing sovereign debt sustainability vulnerabilities.[62] Third, the freed up public funds could be used to serve other purposes in the economy (e.g., education).

A highly innovative example of how blended finance might work in practice in a public-private partnership model is the emerging market green bond fund jointly implemented by the International Finance Corporation (IFC)[63] and the asset management firm Amundi. In that deal, an asset backed security (ABS) fund was constructed in which a development institution (IFC) took the first-loss tranche of $125 million. The senior tranches were thereby sufficiently de-risked by public sector investments so as to receive investment grade rating, and were all successfully placed in the marketplace. The fund invested in due time in climate-friendly assets. The total size of the deal was about $2 billion. Importantly, the senior tranche was 90% of the value of the fund. This indicates the enormous potential of public money provided by a multilateral institution to channel private money to green projects (typically at 1:9 or even 1:10 ratios).

Taking the IFC-Amundi deal as a representative blended finance model, approximately 10% of public funds worldwide would have to be committed to finance the renewable energy capacity required to replace coal. This means that governments would have to commit around 2.9 trillion dollars (in present value terms) into junior tranches.[64] The remaining 90% (around

[61] The MCPF differs across countries, but it tends to range between 1.1 and 1.6. If we apply the conservative estimate of 1.6 to the public investments of $2.9 trillion, the present value of public's costs rises to around $4.5 trillion, reducing the global net gain from phasing out coal and phasing in renewables from our conversative baseline estimate of around $85 trillion to around $80 trillion. Ignoring the MCPF in our analysis thus does not qualitatively or quantitatively alter significantly our headline finding that a large net gain can be reaped from phasing out coal.

[62] As described in Prasad et al. (2022), a significant number of countries – 73 in total – were in debt distress or at risk of debt distress in 2020 and therefore made eligible for the Debt Service Suspension Initiative (DSSI), set up by the G20, and encouraged by the World Bank and International Monetary Fund. Countries that would need most climate financing to replace coal with renewables are typically not those that are most at risk of debt distress (not shown here). In fact, none of the top-10 countries in terms of climate financing needs were eligible for the DSSI. When countries are, however, grouped according to the amount of climate debt they would need to replace coal with renewables relative to their GDP, we find that several countries that feature atop the list are at risk of debt distress or in debt distress (not shown). So for these countries, taking on more climate financing would be problematic. Bolton et al. (2022) discuss ways in which sovereign debt of countries with a weak existing fiscal position can be restructured to create sufficient fiscal space to take on additional debt for the purposes of climate adaptation or mitigation financing.

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

[64] Such government financing could be seen as subsidies (whenever these contribute to the domestic replacement of coal with renewables) or transfers (whenever these contribute to foreign replacement of coal with renewables) given their high risk profile. It is entirely possible, however, that governments earn all their investments back with a positive return, as viable renewable plants built to replace coal generate a revenue stream for (public)

26.1 trillion dollars) would come from capital markets. Importantly, this blended finance model substantially changes the calculus of governments in deciding whether to pursue a coal phase-out. With only 10% of the cost directly coming from public funds it is much easier to make a case for such a phase-out.

In reality, the impacts of climate change are unevenly distributed across the world (IPCC (2021)).

7 Country Costs and Benefits: An Economic Basis for Coasian Bargaining on Climate Finance

We take the country-level SCC estimates $\hat{\theta}^y$ of Ricke et al. (2018) as our basis to determine a country-level mean SCC. For consistency, the sum of country-level mean SCCs θ^y across countries y must add up to the global mean SCC θ. Accordingly, we take the share of the global mean SCC ($\theta =$\$80/tCO_2 in our benchmark calculations) assigned to each country to be the ratio of the Ricke et al. (2018) country-level SCC to the global SCC, $\frac{\hat{\theta}^y}{\hat{\theta}}$.[65]

The present value of benefits to country y in a *global* deal to phase out coal is then given by:

$$B^{s_1,s_2,\theta^y}_{y,t,T} = \theta^y \times \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \Delta E^{s_1,s_2}_{i,\tau}, \quad (18)$$

[66]

where $\theta_y = \theta \times \frac{\hat{\theta}_y}{\hat{\theta}}$. The present value of costs to country y in a global deal to phase out coal is given by $C^{s_1,s_2,s_r}_{y,t,T}$ (defined in Section 3.2). A plausible baseline position in a Coasian bargain to phase out coal is that each country pays for its own costs $C^{s_1,s_2,s_r}_{y,t,T}$ to replace coal with renewables. The country-level costs versus benefits in a global deal to phase out coal and replace it with renewables are shown in Figure 10. There is significant heterogeneity across countries. Yet, most countries (all those above the diagonal) are better off joining a global phase-out even if they must cover all their country-level costs.

---

investors.

[65]The country-level SCC estimates of Ricke et al. (2018) capture temperature-related climate damages, which are based on empirical country-level damage functions estimated by Burke et al. (2015). In particular, we use the long-run, median, country SCC estimates based on SSP2, RCP6.5 and a pure rate of time preference. We have conducted sensitivity analysis to show that our results are robust to using other parameter settings in the study of Ricke et al. (2018). Ricke et al. (2018) discuss how the various types of climate damages could be better captured in the country-level SCC in future research. We expect country-level SCC estimates to further improve.

[66]Equation 18 on country-level benefits is defined similarly to equation 2 on global benefits in a global deal to phase out coal.

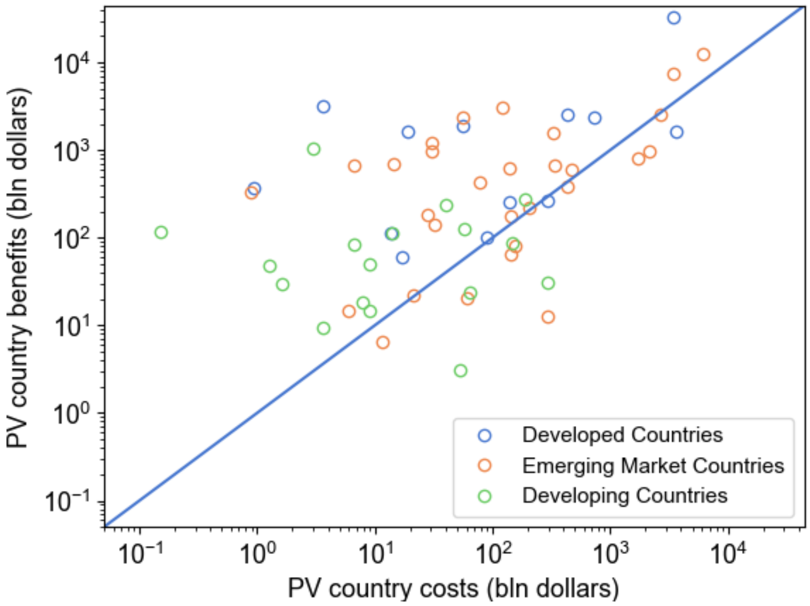


Figure 10: The present value of country-level costs and benefits in a global deal to phase out coal.

In a global agreement to phase out coal, an individual country y could offer financing $F_{y,w}$ for costs to replace coal with renewables in (one or more) foreign countries w, in addition to paying for its domestic costs $C^{s_1,s_2,s_r}_{y,t,T}$, and still be better off as long as $B^{s_1,s_2,\theta^y}_{y,t,T} - C^{s_1,s_2,s_r}_{y,t,T} - \sum_{w\in\mathcal{Y}\setminus y} F_{y,w} > 0$. We observe from Figure 10 that most countries sit far above the diagonal line, so can offer finance for foreign costs to replace coal with renewables while retaining a substantial net benefit.

Instead of a global deal, regional deals could also be struck. The obstacles to bargaining and transaction costs will be lower when regional deals are struck as fewer parties have to come together. Tangible benefits from reduced emissions can be reaped even if only a climate club (e.g., one region or country) strikes a deal to phase out coal. The larger the climate club in terms of the coal emissions it can avoid, the closer a deal of such climate club gets to a global deal in terms of the magnitude of benefits it can deliver (i.e., climate damages it can avoid).

The present value of benefits to countries $y \in \mathcal{Y}^U$ resulting from the phase out of coal by countries $w \in \mathcal{Y}^W$ participating in *climate club* W is given by the product of the collective SCC θ^U of countries $y \in \mathcal{Y}^U$ in U and the emission reductions by *climate club* W $(\sum_{y\in\mathcal{Y}^W}\sum_{i\in\mathcal{C}}\sum_{\tau=t+2}^{T}\Delta E^{s_1,s_2}_{i,y,\tau})$, i.e.:

$$B^{s_1,s_2,\theta^U,W}_{U,t,T} = \theta^U \times \sum_{y\in\mathcal{Y}^W}\sum_{i\in\mathcal{C}}\sum_{\tau=t+2}^{T}\Delta E^{s_1,s_2}_{i,y,\tau}, \tag{19}$$

where the collective SCC θ^U for countries $y \in \mathcal{Y}^U$ is given by the sum of the country-level SCCs of the countries belonging to U; $\theta^U = \sum_{y \in \mathcal{Y}^U} \theta^y$.[67] By setting $\mathcal{Y}^U = \mathcal{Y}^W$, we can consider benefits to climate club U of its own emission reductions. By setting $|\mathcal{Y}^U| = 1$ and $|\mathcal{Y}^W| = 1$, we can consider benefits of the phase out of coal of one country $U = y$ to another country $W = w$, as well as to itself (by setting $|\mathcal{Y}^U| = |\mathcal{Y}^W| = 1$).

In Figure 11a, we compare the costs of reducing emissions in one region (associated with replacing its coal with renewables) against the benefits from avoided emissions for that region, as well as for other regions. We observe for example that the present value of investments Africa would need to make to replace its coal with renewables is \$2.3 trillion. The benefits from its own avoided emissions are \$0.5 trillion in avoided climate damages, taking the collective SCC of Africa into account. The left panel of Figure 11a shows in orange circles benefits to other regions if Africa were to phase out coal. For instance, the orange circle with the green dot inside shows the benefits for North America of Africa's coal phase out are around \$3.0 trillion. Hence, it is squarely in North America's economic interest to offer foreign climate finance to help Africa decarbonize. North America could in fact offer to pay for Africa's phase out in its entirety and still be better off. Hence, contributing foreign climate finance (to developing countries) is not just equitable. It is enlightened self-interest whenever $B^{s_1,s_2,\theta^y,W}_{U,t,T} - F^{U,W} > 0$.[68]

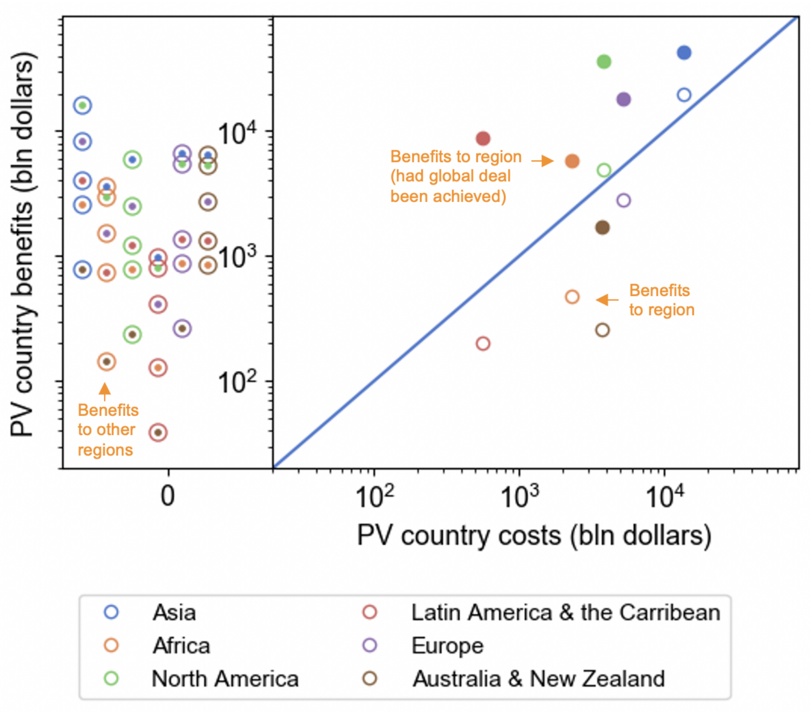
Figure 11b shows the costs of phasing out coal for each of the top-9 countries in terms of 2022 coal production, as well as the benefits this brings to other countries in the world. Take emerging-market country A as an example. We observe that country A's costs to replace its coal with renewables equals \$6.1 trillion, while its benefits from its emission reductions are \$2.9 trillion in estimated avoided climate damages (open dot).[69] The benefits to other countries if country A were to phase out coal are displayed in blue dots in the left panel. As an example, developed country B would benefit from country A's phase out of coal by \$7.6 trillion. Hence, it is in developed country B's enlightened self-interest to (help) pay for emerging-market country A's phase out of coal.[70]

[67] The collective SCC θ^U for countries $y \in \mathcal{Y}^U$ is consistent with a global average SCC of θ =\$80/tCO$_2$ when emissions are reduced from a business-as-usual emission pathway s_1 to a net zero 2050 emission pathway s_2. In future research, one would like to determine the collective SCC θ^U for countries $y \in \mathcal{Y}^U$ consistent with emission reductions where in region W moves from a business-as-usual pathway s_1 to a (net zero 2050) pathway s_2. The two could be different in so far as avoided climate damages from reduced emissions grow non-linearly.

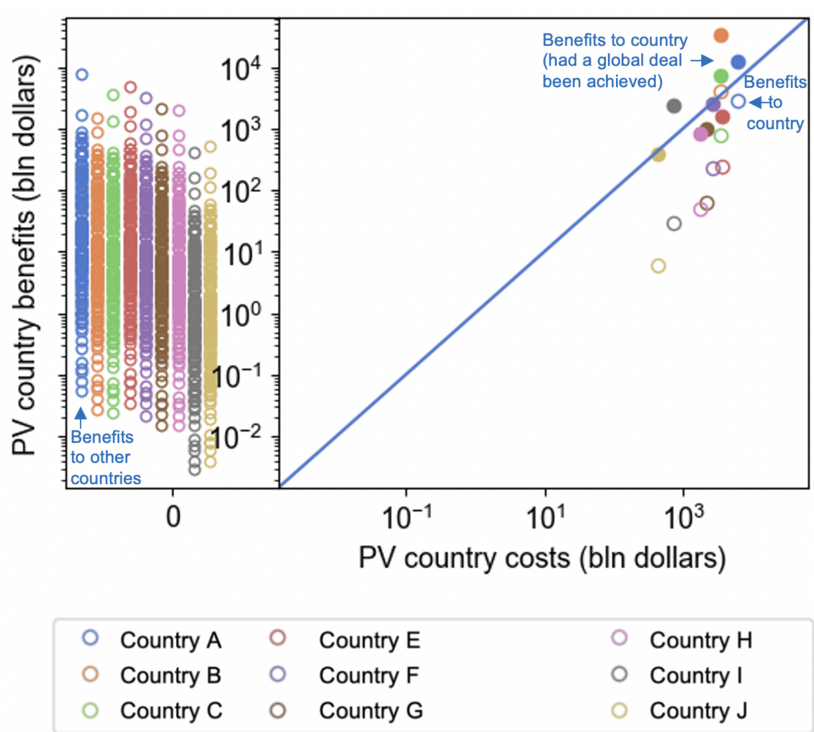
[68] The contributed amount $F^{U,W}$ by U could cover part or all costs of W (i.e., $F^{U,W} \leq C^{s_1,s_2,s_r}_{W,t,T}$). A region U would typically only offer foreign climate finance to a region W for public investments that W needs to replace its coal with renewables. In such case the foreign climate finance provided need not be more than $F^{U,W} \leq \alpha \times C^{s_1,s_2,s_r}_{W,t,T}$ (=\$0.23 trillion), where $\alpha = 10\%$ if a 1:9 blended finance arrangement is in place.

[69] The benefit country A reaps in a global deal to phase out coal (solid dot) is \$12.8 trillion dollars, which should motivate it to advocate a global deal to end coal.

[70] Country y would benefit from providing $F^{y,w}$ of climate finance as long as $B^{s_1,s_2,\theta^w,w}_{y,t,T} - F^{y,w} > 0$ holds true, where the contributed amount $F^{y,w}$ by country y could cover part or all costs of country w (i.e., $F^{y,w} \leq C^{s_1,s_2,s_r}_{w,t,T}$). Country y would typically not need to provide more than $F^{y,w} \leq \alpha \times C^{s_1,s_2,s_r}_{w,t,T}$, where $\alpha = 10\%$ if a 1:9 blended finance arrangement is in place, since it would invest only in the junior equity tranche investments so the remainder



(a) Regional deal to phase out coal.



(b) Unitary country deal to phase out coal.

Figure 11: Present value of costs to phase out coal in one region (country) and present value of benefits this brings both to the region (country) that is phasing out coal (see right panel), as well as other regions (countries) in the world.

of funding could be drawn from capital markets.

Indeed, Coase tells us that it is sound economic logic to pay the polluter to stop polluting if that makes us better of. Equivalently, Coase tells us that the polluter (e.g., country A) could keep polluting and pay other countries to compensate for climate damages its emissions inflict upon them (e.g., it would pay country B \$7.6 trillion). Coase thus provides a new perspective on and rationale for cross-country transfers towards climate change mitigation. of carbon leakage. The reason is that along the decarbonization pathway we match any reduction in coal with an energy-equivalent addition in renewables. An important aspect of our analysis of cross-country transfers to cover the costs of building renewable capacity in developing countries is that these transfers could be in the self-interest of rich countries if they result in significant carbon emission reductions from the phase-out of coal in developing countries. Note, however, that this can only be achieved if climate finance to expand renewable energy capacity is made conditional on phasing out coal.

Carbon Leakage

Carbon leakage means that emission reductions in one set of countries result in emission increases in other set of countries. Our analysis above has abstracted from any carbon leakage considerations. But in the absence of a global agreement to phase out coal carbon leakage could be a major concern. The way we have framed the phase-out of coal, however, reduces the risk.

8 Conclusion

Our quantitative analysis in this paper makes a simple but important observation: phasing out coal and replacing it with renewables is not just a matter of urgent necessity to limit global warming. When its costs and benefits are considered, it also turns out to be a source of considerable net economic and social gain – the economic gain is around \$85 trillion under a conservative estimate. Benefits consist of the avoided climate damages from reduced emissions by shutting coal mines down early, and are under our baseline conservatively priced at an average social cost of carbon of \$80/tCO_2. Costs consist of investment costs to build replacement renewable energy and compensate for opportunity costs of coal. To our knowledge this is the first valuation of the net global benefits from replacing coal with renewable energy.

In practice, obstacles to bargaining or poorly defined property rights can prevent Coasean bargaining to strike a global agreement on climate finance to replace coal with renewables, but our point is that in light of the large net gains we identify there should be renewed efforts to lift these obstacles. Possibly, the main obstacle to a global agreement to phase out coal could be the perceived limited benefit from doing so. We point to promising avenues to overcome such obstacles, and discuss how to make the funding to replace coal with renewables in the economic interests of all key stakeholders involved (i.e., governments, investors, and coal communities). In particular, we identify blended climate finance as a promising avenue to catalyze public investments. We quantify climate financing needs for replacing coal with renewables across countries in the world.[71]

It seems a reasonable baseline under Coasian bargaining that each country cover its own costs to domestically replace coal with renewables. We find that it is in the economic interest of most countries to participate in a global deal to end coal, even in absence of cross-country compensatory transfers. Contributions to help cover foreign climate finance needs may be called for, however, if foreign countries have insufficient fiscal means to pay for their own share, and may be justified based on unequal historical carbon emissions. Such equity considerations have so far not proved to be a strong impetus for action, however, as the difficulties of garnering a mere $100 billion a year in climate finance for developing countries have demonstrated (far less than the $\frac{1}{2}$ to 2 trillion dollars a year necessary to phase out coal around the world). Once one takes account of the benefits to each country from emission reductions brought about by replacing coal with renewables anywhere in the world, there is a much more direct impetus for action: self interest. Indeed, the Coase theorem states that it is in the economic interests of a country A to pay a polluting country B to stop polluting if that makes country A better off. From a Coasian perspective it thus is sound economic logic to pay polluters for the costs of replacing coal with renewables, if the benefits exceed the cost. Indeed, Coase provides a new perspective on and rationale for (foreign transfers of) climate finance. We show that tangible net benefits can be reaped even if only a coalition of the willing (e.g., a region) strikes a Coasian deal to phase out of coal. The larger the climate club in terms of the coal emissions it can avoid, the closer the net benefits of such a deal get to the large net benefits we identify in a global deal to end coal. Critical for benefits to materialize is that rich countries offer finance to build out renewables, as well as funding to compensate for the opportunity costs of coal of developing countries, conditional on the commitment to end coal. Otherwise, emission reductions might not take place, carbon leakage could be profound, and benefits to countries in terms of avoided climate damages may not be realized. Phasing in renewables and phasing out coal concurrently is moreover critical to ensure sufficient energy supply.

Take the Indonesia Just Energy Transition Partnership, struck during G20/COP27, as an

[71] Download climate finance estimates at: https://greatcarbonarbitrage.com.

example. In this deal, $20 billion in climate finance has been promised to help Indonesia build out renewables, conditional on its commitment to phase out coal. The deal is a blended finance deal in which 50% of financing comes from capital markets. It is meant to be a “just deal” in which compensation is offered for the opportunity cost of coal. We can show that paying the polluter, Indonesia, to stop polluting makes individual G7 countries who are financing this deal better off.

The Indonesian case (as well as the South-African one) illustrates that rather than relying on a global Coasian deal on climate finance to replace coal with renewables, we can move by *blocks*. Indeed, a Coasian bargain is much more likely to work out if the number of contracting parties involved in the deal is smaller. There is value to focus on coal. There is, moreover, value to focus on the most coal polluting countries first. From the approximately 1425 $GtCO_2$ we can avoid by phasing out coal over the course of this century according to a net zero 2050 scenario, around 1210 $GtCO_2$ are in the top-9 coal reliant countries. Hence, we can strike conditional blended financing deals with each of these 9 countries, and move by blocks. As we move by blocks and strike financing deals with each of the top coal-reliant countries, we can soon get close to the large net benefits we identify in a global deal to end coal.

References

Arezki, M. R., Bolton, M. P., Peters, S., Samama, F. and Stiglitz, J. (2016), From global savings glut to financing infrastructure: The advent of investment platforms, International Monetary Fund.

Bolton, P., Buchheit, L. C., Panizza, U., Weder di Mauro, B. and Gulati, M. (2022), ‘Environmental protection and sovereign debt restructuring’, Capital Markets Law Journal (forthcoming 2022) .

Bolton, P., Musca, X. and Samama, F. (2020), ‘Global public-private investment partnerships: A financing innovation with positive social impact’, Journal of Applied Corporate Finance **32**(2), 31–41.

BP (2021), Statistical review of world energy 2021, Technical report, BP Statistical Review of World Energy.

Browning, E. K. (1976), ‘The marginal cost of public funds’, Journal of Political Economy **84**(2), 283–298.

Burke, M., Hsiang, S. M. and Miguel, E. (2015), ‘Global non-linear effect of temperature on economic production’, Nature **527**(7577), 235–239.

Clark, A. and Zhang, W. (2022), ‘Estimating the employment and fiscal consequences of thermal coal phase-out in china’, Energies **15**(3), 800.

Coase, R. H. (1960), 'The problem of social cost', The journal of Law and Economics **56**(4), 837–877.

Collier, P. and Venables, A. J. (2014), 'Closing coal: economic and moral incentives', Oxford Review of Economic Policy **30**(3), 492–512.

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G. and Pietzcker, R. C. (2017), 'The underestimated potential of solar energy to mitigate climate change', Nature Energy **2**(9), 1–9.

Daniel, K. D., Litterman, R. B. and Wagner, G. (2016), Applying asset pricing theory to calibrate the price of climate risk, Technical report, National Bureau of Economic Research.

Daniel, K. D., Litterman, R. B. and Wagner, G. (2019), 'Declining co2 price paths', Proceedings of the National Academy of Sciences **116**(42), 20886–20891.

Dietz, S. and Stern, N. (2015), 'Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions', The Economic Journal **125**(583), 574–620.

Dimson, E., Marsh, P. and Staunton, M. (2003), 'Global evidence on the equity risk premium', Journal of Applied Corporate Finance **15**(4), 27–38.

Gollier, C. (2012), Pricing the planet's future, Princeton University Press.

Greenstone, M., Kopits, E. and Wolverton, A. (2013), 'Developing a social cost of carbon for us regulatory analysis: A methodology and interpretation', Review of environmental economics and policy .

Harstad, B. (2012), 'Buy coal! a case for supply-side environmental policy', Journal of Political Economy **120**(1), 77–115.

Heal, G. (2017), 'The economics of the climate', Journal of Economic Literature **55**(3), 1046–63.

Hepburn, C., Stern, N. and Stiglitz, J. E. (2020), '"carbon pricing" special issue in the european economic review', European economic review **127**, 103440.

Hertwich, E., de Larderel, J. A., Arvesen, A., Bayer, P., Bergesen, J., Bouman, E., Gibon, T., Heath, G., Peña, C., Purohit, P. et al. (2016), Green energy choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production, Technical report.

Hope, C., Anderson, J. and Wenman, P. (1993), 'Policy analysis of the greenhouse effect: an application of the page model', Energy Policy **21**(3), 327–338.

IEA (2007), 'Contribution of renewables to energy security', https://iea.blob.core.windows.net/assets/682ee8e1-a423-4775-bcd1-38bf4c18717f/so_contribution.pdf.

IEA (2019), 'The future of hydrogen', https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

IEA (2020a), 'Projected costs of generating electricity', https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf.

IEA (2020b), 'World energy investment 2020', https://iea.blob.core.windows.net/assets/ef8ffa01-9958-49f5-9b3b-7842e30f6177/WEI2020.pdf.

IEA (2021a), 'Annual co2 emissions from coal-fired power plants, 2000-2050', https://www.iea.org/data-and-statistics/charts/annual-co2-emissions-from-coal-fired-power-plants-2000-2050.

IEA (2021b), 'Global hydrogen review 2021', https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database.

IEA (2021c), 'Is carbon capture too expensive?', https://www.iea.org/commentaries/is-carbon-capture-too-expensive.

IEA (2021d), 'Net zero by 2050', https://www.iea.org/reports/net-zero-by-2050.

IEA (2021e), 'Net zero by 2050 – A roadmap for the global energy sector', https://iea.blob.core.windows.net/assets/4719e321-6d3d-41a2-bd6b-461ad2f850a8/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf.

IEA (2021f), 'World energy investment 2021', https://iea.blob.core.windows.net/assets/ef8ffa01-9958-49f5-9b3b-7842e30f6177/WEI2020.pdf.

IEA (2021g), 'World energy outlook 2021', https://www.iea.org/reports/world-energy-outlook-2021.

IEA (2022), 'Direct air capture', https://www.iea.org/reports/direct-air-capture-3.

IPCC (2021), 'Ipcc, 2021: Summary for policymakers. In: Climate change 2021: The physical science basis. Contribution of working group i to the sixth assessment report of the Intergovernmental Panel on Climate Change'.

IRENA (2021a), Renewable capacity statistics 2021, Technical report, International Renewable Energy Agency.

IRENA (2021b), Renewable power generation costs in 2021, Technical report, International Renewable Energy Agency.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A., Goodman, S. C., Chapman, W. E., Cameron, M. A., Bozonnat, C., Chobadi, L., Clonts, H. A., Enevoldsen, P. et al. (2017), '100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world', Joule **1**(1), 108–121.

Jordan, D. C. and Kurtz, S. R. (2013), 'Photovoltaic degradation rates—an analytical review', Progress in photovoltaics: Research and Applications **21**(1), 12–29.

Liu, Y. and Lu, Y. (2015), 'The economic impact of different carbon tax revenue recycling schemes in china: A model-based scenario analysis', Applied Energy **141**, 96–105.

Llavador, H., Roemer, J. E. and Silvestre, J. (2015), Sustainability for a warming planet, Harvard University Press.

Louie, E. P. and Pearce, J. M. (2016), 'Retraining investment for us transition from coal to solar photovoltaic employment', Energy Economics **57**, 295–302.

Lu, Y., Cohen, F., Smith, S. M. and Pfeiffer, A. (2022), 'Plant conversions and abatement technologies cannot prevent stranding of power plant assets in 2° c scenarios', Nature Communications **13**(1), 1–11.

Matthews, H. D., Gillett, N. P., Stott, P. A. and Zickfeld, K. (2009), 'The proportionality of global warming to cumulative carbon emissions', Nature **459**(7248), 829–832.

McKinsey (2022), The net-zero transition. what it would cost, what it could bring, Technical report, McKinsey Global Institute.

Meng, J., Way, R., Verdolini, E. and Anadon, L. D. (2021), 'Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition', Proceedings of the National Academy of Sciences **118**(27).

NGFS (2021), 'NGFS climate scenarios for central banks and supervisors'.

Nordhaus, W. (2013), Integrated economic and climate modeling, in 'Handbook of computable general equilibrium modeling', Vol. 1, Elsevier, pp. 1069–1131.

Nordhaus, W. D. (1993), 'Rolling the 'dice': an optimal transition path for controlling greenhouse gases', Resource and Energy Economics **15**(1), 27–50.

Nordhaus, W. D. (2017), 'Revisiting the social cost of carbon', Proceedings of the National Academy of Sciences **114**(7), 1518–1523.

Pigou, A. (1920), 'The economics of welfare. macmillan', New York .

Pindyck, R. S. (2019), 'The social cost of carbon revisited', Journal of Environmental Economics and Management **94**, 140–160.

Prasad, M. A., Loukoianova, M. E., Feng, A. X. and Oman, W. (2022), Mobilizing Private Climate Financing in Emerging Market and Developing Economies, International Monetary Fund.

Rauner, S., Bauer, N., Dirnaichner, A., Van Dingenen, R., Mutel, C. and Luderer, G. (2020), 'Coal-exit health and environmental damage reductions outweigh economic impacts', Nature Climate Change **10**(4), 308–312.

Rennert, K., Prest, B. C., Pizer, W. A., Newell, R. G., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A. E., sevcíková, H. and Errickson, F. (2021), The social cost of carbon: Advances in long-term probabilistic projections of population, gdp, emissions, and discount rates, Technical report, Resources for the Future, Working Paper 21-28.

Ricke, K., Drouet, L., Caldeira, K. and Tavoni, M. (2018), 'Country-level social cost of carbon', Nature Climate Change **8**(10), 895–900.

Ruppert Bulmer, E., Pela, K., Eberhard-Ruiz, A. and Montoya, J. (2021), 'Global perspective on coal jobs and managing labor transition out of coal'.

Samadi, S. (2018), 'The experience curve theory and its application in the field of electricity generation technologies–a literature review', Renewable and Sustainable Energy Reviews **82**, 2346–2364.

Schmidt, O., Hawkes, A., Gambhir, A. and Staffell, I. (2017), 'The future cost of electrical energy storage based on experience rates', Nature Energy **2**(8), 1–8.

Sharpe, W. F. (1964), 'Capital asset prices: A theory of market equilibrium under conditions of risk', The journal of finance **19**(3), 425–442.

Staffell, I. and Green, R. (2014), 'How does wind farm performance decline with age?', Renewable energy **66**, 775–786.

Stern, N. and Stern, N. H. (2007), The economics of climate change: the Stern review, cambridge University press.

Way, R., Ives, M. C., Mealy, P. and Farmer, J. D. (2022), 'Empirically grounded technology forecasts and the energy transition', Joule .

Way, R., Ives, M., Mealy, P. and Farmer, J. (2021), Empirically grounded technology forecasts and the energy transition, Technical report, INET Oxford Working Paper 2021-01.

Way, R., Lafond, F., Lillo, F., Panchenko, V. and Farmer, J. D. (2019), 'Wright meets markowitz: How standard portfolio theory changes when assets are technologies following experience curves', Journal of Economic Dynamics and Control **101**, 211–238.

A Online 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. $B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}} = \theta \times \sum_{\tau=T+1}^{\bar{T}} \sum_{y \in \mathcal{Y}} \Delta E^{s_1,s_2,s_r}_{y,t,T,\tau}$.[72] A natural choice for $\bar{T} - T$ is the lifetime of renewables (30 years in our baseline), since this is how long residual benefits accrue. Avoided emissions in year τ in country y from earlier-built renewable capacity are given by the energy $R^{s_1,s_2,s_r}_{y,t,T,\tau}$ that earlier-built capacity produces, converted with function g^{-1} to how much avoided coal production that amounts to, and multiplied with the weighted-average emission intensity $\tilde{\epsilon}_y$ of coal production in that country. This gives $\Delta E^{s_1,s_2,s_r}_{y,t,T,\tau} = g^{-1}(R^{s_1,s_2,s_r}_{y,t,T,\tau}) \times \tilde{\epsilon}_y$, where $R^{s_1,s_2,s_r}_{y,t,T,\tau} = \sum_{q \in \mathcal{R}} R^{s_1,s_2,s_r,q}_{y,t,T,\tau}$.

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

The renewable energy that renewable type q built over $[t+2, T]$ can produce at a time $\tau > T$ is given by $R^{s_1,s_2,s_r,q}_{y,t,T,\tau} = h(S^{s_1,s_2,s_r,q}_{y,t,T,\tau}) \times f^q$, which represents a modification of equation 14. 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 15.

Table 7 shows that societal benefits of building a renewable plant should not only capture the emissions that the plant can avoid in the year it is built, or in the years up to the end of its estimated date of amortization, but should also include all coal emissions that the renewable plant can help avoid over its remaining lifetime past the date of amortization. Take as an example a time horizon $[t+2, T]$ with end date $T = 2070$, the year in which not only developed countries but also developing and emerging countries plan to be net zero. The year $T = 2070$ represents the last year investment costs are made to build replacement renewable plants as part of the carbon arbitrage strategy. Suppose a solar plant is built in year 2069. It will then

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

run and produce renewable energy for 30 years (in our baseline), thereby enabling a reduction in coal production and associated coal emissions in the years 2069-2099. This results in a social gain over the period 2069-2099, priced at the SCC times the amount of avoided emissions.[73] This social gain stretches beyond the last year $T = 2070$ in which investments costs are made. Table 7 shows that the carbon arbitrage gain is underestimated by \$44-\$23=\$21 trillion, using $\theta_{pindyck} = \$80/tC0_2$, if the benefits of avoided coal emissions are truncated at $T = 2070$, while these accrue up to 2099, the final year of the lifetime of the renewable plant.

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

	Carbon arbitrage		
	θ_{lower}	$\theta_{pindyck}$	θ_{higher}
PV of benefits	28	44	121
PV of benefits truncated at T	12	22.66	75

Investment Costs in Short-Term and Long-Term Batteries and Grid Extension
Intermittent renewable energy will typically require complementary investments into energy storage and systems providing flexibility to the grid to manage supply and demand fluctuations (see e.g., Creutzig et al. (2017)) – especially as share of renewables on the power grid increases. Way et al. (2021) estimate that the electricity grid will have *more than sufficient* storage capacity in a high renewable scenario (with a share of up to 85% renewables on the grid) if 20% of daily electricity generated from renewable sources can be stored in short-term batteries (e.g., Li-ion batteries) and one month of annual renewable energy generated can be stored long term (e.g., by means of green hydgrogen generated by electrolyzers). Short-term and long-term batteries not only provide storage, but their built-in systems also provide flexibility to the grid by managing demand and supply shocks.[74] Grid extensions may also be necessary if newly built renewable plants are not located close to existing grids, and may be necessary to manage larger peak loads of energy on the grid resulting from variable renewable energy. The more batteries are built the less need exists for expanding grid capacity as peak loads can be smoothed by storing excess energy. Hence, grid capacity and battery capacity are to some extent substitutes.

In our baseline, we capture investment costs in expanding renewable capacity, but do not capture the additional investments that may have to be made in storage capacity and grid extensions as coal is phased out. We would like to make a conservative (i.e., high) cost estimate of creating a reliable grid when coal is phased out according to pathway s_2 compared to a business-as-usual pathway s_1 and replaced with renewables. In line with Way et al. (2021), we assume that an amount of short-term batteries must be built that can store 20% of daily electricity generated from renewable sources and an amount of long-term batteries must be built that can storage one month worth of annual generated renewable energy to create a reliable grid as coal is phased out according to scheme s_2. We also make a conservative estimate of investments that would have to be made in grid extension. As we only replace coal with renewables, and do not consider the decarbonization of the entire economy, in our phase out scenario s_2 the renewable penetration on the grid will in many cases stay far below 85% in which case long-term storage is likely not even necessary (Way et al. (2021)). Our estimate of complementary investment costs in storage and grid extension could be seen as an upper bound;

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

[74]Short-term batteries can smooth daily demand and supply shocks; for instance, by releasing stored energy at peak-demand hours or at night when the sun does not shine, and storing energy when excess energy is supplied by renewables. Long-term batteries can supply energy when longer-term lulls in renewable energy generation occur.

costs for building a minimum viable system of storage will likely be (much) smaller.[75]

Investment Costs in Short-Term Storage

The requisite amount of short-term battery capacity $G_{y,\tau}^{s_1,s_2,s_r,b}$ of type b (where we take b to be Li-ion batteries) that must be added in year τ in country y depends on the shortfall of renewable energy $D_{y,\tau}^{s_1,s_2,s_r,b}$ that existing short-term batteries have capacity to store. This shortfall is given by the positive difference between the share α% of annual renewable energy generation $R_{y,\tau}^{s_1,s_2,s_r}$ that should be stored $R_{y,\tau}^{s_1,s_2,s_r} \times \alpha$ and the amount of renewable energy that can already be stored $R_{y,\tau}^{s_1,s_2,s_r,b}$ based on the existing stock $S_{y,\tau}^{s_1,s_2,s_r,b}$ of short-term batteries (taking into account only those that have been built for the replacement of coal with renewables) i.e.,

$$D_{y,\tau}^{s_1,s_2,s_r,b} = \max\{R_{y,\tau}^{s_1,s_2,s_r} \times \alpha - R_{y,\tau}^{s_1,s_2,s_r,b}, 0\}, \tag{20}$$

where $\alpha = \frac{0.2}{365}$ in our baseline. Taking α as such means that sufficient storage capacity must exist to store 20% of daily renewable generation in short-term batteries. As coal is gradually phased out (according to pathway s_2) over time more renewable energy will be generated annually $R_{y,\tau}^{s_1,s_2,s_r}$, so more short-term storage will be needed.

As investment costs in short-term batteries are expressed in dollars per unit of energy that can be stored (rather than in dollars per unit of installed capacity). The investment costs $I_{y,\tau}^{s_1,s_2,s_r,b}$ in short-term batteries in country y in year τ are thus given by the multiplication of the shortfall in short-term energy storage $D_{y,\tau}^{s_1,s_2,s_r,b}$ (which determines indirectly how much short-term storage capacity $G_{y,\tau}^{s_1,s_2,s_r,b}$ must be added)[76] and the unit investment costs in short-term energy storage $i_{\tau}^{s_1,s_2,s_r,b}$, i.e.,

$$I_{y,\tau}^{s_1,s_2,s_r,b} = D_{y,\tau}^{s_1,s_2,s_r,b} \times i_{\tau}^{s_1,s_2,s_r,b}. \tag{21}$$

The present value of investment costs in short-term batteries in country y is then given by $I_{y,t,T}^{s_1,s_2,s_r,b} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} I_{y,\tau}^{s_1,s_2,s_r,b}$.

The investment costs $i_{\tau}^{s_1,s_2,s_r,b}$ in batteries of type b have fallen exponentially over the last decades, with an estimated reduction of $\Theta_b = 25.3\%$ in investment costs for each doubling of installed capacity (Way et al. (2021)), which corresponds to a learning rate of $\gamma_b = 0.42$. We apply Wright's Law (see equation 16) to project how investment costs $i_{\tau}^{s_1,s_2,s_r,b}$ in short-term batteries b may further fall in the future as a function of global cumulative installed capacity in batteries b.[77] To obtain the normalization constant α^b in equation 16, we take the energy that the global cumulative installed capacity of batteries b up to time $t-1 = 2021$ can store as (the 2020 estimate by Way et al. (2021)); i.e., 4222800 GJ (1173 GWh). We take the $t = 2021, 2022$ unit investment costs $i_t^{s_1,s_2,s_r,b}$ in batteries b to be (equal to the 2020 estimate of IEA (2021g)); i.e., \$86111/GJ (\$310/kWh).

Investment Costs in Long-Term Storage

[75] We model requisite capacity additions in storage in a consistent way as we model requisite capacity additions in renewables as coal is phased out. We also model experience curves for storage (driving down investment costs over time as cumulative capacity is built up) in a consistent way as we do for renewables.

[76] The energy that can be stored by the stock of batteries at time τ is given by $R_{y,\tau}^{s_1,s_2,s_r,b} = \sum_{\tau_d=t+2}^{\tau-1} D_{y,\tau_d}^{s_1,s_2,s_r,b} \times (1-d_b)^{(\tau-\tau_d)} \mathbb{I}_{\{\tau-\tau_d \le l_b\}}$ (analogous to equation 15), where $d_b = 0$ is taken to be the depreciation rate of a battery type b, and $l_b = 12$ is its estimated lifetime, assuming one charge/discharge cycle per day (Way et al. (2021)). The extra capacity of batteries that must be built in year τ to make up for the shortfall of energy $D_{y,\tau}^{s_1,s_2,s_r,b}$ that can be stored in existing batteries b is given by $G_{y,\tau}^{s_1,s_2,s_r,b} = h^{-1}(D_{y,\tau}^{s_1,s_2,s_r,b})$ (analogous to equation 11).

[77] Our estimate of the projected global drop in investment costs for batteries b is conservative, as we only capture global capacity (i.e., experience) that is built up to stabilize the grid accounting for the phase out of coal, while in reality global capacity of batteries b will also expand when batteries are built for other purposes, such as powering electric vehicles and creating storage capacity when other fossil fuels are phased out from the grid.

Power-to-X (P2X) stands for a number of electricity conversion, energy storage, and reconversion pathways powered by surplus electric power (e.g., powered by excess renewable energy generation). In particular, power-to-power (where X stands for power) enables large amounts of energy to be stored for an extended time period, and then be released again, which is ideal in an electricity grid with a high variable renewable energy penetration where extended lulls in renewable energy generation may occur. Way et al. (2019) estimate that an electricity grid with a high penetration of renewables has more than sufficient long-term storage capacity whenever one month worth of annual renewable energy generation can be generated with P2X fuels – in particular, green hydrogen. Hydrogen is produced in a chemical process called electrolysis capable of separating the hydrogen and oxygen molecules of which water is composed. When electrolysis is powered by 'green' renewable energy it is said to produce 'green' hydrogen. The investment costs to produce green hydrogen thus consist of the the costs to install electrolyzer capacity (as well as the costs to generate sufficient renewable electricity to power electrolysis). There are three established types of electrolyzers, with different characteristics and different potential for future development: alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM) and solid oxide electrolysis cells (SOEC).

The requisite amount electrolyzer capacity $G^{s_1,s_2,s_r,e}_{y,\tau}$ of type e (where we take e to be a PEM electrolyzer as in Way et al. (2019)) that must be built in year τ in country y depends on the positive difference between the electrolyzer capacity that is needed $\frac{h^{-1}(R^{s_1,s_2,s_r}_{y,\tau}\times\sigma\times\frac{1}{\psi})}{f^e}$ and the existing stock of electrolyzers $S^{s_1,s_2,s_r,e}_{y,\tau}$,[78] i.e.,

$$G^{s_1,s_2,s_r,e}_{y,\tau} = \max\{\frac{h^{-1}(R^{s_1,s_2,s_r}_{y,\tau}) \times \sigma}{f^e \times \psi} - S^{s_1,s_2,s_r,e}_{y,\tau}, 0\}. \tag{22}$$

The requisite electrolyzer capacity in year τ in country y must be able to store and then reproduce one month $\sigma = \frac{1}{12}$ of the generated renewable energy $R^{s_1,s_2,s_r}_{y,\tau}$ in year τ in country y. In the process of converting hydrogen back to electricity energy with PEM around 30% is projected to be lost (IEA (2019)). Hence, we take a conversion efficiency of $\psi = 0.7$. The capacity factor of electrolyzers is around 50% (i.e., $f^e = 0.5$). The function $h^{-1}(y)$ informs how much capacity is needed to store y amount of energy. The existing stock of electrolyzers is given by $S^{s_1,s_2,s_r,e}_{y,\tau} = \sum_{\tau_d=t+2}^{\tau-1} G^{s_1,s_2,s_r,e}_{y,\tau_d} \times (1-d_e)^{\tau-\tau_e} \times \mathbb{I}_{\{\tau-\tau_d \leq l_e\}}$ (analogous to equation 15), where the lifetime of electrolyzers is taken to be $l_e = 16$ years and the depreciation rate $d_e = 0$ as in Way et al. (2019). Investment costs in electrolyzer capacity in country y in year τ are then given by the multiplication of the shortfall in electrolyzer capacity $G^{s_1,s_2,s_r,e}_{y,\tau}$ and the unit investment cost $i^{s_1,s_2,s_r,e}_{\tau}$ in electrolyzer capacity, i.e.,

$$I^{s_1,s_2,s_r,e}_{y,\tau} = G^{s_1,s_2,s_r,e}_{y,\tau} \times i^{s_1,s_2,s_r,e}_{\tau}. \tag{23}$$

The present value of investment costs in electrolyzers in country y is given by $I^{s_1,s_2,s_r,e}_{y,t,T} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} I^{s_1,s_2,s_r,e}_{y,\tau}$.

Investment costs $i^{s_1,s_2,s_r,e}_{\tau}$ in electrolyzers of type e have fallen exponentially over the last decades, with an estimated learning rate of $\Theta_e = 8.6\%$ (Way et al. (2021)). We apply Wright's Law (see equation 16) to project how investment costs $i^{s_1,s_2,s_r,e}_{\tau}$ in short-term electrolyzers e may further fall in the future as a function of global cumulative installed capacity in electrolyzers e. To obtain the normalization constant α^e in equation 16, we take the global cumulative installed capacity of electrolyzers e at time $t-1 = 2021$ to be (equal to the 2020 estimate of IEA (2021b)); i.e., 0.08024 GW (80.24 MW). We take the unit investment costs $i^{s_1,s_2,s_r,e}_{t}$ in electrolyzers e at time $t = 2022$ to be (equal to the 2020 estimate of IEA (2021g)); i.e.,

[78] The variable $S^{s_1,s_2,s_r,e}_{y,\tau}$ captures only the electrolyzer stock that is built to meet the long-term storage needs as coal is is phased out according to pathway s_2 and replaced with renewables. It does not capture any existing electrolyzers connected to the grid.

\$1313000000/GW (\$1313/kW).

Investment Costs to Power Electrolyzers with Renewable Energy
As the conversion efficiency ψ of electrolyzers is less than one, extra renewable electricity must be generated to avoid a shortfall in requisite energy supply. The present value of the investment costs to install extra renewable capacity to power electrolyzers (pe) is given by $I_{y,t,T}^{s_1,s_2,s_r,pe} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} I_{y,\tau}^{s_1,s_2,s_r,pe}$. The annual investment costs to install extra renewable capacity to power electrolyzers is given by $I_{y,\tau}^{s_1,s_2,s_r,pe} = \sum_{q\in\mathcal{R}} G_{y,\tau}^{s_1,s_2,s_r,q,pe} \times i_{\tau}^{q,s_1,s_2,s_r}$ (analogous to equation 10). The renewable capacity of type q that must be built for the purpose of powering electrolyzers (pe) is given by $G_{y,\tau}^{s_1,s_2,s_r,q,pe} = \omega_{\tau}^{q,s_r} \times h^{-1}(D_{y,\tau}^{s_1,s_2,s_r,q,pe}) \times \frac{1}{f^q}$ (analogous to equation 11). How much renewable capacity $G_{y,\tau}^{s_1,s_2,s_r,q,pe}$ of type q must be built in year τ in country y for the purpose of powering electrolyzers (pe) is given by the positive difference between the electricity that electrolyzers need $R_{y,\tau}^{s_1,s_2,s_r} \times \sigma \times (\frac{1}{\psi} - 1)$ and the energy the existing stock of renewables $R_{y,\tau}^{s_1,s_2,s_r,pe}$ in country y (built to power electrolyzers) provides,[79] i.e.,

$$D_{y,\tau}^{s_1,s_2,s_r,pe} = \max\{R_{y,\tau}^{s_1,s_2,s_r} \times \sigma \times (\frac{1}{\psi} - 1) - R_{y,\tau}^{s_1,s_2,s_r,pe}, 0\}.^{80} \tag{24}$$

Since extra renewable capacity is built to power electrolyzers (over and above the renewable capacity built to replace coal), the cumulative capacity in renewable energy will expand more quickly resulting in greater learning-by-doing effects and thus larger projected falls in renewable investment costs: i.e.,

$$i_{\tau}^{s_1,s_2,s_r,q} = \alpha_q \left(\sum_{y\in\mathcal{Y}} \left(\sum_{\tau_d \le t-1} G_{y,\tau_d}^{q} + \sum_{\tau_b=t+2}^{\tau-1} G_{y,\tau_d}^{s_1,s_2,s_r,q} + G_{y,\tau_d}^{s_1,s_2,s_r,q,pe} \right) \right)^{-\gamma_q} \tag{25}$$

Equation 25 is analogous to equation 16 except that the second sum now includes experience gained from building renewable capacity to power electrolyzers $G_{y,\tau_d}^{s_1,s_2,s_r,q,pe}$).

Investment Costs in Grid Extension
The average global annual investments in electricity networks over the 2012-2021 period were fairly stable and on average equal to around \$280 billion per year, while the average annual electricity generation of this period was around 26.9 PWh (IEA (2020b) and IEA (2021f)). Hence, the annual investment per unit of electricity generation was on average \$10.4 billion/PWh over 2012-2021. The replacement of coal with renewables will likely require some investments in extending the capacity of the grid. To increase the capacity of the grid one can either install more lines or install higher voltage lines. Way et al. (2022) estimate that the unit costs of building triple voltage lines is about \$14.9 billion/PWh, when both costs of increasing the network capacity of the transmission and distribution grids are captured. We conservatively assume that *any* replacement of coal with renewables will require investments in grid extension using increased voltage lines (in line with Way et al. (2022)). Given an amount of renewable energy generation of $R_{y,\tau}^{s_1,s_2,s_r}$ in country y in year τ (as coal is phased according to pathway s_2) and grid unit costs c^g = \$4.14/GJ (=\$14.9 billion/PWh), the grid investments costs in year τ

[79] Note that our measure of renewable stock $R_{y,\tau}^{s_1,s_2,s_r,pe}$ excludes electrolyzers built for other purposes outside of phasing out coal.

[80] Here $R_{y,\tau}^{s_1,s_2,s_r,pe} = \sum_{q\in\mathcal{R}} R_{y,\tau}^{s_1,s_2,s_r,q,pe}$ (analogous to equation 13), $R_{y,\tau}^{s_1,s_2,s_r,q,pe} = h(S_{y,\tau}^{s_1,s_2,s_r,q,pe})$ (analogous to equation 14), and $S_{y,\tau}^{s_1,s_2,s_r,q,pe} = \sum_{\tau_d=t+2}^{\tau-1} G_{y,\tau_d}^{s_1,s_2,s_r,q,pe} \times (1-d_q)^{(\tau-\tau_d)} \mathbb{I}_{\{\tau-\tau_d \le l_q\}}$ (analogous to equation 15). We keep the stock of renewables of type q to replace coal $S_{y,\tau}^{s_1,s_2,s_r,q}$ (defined in equation 15) separate from the stock of renewables of type q to power electrolyzers $S_{y,\tau}^{s_1,s_2,s_r,q,pe}$ to avoid inflating our measure $R_{y,\tau}^{s_1,s_2,s_r}$ of the supply of annual renewable electricity generation for end-user consumption purposes.

in country y under coal phase out scenario s_2 are given by

$$I_{y,\tau}^{s_1,s_2,s_r,g} = c^g \times R_{y,\tau}^{s_1,s_2,s_r}. \tag{26}$$

The present value of investment costs to maintain a renewable grid (g) is then given by $I_{y,t,T}^{s_1,s_2,s_r,g} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} I_{y,\tau}^{s_1,s_2,s_r,g}$.

Our estimate of requisite annual investment cost in the grid $I_{y,\tau}^{s_1,s_2,s_r,g}$ in a country y is extremely crude. It is best interpreted as an upper bound. Grid investment costs are likely lower for at least three reasons. First, only grid investment costs in phase out scenario s_2 over and above those that would anyway be made in a business-as-usual scenario s_1 (around \$280 billion per year currently) should be considered. Second, grid extensions will only become salient when a greater electrification of the economy takes place. Replacing coal in the power sector with renewables (which is the first coal-use that must be phased out according to most net zero 2050 scenarios s_2) will not contribute to a greater electrification of the economy. Third, the excess capacity of short- and long-term batteries we build in scenario s_2 will reduce peak loads on the grid and hence limit the need for expanding grid capacity.

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.

$$I_{t,T}^{s_1,s_2,s_r} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} \times g(\Delta P_\tau^{s_1,s_2}) \times \left(\sum_{q\in\mathcal{R}} \omega^{q,s_r} \times L_\tau^q \right). \tag{27}$$

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 suppose that the LCOE L_τ^q of energy of type q experiences the same learning rate γ_q as the investment costs of energy type q (see Section 3.2.2.1),[81] and is equal in 2020 to its global average as estimated by IRENA (2021b), where L_{t2020}^{solar}=10.83, $L_{t2020}^{wind-onshore}$=15.83, and $L_{t2020}^{wind-offshore}$=23.33 (in dollars per GJ).[82] Doing so enables a comparison between apples when we proxy requisite investment costs with the LCOE, and gives

$$L_\tau^q = L_{t2020}^q \times \frac{i_\tau^{s_1,s_2,s_r,q}}{i_{t2020}^{s_1,s_2,s_r,q}}. \tag{28}$$

Coal Replacement with Natural Gas as Transition Fuel

[81] In practice, the LCOE might undergo a somewhat different learning rate than the investment costs, because the annual operations and maintenance expenditures captured in the LCOE in addition to the investment costs could be subject to different learning rates than the investment costs. Further, some cost components in the LCOE such as financing costs and fuel expenditures are not subject to learning.

[82] In dollars per MWh this is L_{t2020}^{solar} =39, $L_{t2020}^{wind-onshore}$ = 57, and $L_{t2020}^{wind-onshore}$ = 84.

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

The present value of costs of replacing coal with a mixture of renewables and natural gas is given by $C^{s_1,s_2,s_r}_{t,T}$ as before, except the present value of investment costs $I^{s_1,s_2,s_r}_{t,T}$ now must have an extra component to capture the present value of investment costs in natural gas plants. (Note that the weights ω^{q,s_r} of renewable types $q \in \mathcal{R}$ will now no longer sum to one, as part of the replacement of coal is with natural gas.) Since we do not have data on investment costs to build natural gas plants, we proxy requisite investment costs with the LCOE. The present value of investment costs in natural gas is then given by $\sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} \times g(\Delta P^{s_1,s_2}_{\tau}) \times \omega^{gas,s_r} \times L^{gas}_{\tau}$ (which represents a modification of equation 27). We take the 2020 global average estimated by IEA (2020a) as the LCOE of natural gas (CCGT), of around L^{gas}_{τ}=\$19.4/GJ (equivalent to \$70/MWh). (Note that the 2020 global average LCOE of natural gas is higher than that of solar PV and wind onshore but lower than that of wind offshore; see Appendix A.)

Coal Replacement with Nuclear Energy

Benefits of replacing coal with nuclear energy are taken to be the same as benefits of replacing coal with renewable energy (given by equation 2), since both sources of energy do not emit carbon.[83] Since we do not have data on investment costs to build nuclear plants, we proxy requisite investment cost in nuclear plants with its LCOE. The present value of investment costs in nuclear energy is then given by $\sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} \times g(\Delta P^{s_1,s_2}_{\tau}) \times \omega^{nuclear,s_r} \times L^{nuclear}_{\tau}$ (which represents a modification of equation 27). We take the 2020 global average LCOE of nuclear estimated by IEA (2020a) of around L^{gas}_{τ}=\$19.4/GJ (equivalent to \$70/MWh).

Broader Opportunity Costs of Coal

The opportunity cost of coal $O^{s1,s2}_{t,T}$ (see equation 5) is given by the discounted value of missed free cash flows of coal companies resulting from shutting down coal mines early as coal is phased out according to schedule s_2 compared to business-as-usual s_1. Under a broader interpretation of the opportunity costs of coal, compensation could furthermore be offered for lost wages of coal workers who will lose their job from an early shut down of coal mines, as well as for costs of retraining coal workers for employment elsewhere (in particular in the renewable industry, which is set to grow as coal phased out and replaced with renewables).

Compensation for lost wages

Ruppert Bulmer et al. (2021) estimate that $W_{t_{2019}} = 4.6$ million workers were employed in the coal industry in 2019, and list the estimated number of the coal workers in the top 20 coal producing countries. Let $W_{y,t}$ be the number of coal workers in country y at time t (where the global number of coal workers in year t is given by $W_t = \sum_{y\in\mathcal{Y}} W_{y,t}$).[84]

[83] As in the case of building renewables to replace coal, building nuclear plants will involve some carbon emissions. We omit these for simplicity, since nuclear plant emissions are small compared to emissions from fossil fuel energy.

[84] We set $W_{y,t_{2019}}$ equal to Ruppert Bulmer et al. (2021)'s estimate for each top-20-coal-production country,

To estimate how many coal jobs might be lost as coal is phased out according pathway s_2, we assume that coal jobs in a country y fall proportional to the reduction in coal production in a country. The number of coal workers who lose their job in country y at time t in phase out scenario s_2 is then given by

$$j_{y,t}^{s2} = W_{y,t_{2022}} \times \frac{P_{y,t-1}^{s2} - P_{y,t}^{s2}}{P_y^{t2022}}. \tag{29}$$

We define the present value of opportunity costs related to coal job (J) losses in country y as the multiplication of the number coal workers $j_{y,\tau}^{s2}$ projected to lose their job at future date τ, with the average coal mining wage $\$\bar{w}_y$ in country y,[85] and with the number of years for which coal workers who lose their job should receive wage compensation l (alternatively, l can be interpreted as representing the multiplication of years of wage compensation and the wage percentage compensated), i.e.,

$$O_{y,t,T}^{s2,J} = \sum_{\tau=t+2}^{T} \frac{j_{y,\tau}^{s2} \times \bar{w}_{y,\tau} \times l}{(1+\rho)^{\tau-t}} \tag{30}$$

For simplicity, we assume the average coal miner wage $\$\bar{w}_{y,\tau}$ in each country y at each future date τ will stay equal to what it is today. As a baseline, we set the number of years during which coal workers will be compensated for their wage loss equal to $l = 5$ years. Five years of wage compensation gives young coal workers sufficient time to find a new job and take any requisite retraining to qualify for employment in another industry, and gives older coal workers the opportunity to retire early. $l = 5$ years is in line with the number of years during which coal workers who will lose their job as coal is phased out in Germany and Australia will be compensated.[86][87][88]

Compensation for retraining

Compensation could further be offered for costs of retraining (R) coal workers who are projected to lose their job in a phase out of coal according to pathway $s2$. As coal is phased out and renewables are phased in, coal workers could, for instance, be retrained to qualify for employment in renewable industry. We define costs to retrain coal workers in country y as the multiplication

---

where we denote the set consisting of the top-20-coal-production countries by $\mathcal{Y}^{T20}$. From the AR data, we know the coal production $P_{y,t_{2019}}^{s1}$ of each country y in 2019 (where $P_t^{s1} = \sum_{y \in \mathcal{Y}} P_{y,t}^{s1}$). We infer the number of workers in each of non-top-20-coal-production country y as follows: $W_{y,t_{2019}} = (W_{t_{2019}} - \sum_{y \in \mathcal{Y}^{T20}} W_{y,t_{2019}}) \times \frac{P_{y,t_{2019}}^{s1}}{P_{t_{2019}}^{s1} - \sum_{y \in \mathcal{Y}^{T20}} P_{y,t_{2019}}^{s1}}$. As we do not know the number of coal workers in each country y at time $t = 2022$, we assume $W_{y,t_{2022}} = W_{y,t_{2019}}$ for all $y \in \mathcal{Y}$.

[85] We constructed a data set of average wages of coal workers around the world in 2022, relying on sources such as Salary Explorer and Paylab. Find this data set at: https://greatcarbonarbitrage.com. Whenever average coal miner wages were not available for a country y, we used average mining wages in that country instead. We applied the exchange rate as of October 22 2022 to convert the local currency average wage of coal miners in each country y to the corresponding average wage $\bar{w}_y$ expressed in US dollars.

[86] Taking $l = 5$ years can alternatively be interpreted as providing compensation for 10 years at 50% wage compensation. Such compensation scheme is envisioned by The Greens (a political party) in Australia's transition away from coal. The Greens propose a job-for-job guarantee package that will provide 50% of a coal worker's wage for a decade, offered as a wage subsidy to employers who provide an equivalent paying job. Workers who cannot find alternative work can receive the subsidy directly. The plan of The Greens encourages coal workers to find employment elsewhere, as otherwise they only receive 50% of their original income. The plan of The Greens recognizes that it is not always possible for coal workers to find an equivalent paying job in another industry. This is particularly true for low-skilled coal workers who typically earn more in the coal industry than in other jobs needing similar skill sets (Louie and Pearce (2016)).

[87] See: https://greens.org.au/news/media-release/greens-release-plan-subsidise-wages-coal-workers-and-support-communities-0.

[88] The German draft coal exit law proposes to compensate lost coal wages (for a total of 5 billion euros by 2048). See: https://www.cleanenergywire.org/factsheets/spelling-out-coal-phase-out-germanys-exit-law-draft.

of the number of workers $j^{s2}_{y,\tau}$ (defined in equation 29) who are projected to lose their job in future year τ in country y with the average retraining costs \$$\bar{i}^R_{y,\tau}$ per coal worker in country y in year τ. By appropriately discounting these future retraining costs, we obtain the present value of costs to retrain workers, i.e.,

$$O^{s2,R}_{y,t,T} = \sum_{\tau=t+2}^{T} \frac{j^{s2}_{y,\tau} \times \bar{i}^R_{y,\tau}}{(1+\rho)^{\tau-t}}. \tag{31}$$

Louie and Pearce (2016) estimate the retraining costs for coal workers as coal is phased out in the United States. They note that a percentage of coal workers who are projected to lose their job should be able to find near-equivalent jobs in the renewable industry or other industries without needing retraining (e.g., a secretary and electrician). Hence, Louie and Pearce (2016) count retraining costs only for those coal workers who have coal jobs that do not have close equivalents. In particular, Louie and Pearce (2016) quantify the retraining time and investments needed to qualify them for closest equivalent position in the renewable industry. Louie and Pearce (2016) estimate that the average retraining cost per coal worker in the United States as of 2012 is: $\bar{i}^R_{y_{US},t_{2012}} = \$2014.60$ (best case, low), $\bar{i}^R_{y_{US},t_{2012}} = \$7231$ (best case, high), $\bar{i}^R_{y_{US},t_{2012}} = \$6009$ (worst case, low), $\bar{i}^R_{y_{US},t_{2012}} = \$20863.18$ (worst case, high).[89] In the best case scenario (least expensive to retrain), all employees who work non-coal specific positions are assumed to be able to find a job outside of the renewable industry and thus do not need retraining. In the worst case scenario (most expensive to retrain), all employees in coal mining industry will have to be retrained to qualify for employment in the renewable industry. As a baseline, we take $\bar{i}^R_{y_{US},t_{2012}} = \$7231$ (best case, high), since we'd like to take a conservative (high) estimate, and since it seems reasonable that not all coal workers will have to be retrained. As there are no studies that estimate retraining costs in other countries, we assume that the retraining costs in another country y scales with the average coal wage in country y relative to the average coal wage in the United States y_{USA}. The average retraining costs per worker in country y in year t is then given by

$$\bar{i}^R_{y,t} = \frac{\bar{w}_{y,t}}{\bar{w}_{y_{USA},t}} \bar{i}^R_{y_{USA},t} \tag{32}$$

We assume retraining costs in future year τ in each country $y \in \mathcal{Y}$ are equal to what they were in 2012; i.e., $\bar{i}^R_{y,\tau} = \bar{i}^R_{y,t_{2012}}$, $\forall \tau \in [t+2, T]$, $\forall y \in \mathcal{Y}$.

[89] These numbers are obtained from Table 1 in Louie and Pearce (2016) by dividing total retraining costs by the number of coal mine workers.

Table 8: 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	$P \times 29.3076$ **
Function converting MWh to GJ	$f(y)$: MWh $\rightarrow$ GJ	$y \times 3.6$ ***

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

PUBLICATIONS

The Great Carbon Arbitrage

Working Paper No. WP/2022/107