Supplementary Information

Quantifying the regional stranded asset risks from new coal plants under 1.5°C

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S1. Supplementary figures

This section presents supplementary figures for our main results as well as our sensitivity analysis. Figure S1-1 presents global electricity generation under the scenarios presented in our main results.

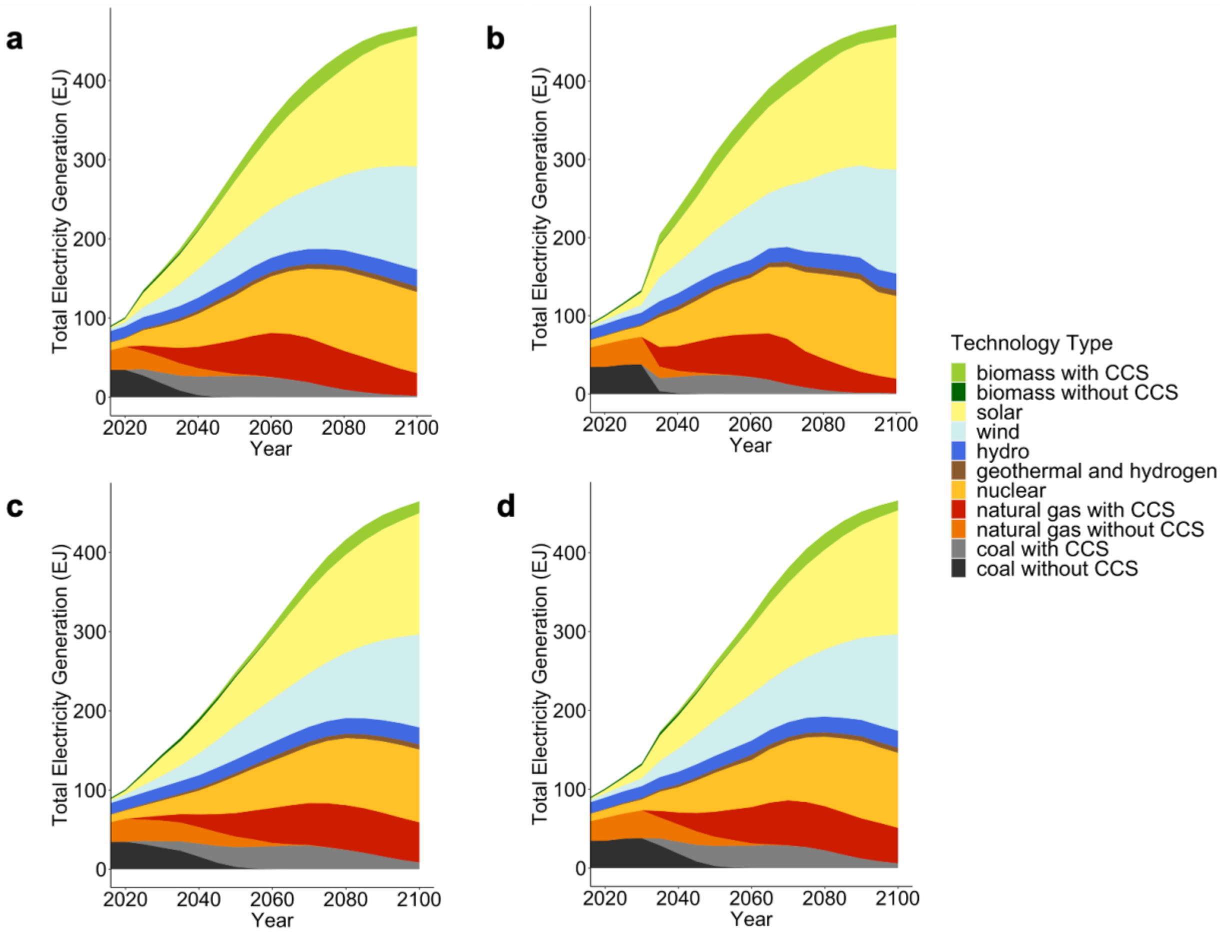

Figure S1-1. *Total global electricity generation (EJ) by technology type for the scenarios presented in our main analysis: (a) 1.5ºC target with no new coal, (b) 1.5ºC target with all new coal, where all plants in the pipeline are built (c) 2ºC target with no new coal, and (d) 2ºC target with all new coal.*

Figures S1-2 to S1-4 present maps of the proportion of assets stranded in different regions in three scenarios: *No New Coal to 1.5ºC*, *No New Coal to 2ºC*, and *All New Coal to 2ºC*. Stranded assets for *All New Coal to 1.5ºC* are presented in Figure 4 of the main text. Figure S1-5 presents the difference in stranded assets by region across all four scenarios when region is determined by the company headquarters or the physical location of the plant. This figure can be compared to Figure 5 in the main text, which presents results for the 1.5ºC scenarios only.

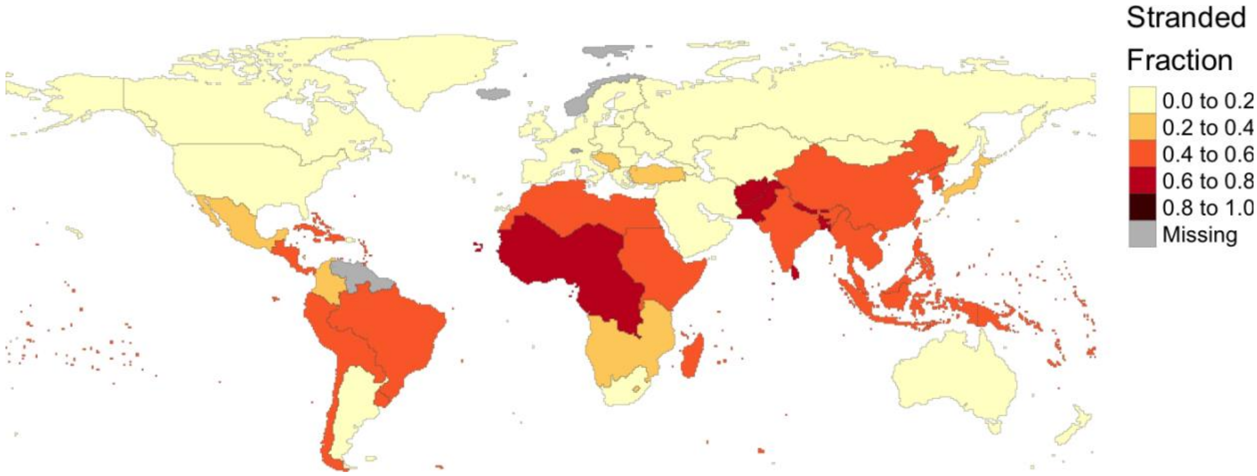

Figure S1-2. *Fraction of coal plant assets stranded by region under a 1.5ºC policy if no new coal plants are built and mitigation begins immediately.*

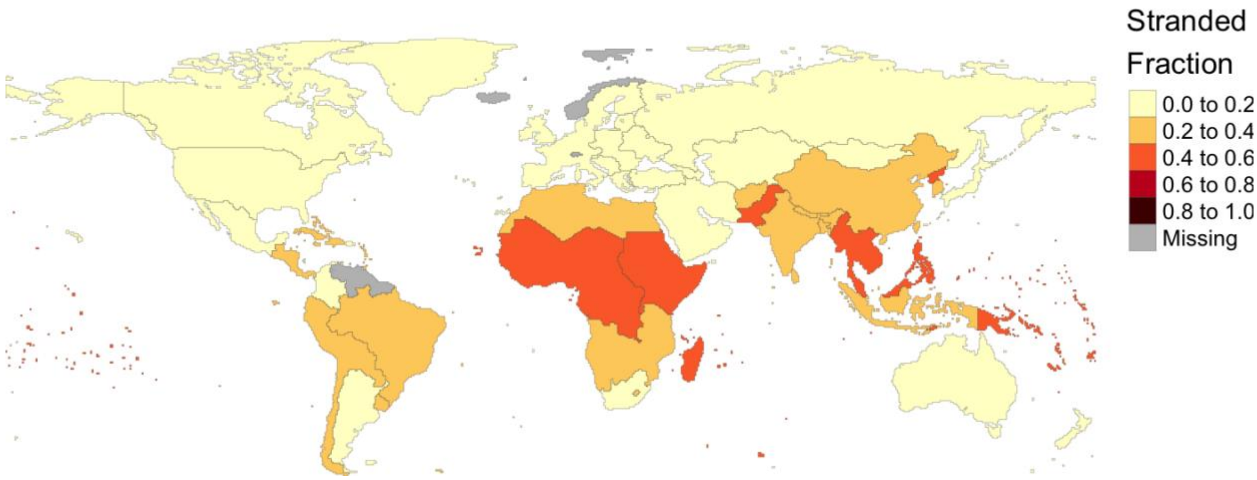

Figure S1-3. *Fraction of coal plant assets stranded by region under a 2ºC policy if no new coal plants are built and mitigation begins immediately.*

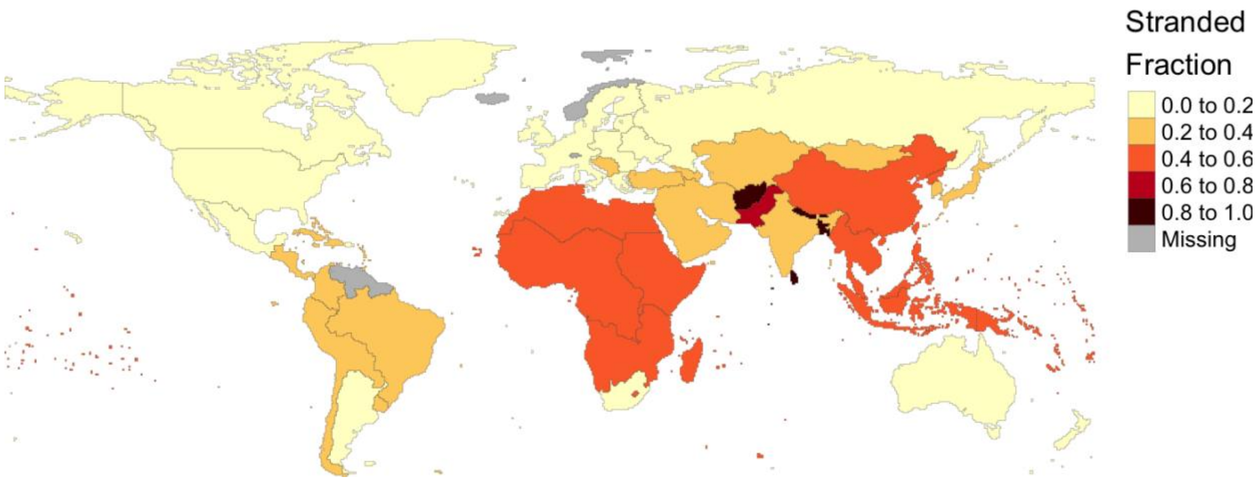

Figure S1-4. *Fraction of coal plant assets stranded by region under a 2ºC policy if all coal plants currently in the pipeline are built.*

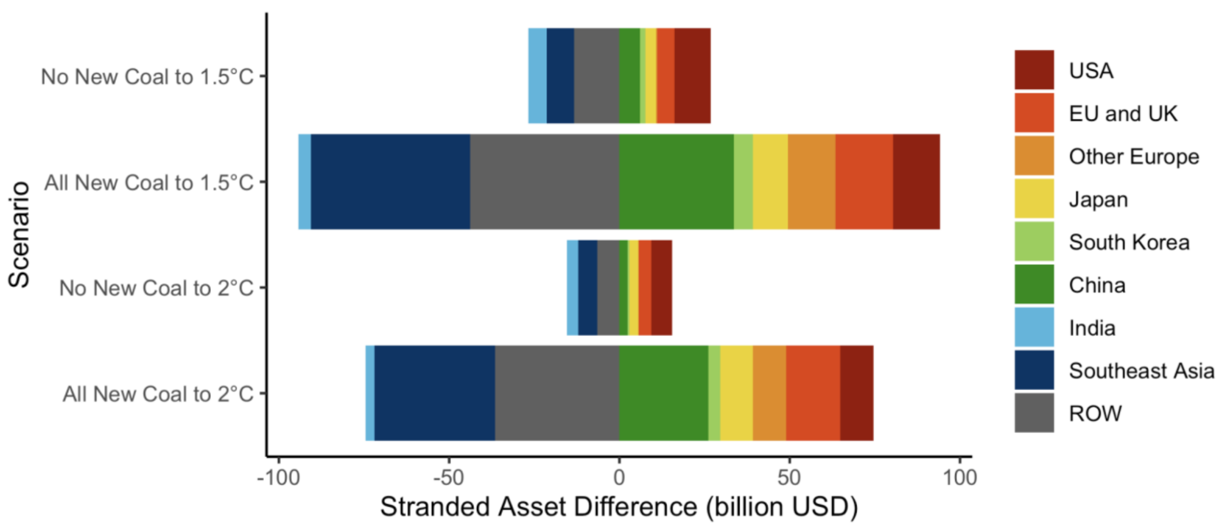

Figure S1-5. *Changes in regional stranded assets when assets are calculated based on the region of the company headquarters rather than the plant location. Positive values indicate that stranded assets are greater when assets are assigned to the location of the company headquarters rather than the location of the plant. The magnitude of the positive and negative values are the same, since the total value of stranded assets in each scenario does not change.*

The age at retirement for coal power plants in our simulations depends on the scenario as well as the plant. We use a lifetime of 50 years for business-as-usual retirement; however, some plants are older (if they have already been operating for more than 50 years when mitigation begins) or younger (if accelerated retirement is required to meet climate policy goals) at retirement. Figure S1-6 presents the distribution of plant lifetimes across the four scenarios. Average lifetimes are shorter for more stringent mitigation targets (1.5ºC versus 2ºC). For the 2ºC target, average lifetimes are also shorter under delayed action on no new coal, as compared to immediate action. For the 1.5ºC target, the average lifetimes are more similar, but the lifetimes show greater spread under the All New Coal scenario, with some plants retiring later (due to delayed climate action) and others retiring earlier (due to the need to rapidly retire new plants once action on climate begins in 2030).

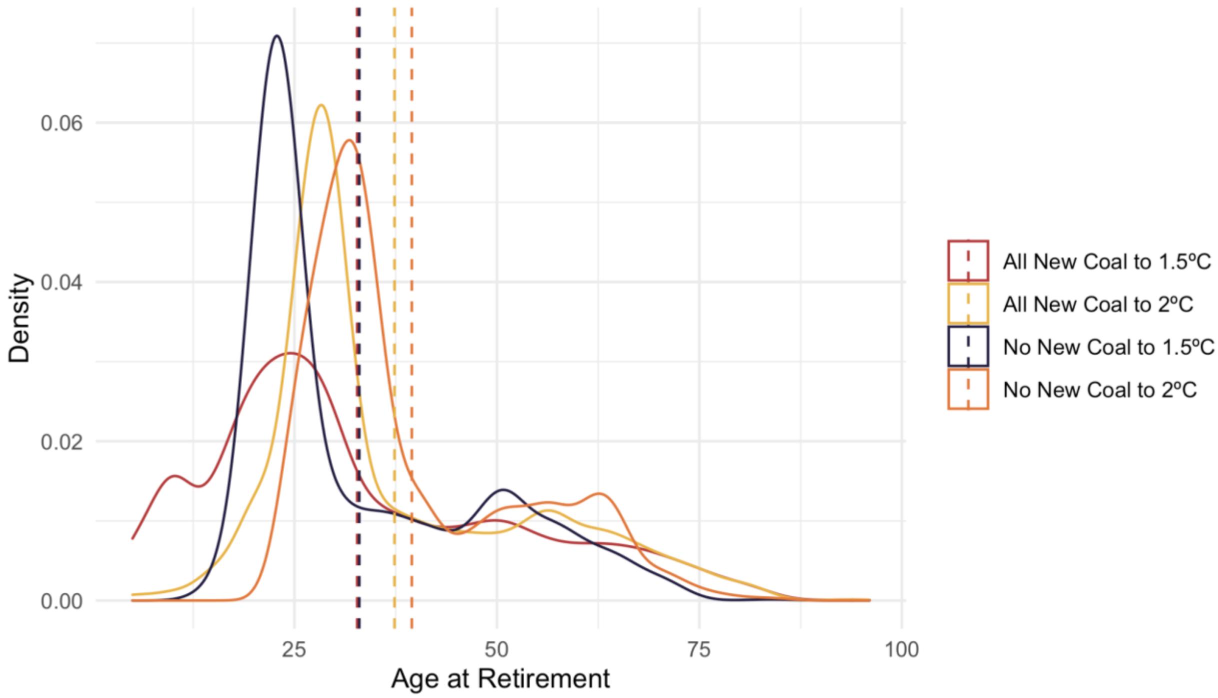

Figure S1-6. *Distribution of plant ages at retirement for four scenarios: No New Coal to 1.5ºC, All Ne Coal to 1.5ºC, No New Coal to 2ºC, and All New Coal to 2ºC.*

S2. Sensitivity analysis

Bioenergy constraint

Near-term pathways for meeting long-term climate policy targets can depend on the level of negative emissions in the later half of the century. In our main results, we place a constraint on the amount of electricity generated from bioenergy sources at 200 EJ per year and examine the sensitivity of our results to more stringent bioenergy constraints. Figure S2-1 presents global electricity generation under a 150 EJ per year bioenergy constraint, and Figure S2-2 presents results under a 100 EJ per year constraint. Note that under the stricter 100 EJ constraint, GCAM does not find a solution for meeting a 1.5ºC temperature target if all coal plants currently in the pipeline come online as scheduled.

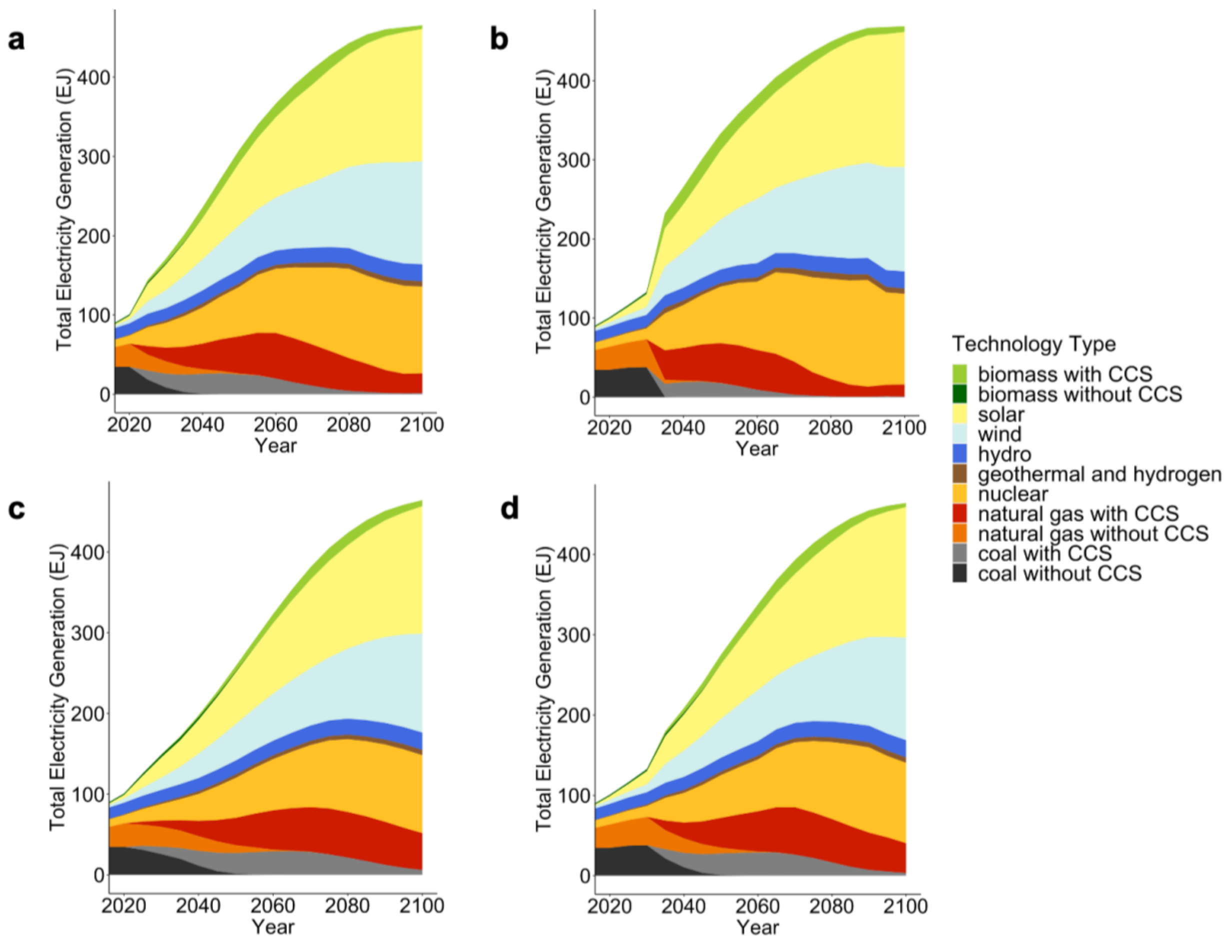

Figure S2-1. *Total global electricity generation (EJ) by technology type under a bioenergy ceiling of 150 EJ for the following climate scenarios: (a) 1.5ºC target with immediate action on no new coal, (b) 1.5ºC target if all coal plants in the pipeline are built, (c) 2ºC target with no new coal and (d) 2ºC warming with all new coal.*

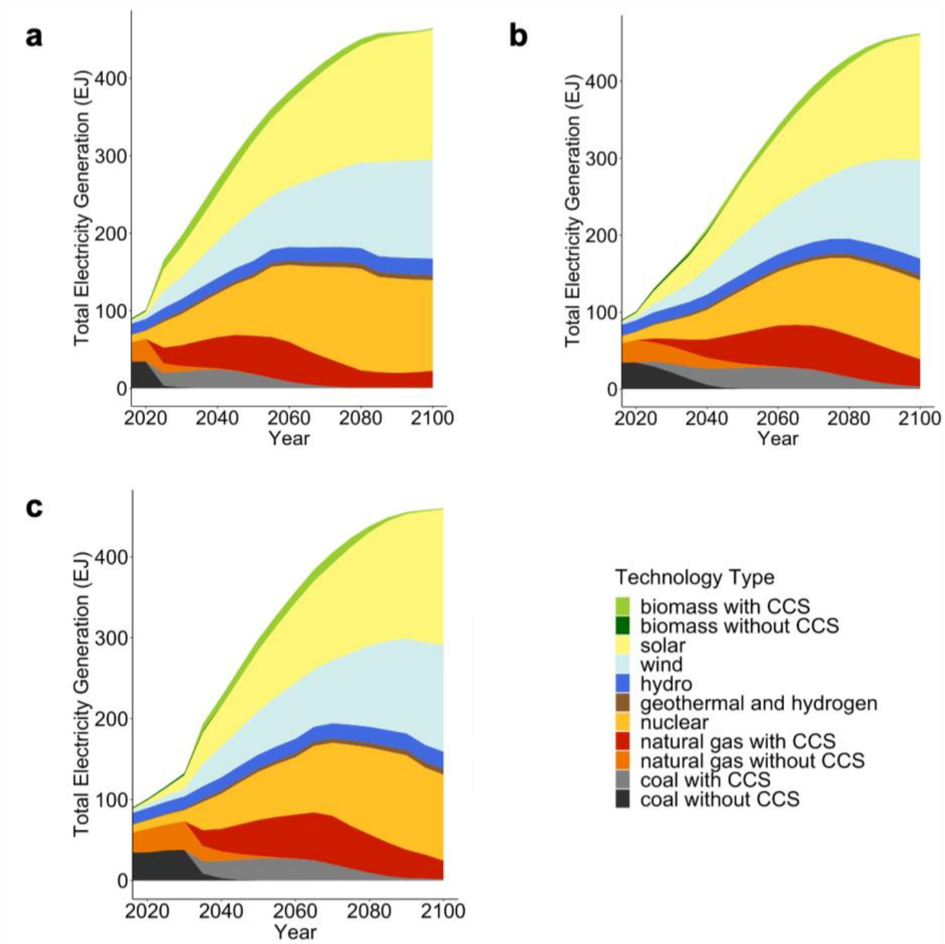

Figure S2-2. *Total global electricity generation (EJ) by technology type under a bioenergy ceiling of 100 EJ for the following climate scenarios: (a) 1.5ºC target with immediate action on no new coal, (b) 2ºC target with no new coal, and (c) 2ºC target if all coal plants in the pipeline are built. Global electricity generation for a 1.5ºC target with all new coal is not pictured because GCAM does not find a solution to this scenario.*

More stringent constraints on annual bioenergy production restrict the role that negative emissions from bioenergy with carbon capture and storage (BECCS) can play in meeting the long-term 1.5 and 2ºC climate goals. With lower amounts of negative emissions later on, near-term transitions away from high-emitting electricity sources, especially coal, must be accelerated. Table S2-1 presents total stranded assets under our baseline scenario (200 EJ bioenergy constraint) and under more stringent constraints. Stranded assets are larger with smaller bioenergy constraints. The relative differences in stranded assets under no new coal and all new coal also became smaller. This is because coal retirement is accelerated in the immediate action scenarios, whereas there is less room to further accelerate retirement in the delayed action scenarios.

Table S2-1. *Stranded assets under different bioenergy constraints for four scenarios: No New Coal to 1.5ºC, All New Coal to 1.5ºC, No New Coal to 2ºC, and All New Coal to 2ºC. More stringent constraints on bioenergy production (and therefore negative emissions from BECCS) lead to higher asset stranding. The All New Coal to 1.5ºC scenario does not solve with a 100 EJ bioenergy constraint.*

Bioenergy Constraint	No New Coal to 1.5ºC	All New Coal to 1.5ºC	No New Coal to 2ºC	All New Coal to 2ºC
200 EJ	$880 billion	$1.4 trillion	$573 billion	$1 trillion
150 EJ	$1.1 trillion	$1.4 trillion	$656 billion	$1.1 trillion
100 EJ	$1.2 trillion	n/a	$784 billion	$1.3 trillion

Plant lifetimes

The value of stranded assets from coal power plants also depends on the plant lifetime. Across scenarios, longer lifetimes lead to larger values for stranded assets, and shorter lifetimes lead to smaller values for stranded assets. Figure S2-3 presents stranded asset values for lifetimes of 20, 30, 40, 50, 60, and 70 years for the four climate policy scenarios: *No New Coal to 1.5ºC*, *All New Coal to 1.5ºC, No New Coal to 2ºC*, and *All New Coal to 2ºC*.

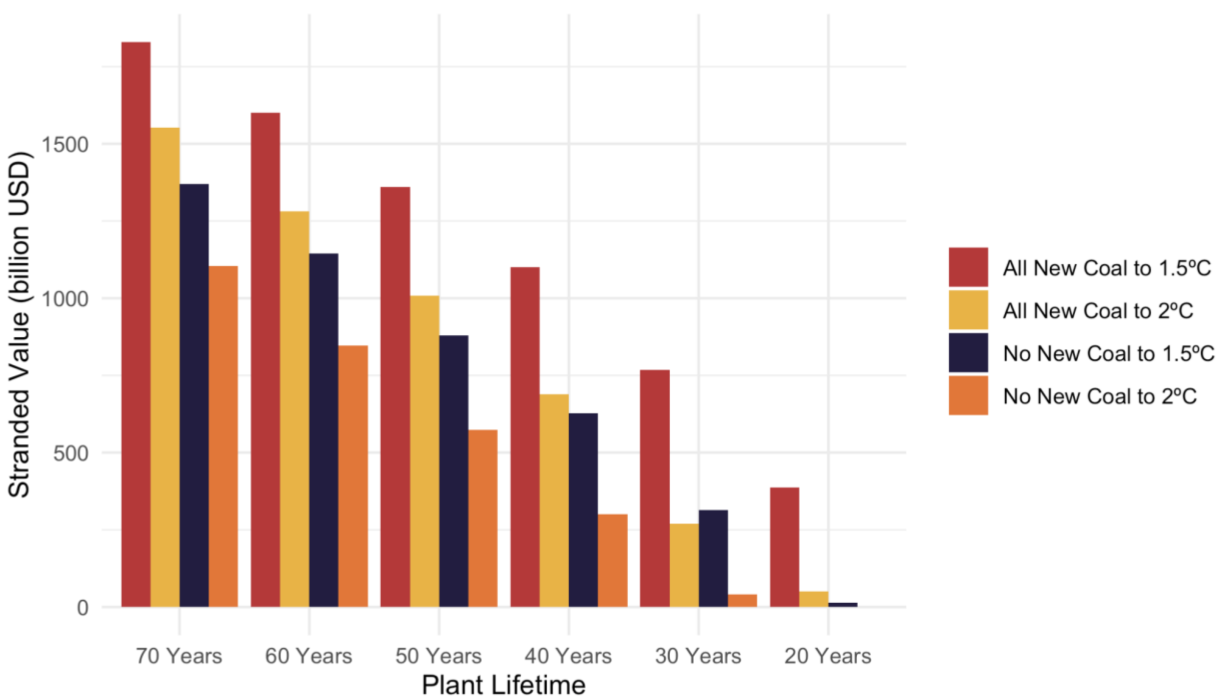

Figure S2-3. *Stranded assets for the four scenarios (All New Coal to 1.5ºC, All New Coal to 2ºC, No New Coal to 1.5ºC, No and New Coal tot 2ºC) for coal plant lifetimes of 20, 30, 40, 50,* *60, and 70. Stranded assets increase with plant lifetime. A lifetime of 50 years is used for results presented in the main text.*

S3. Stranded assets literature

Title	Authors	Published Year	Sector	Coverage	Measurement of Stranded Assets	Methodology & Assumptions	Value of Stranded Assets
Unburnable Carbon 2013: Wasted Capital and Stranded Assets[1]	Carbon Tracker Initiative	2013	Coal, oil, gas (upstream)	Global	Unburnable fossil fuel reserves	80% chance of limiting the rise in global temperature to 2°C	60-80% of coal, oil and gas reserves of listed firms are unburnable; Up to US$6.74 trillion (annually) in wasted capital developing reserves that is likely to become unburnable in the BAU scenario
Oil and Carbon Revisited; Value at Risk from 'Unburnable' Reserves[2]	Spedding et al.	2013	Oil companies (upstream)	Europe	Unburnable oil reserves	Ceiling tests to assess value at risk; 2°C scenario (50%)	Value at risk from unburnable reserves would be equivalent to 40-60% of market capitalization for oil companies
Carbon Supply Cost Curves: Evaluating Financial Risk to Coal Capital Expenditures[3]	Carbon Tracker Initiative	2014	Coal (upstream)	Global (excl. China)	CAPEX of coal mines	2°C scenario (80%)	US$112 billion of potential capex, excluding China, by 2025 would be at the risk of loss
Stranded Assets, Fossilised Revenues[4]	Lewis et al.	2014	Fossil fuel sector	Global	Potential revenue losses in fossil fuel sector	IEA's New Policies Scenario and 2°C scenario	Potential loss of US$28 trillion (in constant 2012 US dollars) of gross revenues over the next two decades (oil: US$19.3 trillion, gas: US$4 trillion, coal: US$4.9 trillion), compared with the BAU

Stranded on a Low-Carbon Planet: Implications of Climate Policy for the Phase-Out of Coal-Based Power Plants[5]	Johnson et al.	2015	Coal-fired power plants without CCS	Global	Value of idle coal capacity running under normal utilization rate	Summing the discounted unrealized annual charges between the time of retirement and the economic lifetime to get stranded assets value; Eight discrete emission scenarios consistent with 2°C target by 2100	US$165 - 550 billion over the 2011 to 2050 period
Subcritical Coal in Australia: Risks to Investors and Implications for Policymakers[6]	Caldecott et al.	2015	Coal-fired power plants	Australia	Net Present Value (NPV) of profits foregone due to premature retirement of plants	Future profits are modelled using a revenues-minus-costs approach; Assuming all subcritical coal power plants in Australia are closed within 5, 10, or 15-year time horizons (2016-2020, 2016-2025, 2016-2030)	AU$8.4-18.3 billion (or AU$560 million - AU$3.66 billion per year)
The Contribution of Paris to Limit Global Warming to 2ºC[7]	Iyer et al.	2015	Power sector	Global	Power generation capacity of premature retired assets	50% chance of limiting the rise in global temperature to 2°C; Baseline scenario: excludes all policies designed to limit GHG emissions; Paris scenario: global emissions through 2030 are based on Intended Nationally Determined Contributions (INDCs); No Paris scenario: no mitigation action until 2030	Up to 2,300 GW under the No Paris scenario

Stranded Assets and Thermal Coal in Japan: An Analysis of Environment-Related Risk Exposure[8]	Caldecott et al.	2016	Coal-fired power plants	Japan	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value; 5-year scenario: coal-fired power plants become stranded by 2021; 10-year scenario: coal-fired power plants become stranded by 2026; 15-year scenario: coal-fired power plants become stranded by 2031	5-year scenario: ¥8,453 billion (US$75 billion); 10-year scenario: ¥8,924 billion (US$80.2 billion), of which ¥6,223 billion (US$56 billion) are plants built after 2016; 15-year scenario: ¥6,857 billion (US$61.6 billion), of which ¥5,307 billion (US$47.7 billion) are plants built after 2016; This is equivalent to 22.6% - 29.4% of the current market capitalization, and 4.5%-5.9% of total assets, of Japan's power utilities
'Climate Value at Risk' of Global Financial Assets[9]	Dietz et al.	2016	All sectors (all financial assets)	Global	Expected 'climate value at risk' (climate VaR) of global financial assets	Monte Carlo simulation to simulate the probability distribution of the present market value of losses on global financial assets due to climate change; estimated VaR under BAU emission path or 2°C pathway is met; 2°C scenario (66%)	BAU: mean 1.8% loss (around US$2.5 trillion); 99th percentile could be 16.86% loss (around US$24.2 trillion) Mitigation to limit warming to 2°C: mean 1.18% loss; 99th percentile 9.17% loss

Stranded Assets and Renewables: How the Energy Transition Affects the Value of Energy Reserves, Buildings and Capital Stock[10]	IRENA	2017	All sectors	Global	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value; REmap scenario (2°C scenario with 66% probability); Delayed Policy Action scenario: BAU until 2030; Following 2030, the deployment of renewables and energy efficiency accelerates sufficiently to ensure that the global energy system remains within the same emissions budget by 2050	Coal power generation stranded value around US$650 billion (read from Figure 7) and 40GW of coal capacity will be stranded annually between 2015 and 2050
Perspectives for the Energy Transition: Investment needs for a Low-Carbon Energy System - Chapter 3, Global Energy Transition Prospects and the Role of Renewables[11]	IEA/IRENA	2017	Fossil fuel power plants	Global	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value; Immediate actions (2°C Scenario with 66% probability); Delayed actions by 2025 and in 2025, a sudden shift in climate policy is assumed to occur, with policy makers seeking to ensure that cumulative energy sector CO2 emissions between 2015 and 2100 remain as in the 66% 2°C Scenario.	Immediate actions: US$320 billion (fossil-fuel power plants). Coal-fired power plants constitute 96% of the number, which would be US$307 billion; Delayed actions: US$400 billion (fossil-fuel power plants). Coal-fired power plants constitute 96% of the number, which would be US$384 billion

Stranded Assets and Thermal Coal in China: An Analysis of Environment-Related Risk Exposure[12]	Caldecott et al.	2017	Coal-fired power plants	China	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value, assuming 40 yrs depreciation; 5-year scenario: coal-fired power plants become stranded by 2021; 10-year scenario: coal-fired power plants become stranded by 2026; 15-year scenario: coal-fired power plants become stranded by 2031; 20-year scenario: coal-fired power plants become stranded by 2036; These scenarios reflect the different speeds and scales at which the environment-related risks identified could materialize.	Five-year scenario: ¥7,201bn (US$1,047 billion). 10-year scenario: ¥5,797bn (US$843 billion). 15-year scenario: ¥4,420bn (US$643billion) 20-year scenario: ¥3,086bn (US$449 billion) This is equivalent to 4.1-9.5% of China's 2015 GDP.
Carving out Coal in the Philippines: Stranded Coal Plant Assets and the Energy Transition[13]	Ahmed et al.	2017	Coal-fired power plants	Philippines	Unearned revenue from surplus/low utilization rate of coal-fired power plants (due to uncontracted capacity/ competition from low-cost hydro power/oversupply of power)	Stranded costs were calculated using capacity payments multiplied by the coal capacity and then multiplied by the difference in plant load factor (PLF) between the actual PLF and standard PLF in PPAs.	From 2014 - 2016, stranded cost in Mindanao is about PHP$3 billion (US$60 billion); The existing coal pipeline of 10,423 MW (about US$20.8 billion) is running the risk of becoming stranded.

Measuring Progress from Nationally Determined Contributions to Mid-century Strategies[14]	Iyer et al.	2017	Power sector	Global	Power generation capacity of premature retired assets	Achieve 80% reductions in economy-wide GHG emissions in 2050 relative to 2005; 'Full Tech' scenario: utilize full suite of GCAM technologies; 'No Nuc' scenario: no new deployment of nuclear technologies, greater deployment of carbon capture and storage (CCS) technologies and renewables; 'No CCS' scenario: no deployment of CCS technologies, greater deployment of nuclear and renewables; 'No Nuc & CCS' scenario: no new deployment of nuclear technologies, all emissions reductions achieved through renewables	10 - 15 GW $year^{-1}$ between 2016 and 2025 across all scenarios; 5 - 10 GW $year^{-1}$ between 2026 and 2050 across all scenarios
Committed Emissions from Existing and Planned Power Plants and Asset Stranding Required to Meet the Paris Agreement[15]	Pfeiffer et al.	2018	Fossil fuel power plants	Global	Idle capacity running under normal utilization rate	Capacity running at low utilization rates would constitute stranding (e.g. 80% of normal utilization rate means 20% of stranding); 1.5°C and 2°C Scenarios	51%–58% of all power plants that are operating, planned and under construction would be stranded; If all currently planned projects were cancelled, 10% - 20% of existing capacity would be stranded

Macroeconomic Impact of Stranded Fossil Fuel Assets[16]	Mercure et al.	2018	All sectors	Global	Remaining value of premature retired plants	'IEA expectations' scenario: fuel use from the IEA's 'new policies scenario'; E3ME-FTT 'Technology Fusion Trajectory' scenario: energy demand from power, road transport, buildings, and other sectors; '2ºC' scenario: achieves 75% probability of remaining below 2ºC while limiting bioenergy use to 95 EJ yr^{-1}	US$12 trillion (in 2016 US dollars) under a 2ºC target, which comprises over 15% of global GDP
Economic and Financial Risks of Coal Power in Indonesia, Vietnam and Philippines[17]	Carbon Tracker Initiative	2018	Coal-fired power plants	Indonesia, Vietnam and Philippines	Net Present Value (NPV) of profits foregone due to premature retirement of plants	Stranded assets value is calculated as the difference between NPV of cash flow in the IEA's beyond 2°C Scenario (which phases-out all coal power by 2040) and the NPV of cash flow in the BAU scenario (which is based on retirements announced in company reports) from both operating and under-construction units; IEA's beyond 2°C Scenario	Indonesia: US$34.7 billion. The cost-optimised retirement schedules show an average plant lifetime of 16 years, which is 24 years less than the typical lifetime of a coal plant; Vietnam: US$11.7 billion. The cost-optimised retirement schedules show an average plant lifetime of 13 years, which is 27 years less than the typical lifetime of a coal plant; Philippines: US$13.1 billion
The Early Retirement Challenge for Fossil Fuel Power Plants in Deep Decarbonisation Scenarios[18]	Kefford et al.	2018	Fossil fuel power plants	US, EU, China and India	Net Present Value (NPV) of unearned revenue due to premature retirement of environmentally unsustainable plants	Summing the discounted unrealised annual charges between the time of retirement and the economic lifetime to assess the value of the stranded assets; IEA 2DS pathway	By 2060, US$541 billion in the US, EU, China, and India alone, of which 66% and 31% of the costs (US$358 billion and US$169 billion) are shared by China and India respectively; Setting a minimum operational capacity factor for retirement of 40% increases the magnitude of the early

							retirement problem significantly for unabated coal and increases the value of stranded assets by 43% to US$773 billion.
Power Sector Asset Stranding Effects of Climate Policies[19]	Saygin et al.	2019	Fossil fuel power plants	Analysis for G20 countries (excluding EU countries); then multiply it by a factor to scale up to all countries	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value, assuming 50-year lifetime and different capital cost in OECD and non-OECD countries; REmap scenario (2°C scenario with 66% probability); Delayed Policy Action scenario: BAU until 2030; Following 2030, the deployment of renewables and energy efficiency accelerates sufficiently to ensure that the global energy system remains within the same emissions budget by 2050	In G20 countries: by 2050, US$1,563 billion under delayed policy action; US$ 792 billion under the RE map case; Global: by 2050, US$1,824 billion under delayed policy action; US$927 billion under the RE map case; By 2050, stranded coal assets would represent around 75% of total stranded assets value (US$695-1,368 billion) and China alone would represent 45% of the total; Delaying action to mitigate climate change until 2030 doubles stranded asset value.
Stranded Asset Implications of the Paris Agreement in Latin America and the Caribbean[20]	Binsted et al.	2020	Fossil fuel power plants	Latin America and the Caribbean	Remaining value of premature retired plants	Straight-line depreciation method to calculate stranded assets value, assuming a 60-year lifetime; Scenarios include NDCs-to-2°C, NDCs-to-1.5°C, Straight-to-2°C and Straight-to-1.5°C	US$40 - 90 billion; 60 - 128 GW of fossil-fuel power plants (15 - 33% of total installed capacity in LAC) stranded between 2021 and 2050, in which natural gas and oil power plants constitute nearly 50%.

How to Waste Over Half a Trillion Dollars: The Economic Implications of Deflationary Renewable Energy for Coal Power Investments[21]	Carbon Tracker Initiative	2020	Coal-fired power plants	Global	Potential loss of capital investment in coal generation capacity due to falling competitiveness of new coal power investment	Evaluating potential loss of capital investment in coal generation capacity in different countries by comparing the cost of coal to alternative energy (LCOE); Scenarios include - Extreme: 45% or more of coal capacity that costs more to operate than new renewable energy today and 100% by 2030; High: 25 - 45% of coal capacity that costs more to operate than new renewable energy today and 100% by 2030; Moderate: 10 - 25% of coal capacity that costs more to operate than new renewable energy today or 45% or more by 2030; Low: 10% or less of coal capacity that costs more to operate than new renewable energy today and 45% or less by 2030.	US$638 billion by 2050 (announced, permitted, pre-permitted and under-construction)
Early Retirement of Power Plants in Climate Mitigation Scenarios[22]	Fofrich et al.	2020	Fossil fuel power plants	Global	Maximum power plant lifetime	Analyze coal and natural gas-fired power plant utilization rates and lifetimes across 171 scenarios and three levels of emissions mitigation (1.9, 2.6, and 4.5 W m^{-2} of radiative forcing; i.e. trajectories likely to avoid 1.5, 2, and 3ºC of global warming by the end of the century)	Coal-fired power plants: maximum power plant lifetimes of 9, 16, and 19 years for 1.9, 2.6, and 4.5 W m^{-2} of radiative forcing, respectively Gas-fired power plants: maximum power plant lifetimes of 12, 17, and 20 years for 1.9, 2.6, and 4.5 W m^{-2} of radiative forcing, respectively

Stranded Investment Associated with Rapid Energy System Changes under the Mid-Century Strategy in Japan[23]	Oshiro et al.	2020	Multiple sectors	Japan	Remaining value of premature retired assets	2030 policy combined with NDC goal (16%, 26%, and 36% reduction); 2050 policy scenario combined with MCS goal (70%, 80% , 85%, and 90% reduction)	US$8-82 billion
A High Ambition Coal Phaseout in China: Feasible Strategies through a Comprehensive Plant-by-Plant Assessment[24]	Cui et al.	2020	Coal-fired power plants	China	Economic losses caused by retirement of assets	Stranded assets value is calculated by summing unrecovered investment costs, unpaid bank loans and the expected return of unrecovered private capital between the retirement year and the end of the 30-year design lifetime; 1.5°C and 2°C Scenarios	US$9.3 - 35 billion under 2°C Scenario; US$34 - 127 billion under 1.5°C Scenario
Reducing Stranded Assets through Early Action in the Indian Power Sector[25]	Malik et al.	2020	Power sector	India	Power generation capacity of premature retired assets	Early action scenario with abatement towards a global well-below 2°C goal after 2020; Delayed action scenario that follows India's current policies and NDC targets until 2030 and abatement towards a global 2°C goal thereafter	14 - 159 GW under early action scenario; 133 - 227 GW under delayed action scenario

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