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A worldwide analysis of stranded fossil fuel assets' impact on power plants' CO_2 emissions

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Don Grant [1,2] ✉, Tyler Hansen [3], Andrew Jorgenson [4,5] & Wesley Longhofer [6]

Will power plants emit less or more CO_2 in anticipation of stronger climate policies that would strand fossil fuel reserves? Here, using a worldwide data source on individual power plants' CO_2 emissions and the value of countries' at-risk fossil fuel assets, we show that between 2009 and 2018, plants emitted more CO_2 in countries where more assets would be devalued under a 1.5 °C scenario, which we theorize is due to these countries' regulatory leniency and plants' vested interest in long-term fossil fuel contracts. Although the extra amount of carbon emitted each year trigged by imperiled assets is relatively small, it would exhaust a sizable portion of the electricity sector's remaining carbon budget when added up over time. This is especially true in the U.S. and Russia where up to 16% and 12% of their budgets, respectively, could be spent within ten years due solely to the stranded asset effect.

The 2015 Paris Agreement commits countries to limit the global average temperature rise to below 2 °C above pre-industrial levels, and to aim for 1.5 °C. To achieve these goals, a significant portion of currently owned fossil fuel reserves must remain in the ground[1], causing these assets to be stranded or "suffer unexpected and sustained reductions in market value"[2–4]. According to Schumpeter's[5] influential "creative destruction" thesis, over-exposed sectors will be gradually dismantled, facilitating the assimilation of new products and procedures that supplant an existing system with a new one[6]. In line with this thesis, most research on low-carbon transitions assumes that the prospect of stranded fossil fuel assets will compel actors to divest away from resources and technologies with high emission intensities and replace them with green niche innovations that will become the foundation of a different way of generating and using energy[7].

In contrast to this optimistic approach focusing on the promise of low-carbon, sunrise industries, a pessimistic perspective, commonly referred to as the "green paradox" approach, has emerged that warns of the defensive measures taken by high-carbon, sunset industries[7–9]. It posits that the fossil fuel industry is part of a larger, regime-level alliance, comprised of conventional energy companies[7], sympathetic policymakers[10,11], and supportive financiers[6,12,13] who actively resist the transition toward a clean energy-based system[7,14–17]. Although the interests of these regime incumbents sometimes clash, such as when oil and gas corporations signal support for a carbon tax to phase out (relatively cheap but carbon intensive) coal that would allow more of their (relatively costly) fuels to be consumed[18], one issue that consistently generates consensus among regime incumbents, especially as resource nationalism has grown[19], is the right to maximize rents from a country's carbon reserves[7].

Both camps suggest that investors and energy suppliers are capable of anticipatory action[20] (i.e., developing and executing strategies based on plausible futures and changes in power relations) within a regulatory environment like that created by the Paris Agreement, which sets ambitious climate goals but delays the implementation of stringent policies well into the future. Optimists stress how investors will divest away from infrastructure with high emission intensities that could be rendered un-economic by future climate policy. In contrast, pessimists emphasize how energy suppliers will maximize their rents by accelerating the extraction of fossil fuels and making them more affordable before those resources are deemed worthless.

Neither side, however, has examined whether major downstream consumers of fossil fuels – namely, power plants – pollute less or more

[1]Department of Sociology, University of Colorado Boulder, Boulder, CO, USA. [2]Renewable and Sustainable Energy Institute, University of Colorado Boulder, Boulder, CO, USA. [3]Department of Environmental Studies, Dartmouth College, Hanover, NH, USA. [4]Department of Sociology, University of British Columbia, Vancouver, BC, Canada. [5]Department of Theoretical Economics, Vilnius University, Vilnius, Lithuania. [6]Goizueta Business School, Emory University, Atlanta, GA, USA. ✉e-mail: dogr2184@colorado.edu

in anticipation of stronger climate policies. This despite the fact that these facilities are responsible for the lion's share of carbon dioxide (CO_2)emissions and are highly susceptible to asset abandonment due to their sunk investments in carbon-intensive operations[21]. Scholars have yet to determine how plants respond to delayed-action climate policy in large part because data on power plants' CO_2 emissions have been lacking. As a result, research has focused almost exclusively on the decisions of investors and energy suppliers, which scholars have modeled using simulation techniques[22]. While this body of work helps to formalize theory about these actors, it stops short of providing sound microevidence needed to determine the impact of imperiled fossil fuel reserves on power stations' CO_2 emissions[23].

To date, the study that comes closest to generating such evidence is Di Maria et al.[24] empirical examination of whether U.S. power plants emitted more sulfur dioxide (SO_2) between the announcement of the Acid Rain Program and its implementation. Consistent with the green paradox thesis, they found that owners of coal deposits responded to this program by extracting more coal and selling it at a cheaper price. However, contrary to that thesis, price decreases had no effect on plants' SO_2 emissions, which the authors attribute to the fact that most plants are locked into long-term coal purchases that prevent them from taking advantage of changes in spot pricing.

Although their study casts doubt on the green paradox hypothesis, Di Maria et al. also overlook several factors that beg further investigation and suggest how climate policies might still inadvertently increase emissions. Besides not examining the CO_2 emissions of power plants in the U.S. and throughout the world, their study does not measure the value of a nation's fossil fuel assets that are at-risk of being stranded. Instead, it examines whether the effect of coal prices on emissions changes as the Acid Rain program came closer to being implemented. Hence, it does not capture how at-risk assets are distributed unevenly across the globe and threaten to disrupt the economies of some countries more than others. In addition, Di Maria et al. confined their study to large, base-load plants that operate at full capacity almost all the time. Consequently, it does not explore how other plants may adjust their capacity factor[25] when many of the reserves they have already purchased are in peril.

In this work, we use a worldwide dataset on individual power plants' CO_2 emission levels (annual tonnes of CO_2 emitted)[26], their operational characteristics, and the value of their countries' potentially stranded fossil fuel reserves[27] to fill these gaps and conduct an empirical analysis of the effects of at-risk fossil fuel assets on plants' carbon pollution under a 1.5 °C (and, in Supplementary Table 1, 2 °C) climate stabilization scenario. We test two simple, alternative models of the green paradox. The first predicts that plants will pollute at higher levels in countries with more at-risk fossil fuel reserves because those countries are more likely to exercise regulatory leniency to soften the otherwise disruptive effects of stranded assets on government revenues, employment, and energy security. Such leniency allows plants to defer maintenance, exploit loopholes in environmental regulation, and delay adopting cleaner technologies, all of which directly add to a plant's carbon pollution. The second model assumes that most plants are locked into long-term fossil fuel contracts and many of the fuels they have acquired are derived from their host country's carbon reserves. It predicts that in countries with more at-risk assets, plants have a vested interest in shifting the processing of fossil fuels forward to capitalize on their purchases of coal, oil, and gas and use their plant equipment while they still can. By incentivizing plants to speed up their operations (i.e., increase their capacity utilization rate) in this way, stranded assets indirectly cause plants' emissions to rise. Joskow[28] provides several examples of how plants subject to long-term contracts can effectively accelerate the burning of already purchased fuels by renegotiating quantity provisions at dates specified within these agreements. Consistent with our two predictions, findings here indicate that not only do power plants release more CO_2 in countries where more fossil fuel assets are in jeopardy of being stranded, but in those same countries, plants also operate closer to full capacity, causing them to emit CO_2 at even higher levels. Results thus point to countries' regulatory leniency and plants' vested interest in their long-term contracts as the mechanisms that might lead to a green paradox. Unlike most past studies that rely on simulation methods, our study also uses a hierarchical linear model (HLM) that rejects specifications that cannot reproduce observations and estimates the magnitude of parameters[29]. This technique allows us not just to empirically assess whether at-risk assets are associated with plants' emissions, but also to calculate the total volume of CO_2 that plants emit in response to those assets. Results suggest that in the case of countries like the United States and Russia, the extra emissions attributed to the stranded asset effect exhaust a significant percent of their electricity sectors' remaining carbon budgets.

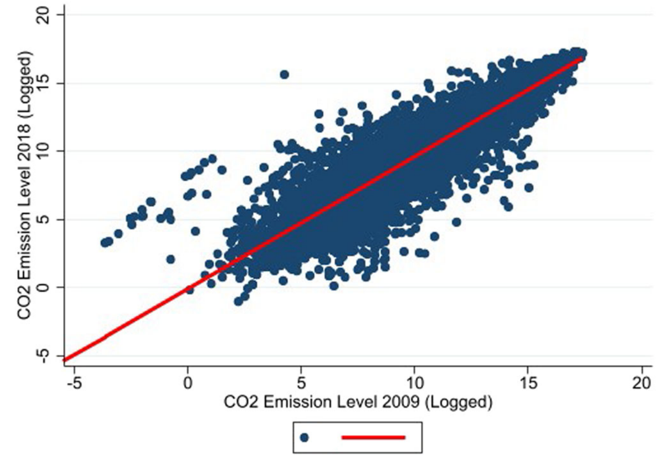

Fig. 1 | presents a scatterplot with 45-degree line of power plants' (logged) CO_2 emission levels in 2009 and 2018. Source data are provided as a Source Data file.

Results

Power plant emissions and characteristics

Figure 1 shows how power plants' CO_2 emission levels differed between 2009 and 2018, three years after the signing of the Paris Agreement. Nearly the same number of cases are above the scatterplot's 45-degree line as below it, suggesting roughly an equal number of plants increased and decreased their emissions during this period. Table 1 presents the means, standard deviations, and correlation coefficients for the variables tested here when the sample is restricted to power plants that were operative in both 2009 and 2018 (N = 11,941). In keeping with our first prediction, it shows that total stranded assets are positively associated with plants' emissions. Consistent with conventional theorizing about the green paradox, Table 1 also reveals that coal, oil, and gas prices, on average, decreased between 2012 (shortly before the Paris Agreement was signed) and 2017 (shortly after the signing of the Paris Agreement). And in keeping with that conventional logic, changes in coal and oil prices are inversely correlated with power plants' CO_2 emissions. We next examine if stranded assets still shape plants' environment performance when tested alongside changes in fossil fuel prices and the other predictors. Specifically, we assess whether some plants pollute more than others because their host countries have more at-risk fossil fuel assets, as our first model would expect, and whether exposure to more at-risk assets incentivizes plants to ramp up their operation, causing their emissions to rise to even higher levels, as our second model would expect.

How stranded assets affect power plant emissions

Table 2 shows the tested effect of countries' stranded fossil fuel assets on power plants' CO_2 emission levels under a 1.5 °C climate

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Table 1 | Means, standard deviations and correlations

	x̄	SD	DV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
DV	9.11	3.42	1																			
1. CO09	9.48	3.27	.90	1																		
2. COAL	.14	.343	.54	.54	1																	
3. GAS	.46	.50	−.06	−.15	−.43	1																
4. CAP	2.43	2.80	.87	.88	.44	−.15	1															
5. AGE	3.15	.52	−.22	−.17	−.06	−.22	−.14	1														
6. HEAT	11.18	7.26	.03	.06	.03	−.17	.08	.05	1													
7. CAPU	.314	.26	.38	.27	.21	.45	.08	−.32	−.15	1												
8. CCAPU	−.06	.31	.18	.04	−.01	.34	−.05	−.17	−.12	.56	1											
9. GDP	95.86	38.0	.02	−.01	.03	.07	.07	−.03	−.03	−.07	.08	1										
10. POPC	.03	.03	.06	.03	−.01	−.05	.14	−.05	.09	−.08	.14	−.15	1									
11. NFF	.80	.08	.02	.11	−.01	.01	.06	−.03	−.01	−.01	.07	−.01	.04	1								
12. P/C	.73	.83	.02	.03	.02	−.11	.11	.03	.08	−.21	.17	.09	.62	.01	1							
13. NESI	.73	.45	−.10	−.07	.06	.22	.20	−.06	.02	.06	.03	.18	.21	−.02	.15	1						
14. POL	9.58	6.47	−.07	−.12	−.17	.16	.05	.10	.01	−.09	.22	.38	−.20	.06	−.18	.15	1					
15. ETS	.36	.48	−.07	−.08	−.09	.29	−.11	−.01	−.05	.10	.19	−.03	−.22	−.03	−.17	.40	−.09	1				
16. LCOES	169.9	42.7	−.20	−.19	−.08	−.08	−.35	.08	−.08	.10	.22	.02	−.37	−.05	−.30	−.63	−.11	−.29	1			
17. TSA	9.15	3.65	.25	.25	.26	−.11	.36	−.06	.10	−.11	.30	.27	.41	.06	.48	.23	.31	−.33	−.42	1		
18. COALP	−.12	.06	−.16	−.19	−.23	.08	−.20	−.02	−.05	−.03	.04	.30	−.13	.01	−.17	−.41	.13	−.13	.36	−.24	1	
19, OILP	−.34	.19	−.31	−.29	−.23	.14	−.39	.13	−12	.07	.25	−.02	−.45	−.07	−.37	−.15	−.02	.35	.48	−.64	.04	1
20. GASP	−.22	.23	.14	.16	−.05	−.07	.25	.05	.11	−.15	.27	.10	.49	.04	.46	.17	.07	−.18	−.49	.43	−.10	−.56

DV = CO_2 Emission Level 2018, COAL = Primary Fuel: Coal, GAS = Primary Fuel: Gas, CAP = Plant Capacity, AGE = Plant Age, HEAT = Heat Rate;
CAPU Plant Capacity Utilization Rate, *CCAPU* Change in Plant Capacity Utilization Rate, *GDP* GDP per Capita, *POPC* Population Change, *NFF* National Fossil Fuel Power Capacity, *P/C* Fossil Fuel Production/Consumption Ratio, *NESI* National Electricity Sector Improvement, *POL* National Climate Policies, *ETS* Emissions Trading Scheme, *LCOES* Levelized Cost of Electricity Using Solar PV, *TSA* Total Stranded Assets, *COALP* Change in Coal Prices, *OILP* Change in Oil Prices, *GASP* Change in Gas Prices.

Table 2 | Determinants of changes in power plants' CO_2 emission levels between 2009 and 2018 under a 1.5 °C scenario

Variables	Baseline Model Model (1)	Effect of Change in Coal Prices Model (2)	Effect of Change in Oil Prices Model (3)	Effect of Change in Gas Prices Model (4)	Full Model Model (5)	Full Model with Interaction Effect of Change in Plant Capacity Utilization Rate Model (6)
CO_2 Emission Level 2009	.310*** (.008)	.310*** (.008)	.309*** (.008)	.309*** (.008)	.310*** (.008)	.286*** (.008)
Primary Fuel: Coal	.727*** (.042)	.728*** (.042)	.728*** (.042)	.729*** (.042)	.730*** (.042)	.734*** (.042)
Primary Fuel: Gas	.069* (.030)	.069* (.030)	.069*** (.030)	.069* (.030)	.069* (.030)	.074* (.030)
Plant Capacity	.702*** (.009)	.702*** (.009)	.702*** (.009)	.702*** (.009)	.702*** (.009)	.725*** (.009)
Plant Age	−.018 (.024)	−.017 (.021)	−.017 (.021)	−.017 (.021)	−.017 (.021)	−.006 (.021)
Heat Rate	.001 (.001)	.001 (.001)	.001 (.001)	.001 (.001)	.001 (.001)	.001 (.001)
Plant Capacity Utilization Rate	2.184*** (.060)	2.184*** (.060)	2.184*** (.060)	2.184*** (.060)	2.184*** (.060)	2.372*** (.064)
Change in Plant Capacity Utilization Rate	1.094*** (.041)	1.095*** (.041)	1.095*** (.041)	1.095*** (.041)	1.095*** (.041)	.114 (.125)
Gross Domestic Product per Capita	−.001 (.002)	−.001 (.002)	−.001 (.002)	−.001 (.002)	−.001 (.002)	−.002 (.002)
Population Change	−1.065 (2.188)	−1.635 (2.194)	−1.440 (2.166)	−1.983 (2.224)	−2.691 (2.206)	−2.983 (2.228)
National Fossil Fuel Power Capacity	1.228*** (.171)	1.227*** (.171)	1.229*** (.171)	1.228*** (.171)	1.228*** (.171)	1.256*** (.171)
Fossil Fuel Production/ Consumption Ratio	−.023 (.048)	−.024 (.048)	−.005 (.050)	−.018 (.047)	−.006 (.050)	−.002 (.048)
National Electricity Sector Improvement	−.249 (.203)	−.188 (.205)	−.216 (.201)	−.210 (.200)	−.134 (.201)	−.129 (.203)
National Climate Policies	−.002 (.016)	−.001 (.016)	.008 (.017)	−.002 (.016)	.008 (.017)	.010 (.017)
Emissions Trading Scheme	.062 (.070)	.066 (.070)	.073 (.070)	.069 (.070)	.082 (.070)	.081 (.070)
Levelized Cost of Electricity Using Solar PV	−.001 (.003)	−.001 (.003)	.001 (.003)	.001 (.003)	.001 (.003)	.001 (.003)
Total Stranded Assets	.050** (.019)	.056** (.019)	.048* (.021)	.047** (.019)	.042* (.021)	.037 (.021)
Change in Coal Prices		1.598 (1.193)			1.402 (1.158)	1.422 (1.170)
Change in Oil Prices			−.667 (.460)		−.520 (.450)	−.547 (.454)
Change in Gas Prices				.475 (.327)	.432 (.320)	.437 (.323)
Total Stranded Assets X Change in Plant Capacity Utilization Rate						.087*** (.011)
Constant	3.519*** (.588)	3.784*** (.610)	3.126*** (.640)	3.550*** (.573)	3.481*** (.658)	3.671*** (.666)
Random Effects of Countries	.212*** (.050)	.204*** (.050)	.204*** (.049)	.200*** (.048)	.188*** (.046)	.192*** (.047)
	(N = 49; $\bar{x}$ Observations per Group = 246)	(N = 49; $\bar{x}$ Observations per Group = 246)	(N = 49; $\bar{x}$ Observations per Group = 246)	(N = 49; $\bar{x}$ Observations per Group = 246)	(N = 49; $\bar{x}$ Observations per Group = 246)	(N = 49; $\bar{x}$ Observations per Group = 246)
Random Effects of Sub-National Areas	.050*** (.007)	.050*** (.007)	.050*** (.006)	.050*** (.007)	.050*** (.007)	.051*** (.007)
	(N = 963; $\bar{x}$ Observations per Group = 12.5)	(N = 963; $\bar{x}$ Observations per Group = 12.5)	(N = 963; $\bar{x}$ Observations per Group = 12.5)	(N = 963; $\bar{x}$ Observations per Group = 12.5)	(N = 963; $\bar{x}$ Observations per Group = 12.5)	(N = 963; $\bar{x}$ Observations per Group = 12.5)
Random Effects of Parent Companies	.228*** (.010)	.228*** (.011)	.228*** (.010)	.228*** (.010)	.228*** (.010)	.224*** (.010)
	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)	(N = 8,942; $\bar{x}$ Observations per Group = 1.3)
Residual Variance	.647***	.647***	.647***	.647***	.647***	.645***
BIC	32852.58	32860.21	32859.9	32859.94	32875.56	32816.68
N	11,941	11,941	11,941	11,941	11,941	11,941

*$P < .05$, **$P < .01$, ***$P < .001$

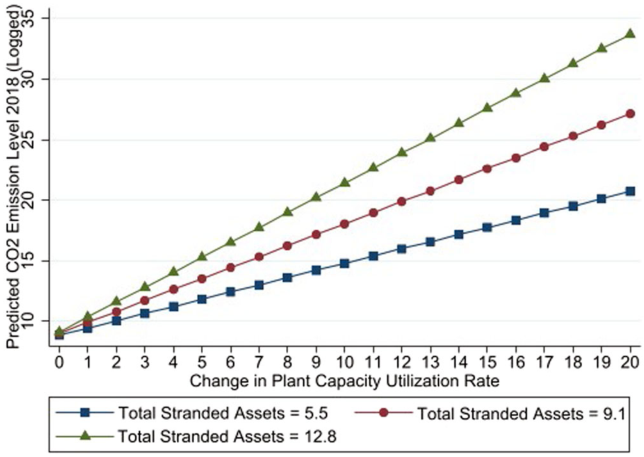

Fig. 2 | How the predicted effect of change in plant capacity utilization rate on power plants' CO2 emission levels varies depending on total stranded assets. Reports the predicted effect of changes in plants' capacity utilization rate on their (logged) CO2 emission levels at a mean level of (logged) stranded assets (9.1), at 1 standard deviation below the mean (5.5), and at 1 standard deviation above the mean (12.8).

stabilization scenario. To isolate this relationship, it controls for the internal characteristics of plants, such as their size and age, as well as external ones, such as the national political economies in which they are located, including changes in fuel prices. And by including a lagged dependent variable for year 2009, we effectively test in Table 2 what factors determined changes in power plants' CO_2 emission levels between 2009 and 2018[30].

The baseline model (model 1) reveals that plants release more carbon when they emitted at high levels in 2009, use coal or gas as their primary fuels, have more electrical capacity, use a higher percentage of their capacity, and have capacity utilization rates that have increased over time. Plants also emit more carbon in countries that are highly dependent on the fossil fuel industry to generate power. After accounting for the effects of these and other controls, the baseline model shows that in countries with more potentially stranded fossil fuel assets, plants have significantly higher emission levels compared to plants whose countries have fewer assets at risk. Specifically, a 1% change (measured in millions of euros) of potentially stranded assets results in a .050% change in emissions, holding constant all other variables in the model. This finding is consistent with our first prediction that stranded assets increase plants' emissions by fostering a more lenient regulatory climate.

In models 2 through 5, we examine whether changes in coal, oil, and gas prices influence plants' emissions and can explain the effect of stranded assets observed in model 1. Findings indicate that none of the price variables has a significant effect on emissions regardless of whether they are added individually (models 2, 3, and 4) or as a group (model 5) to the equation. Their inclusion, therefore, has a negligible effect on the stranded assets effect across all four specifications. These results contradict the conventional green paradox thesis that fossil fuel suppliers will induce more emissions in the short run by lowering the price of coal, oil, and gas inputs. Instead, they comport with Di Maria et al.'s argument that plants' long-term future contracts with fossil fuel suppliers often prevent them from responding to spot market changes in coal, oil, and gas.

To determine whether contractually constrained plants might still burn fossil fuels faster in countries where more carbon reserves are financially at risk, we interact our measures of stranded assets and change in plant capacity utilization rate in model 6. Results indicate there is a statistically significant interaction between these two factors. This is in keeping with our second prediction that when located in countries with more at-risk assets, plants have a stronger incentive to speed up the processing of the fuels they have already purchased and thus increase their CO_2 emissions in the short term. Figure 2 shows the predicted effect of changes in plants' utilization rate on their CO_2 emission levels at a mean level of (logged) stranded assets (9.1), at 1 standard deviation below the mean (5.5), and at 1 standard deviation above the mean (12.8). Here we see that where more fossil fuel reserves are in jeopardy, plants utilize a larger percentage of their capacity over time, causing their emissions to rise. (Supplementary Table 1, which shows the determinants of plants' CO_2 emission levels under a 2 °C climate stabilization scenario that would regularly expose close to three times as many people to extreme heat, reports results nearly identical to those shown in Table 1).

In Table 3, we assess the robustness of the association between our dependent and key independent variables. Models 1 and 2 are estimated for only plants that officially report their emissions, and the latter model includes the interaction between stranded assets and change in plant capacity utilization rate. In Model 3, we operationalize total stranded assets using an inverse hyperbolic sine function. The results of these three models are nearly identical to those reported in models 5 and 6 in Table 2. In models 4, 5, and 6, we examine whether plants emit more carbon because particular types of fossil fuels are at risk. Findings reveal that unburnable coal, gas, and oil are each significantly related to plants' CO_2 emission levels, providing further proof that the effects of our key independent variable – total stranded assets – are robust.

Relative magnitude of the stranded assets effect

Having determined that stranded assets have a statistically significant effect on plants' CO_2 emission levels, we now consider the relative magnitude of that effect. In Table 4, we compare the total annual tonnes of carbon released by (the world's or a nation's) plants solely in response to at-risk assets to the remaining annual carbon budgets[31] of the world's and individual nations' electricity sectors (see Methods). The first two columns of Table 4 reveal that for the world as a whole, the increase in annual CO_2 emissions triggered by potentially stranded assets is 12.08 million metric tonnes per year or 0.21% of the electricity sector's annual carbon budget when the chance of limiting global warming to 1.5 °C above pre-industrial levels is set to 50%. The third column shows that when the world's annual budget is constrained further to have a 66% chance of staying below 1.5 °C, the relative magnitude of plants' emissions is 0.28%.

The first three columns of Table 4 also report the same estimates for the five countries with the most absolute CO_2 emissions. Here we see, for instance, that the additional annual emissions associated with at-risk assets in China (3.09 million metric tonnes) are 0.19% to 0.26% of the budget for this country's electricity sector. The extra emissions triggered by at-risk assets amount to even smaller percentages for India (0.02% to 0.04%) and Japan (0.0010% to 0.0013%). The relative magnitudes of plants' extra emissions in the United States and Russia are higher, ranging, respectively, from 1.12% to 1.61% and .84% to 1.19%.

Although these findings might suggest that the percentage of carbon budgets used up by plants due to potentially stranded assets is modest, when one adds up these percentages over time, a more concerning picture emerges. As the last column reveals, during a period when the carbon budget will almost surely be breached and, therefore, every fractional "expenditure" of that budget matters[32], the extra emissions associated with stranded assets could amount to between 2.1% to 2.8% of the world's carbon allowance over a ten-year period. In the United States and Russia, the situation is even more troubling. These countries could exhaust 11.2% to 16.1% and 8.4% to 12%, respectively, of their electricity sectors' carbon budgets due just to the stranded assets effect. This suggests that the financial pressures to "use it or lose it" are especially great among these two key incumbents

Table 3 | Robustness checks of the association between the dependent and key independent variables

Variables	Full Model for Reporting Plants Only	Full Model with Interaction Effect of Change in Plant Capacity Utilization Rate for Reporting Plants Only	Total Stranded Assets Using an Inverse Hyperbolic Sine Function	Coal Assets	Oil Assets	Gas Assets
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
CO_2 Emission Level 2009	.348*** (.011)	.323*** (.012)	.310*** (.008)	.310*** (.008)	.307*** (.008)	.310*** (.008)
Primary Fuel: Coal	.600*** (.017	.604*** (.066)	.730*** (.042)	.730*** (.042)	.711*** (.043)	.731*** (.042)
Primary Fuel: Gas	.017 (.044)	.025 (.044)	.069* (.029)	.070* (.030)	.055 (.031)	.069 (.030)
Plant Capacity	.630*** (.014)	.651*** (.015)	.702*** (.009)	.702*** (.009)	.704*** (.009)	.702*** (.009)
Plant Age	.045 (.024)	.059 (.033)	−.017 (.021)	−.017 (.021)	−.010 (.021)	−.017 (.021)
Heat Rate	.002 (.002)	.002 (.002)	.001 (.001)	.001 (.001)	.001 (.001)	.001 (.002)
Plant Capacity Utilization Rate	2.539*** (.090)	2.770*** (.098)	2.184*** (.060)	2.183*** (.060)	2.223*** (.061)	2.185*** (.060)
Change in Plant Capacity Utiliza-tion Rate	1.137*** (.056)	.111 (.182)	1.095*** (.041)	1.095*** (.041)	1.117*** (.042)	1.094*** (.0410
Gross Domestic Product per Capita	−.002 (.002)	−.002 (.002)	−.002 (.002)	−.002 (.002)	.001 (.002)	−.001 (.002)
Population Change	2.004 (3.067)	2.238 (3.049)	−2.779 (2.209)	2.378 (2.203)	−1.904 (2.570)	−2.799 (2.230)
National Fossil Fuel Power Capacity	1.210*** (.226)	1.254*** (.226)	1.227*** (.170)	1.228*** (.171)	1.225*** (.173)	1.228*** (.171)
Fossil Fuel Production/ Consump-tion Ratio	−.049 (.183)	−.039 (.181)	−.006 (.048)	.014 (.045)	−.003 (.046)	−.010 (.050)
National Electricity Sector Improvement	−.323 (.290)	−.326 (.289)	−.135 (.201)	−.149 (.201)	−.276 (.212)	−.130 (.202)
National Climate Policies	−.018 (.029)	−.017 (.029)	.007 (.017)	.012 (.017)	.004 (.020)	.004 (.018)
Emissions Trading Scheme	.272 (.207)	.271 (.208)	.082 (.070)	.079 (.070)	.082 (.072)	.080 (.070)
Levelized Cost of Electricity Using Solar PV	−.005 (.004)	−.006 (.004)	.001 (.003)	.001 (.003)	.002 (.004)	.001 (.003)
Total Stranded Assets	.039* (.017)	.033 (.027)	.045* (.022)	.027* (.015)	.040* (.019)	.040* (.013)
Change in Coal Prices	.627 (1.321)	.675 (1.311)	1.358 (1.152)	1.012 (1.127)	.448 (1.273)	1.195 (1.149)
Change in Oil Prices	−.080 (.576)	−.066 (.572)	−.523 (.450)	−.703 (.422)	−.674 (.493)	−.474 (.477)
Change in Gas Prices	1.657 (1.389)	1.624 (1.379)	.435 (.320)	.510 (.321)	.444 (.330)	.428 (.323)
Total Stranded Assets X Change in Plant Capacity Utilization Rate		.088*** (.015)				
Constant	4.517*** (1.016)	4.830*** (1.010)	3.397*** (.655)	3.502*** (.662)	3.243*** (.801)	3.476*** (.664)
Random Effects of Countries	.112*** (.039)	.110*** (.039)	.187*** (.045)	.188*** (.046)	.199*** (.049)	.191*** (.046)
	(N = 30; x̄ Observations per Group = 230.3)	(N = 30; x̄ Observations per Group = 230.3)	(N = 49; x̄ Observations per Group = 246)	(N = 49; x̄ Observations per Group = 246)	(N = 49; x̄ Observations per Group = 246)	(N = 49; x̄ Observations per Group = 246)
Random Effects of Sub-National Areas	.053*** (.010)	.055*** (.010)	.050*** (.007)	.050*** (.007)	.052*** (.007)	.050*** (.007)
	(N = 565; x̄ Observations per Group = 12.2)	(N = 565; x̄ Observations per Group = 12.2)	(N = 963; x̄ Observations per Group = 12.5)	(N = 963; x̄ Observations per Group = 12.5)	(N = 963; x̄ Observations per Group = 12.5)	(N = 963; x̄ Observations per Group = 12.5)
Random Effects of Parent Companies	.339*** (.020)	.334*** (.023)	.227*** (.010)	.228*** (.010)	.232*** (.011)	.228*** (.010)
	(N = 5,053; x̄ Observations per Group = 1.4)	(N = 5,053; x̄ Observations per Group = 1.4)	(N = 8,942; x̄ Observations per Group = 1.3)	(N = 8,942; x̄ Observations per Group = 1.3)	(N = 8,942; x̄ Observations per Group = 1.3)	(N = 8,942; x̄ Observations per Group = 1.3)
Residual Variance	1.004***	1.001***	.647***	.647***	.661***	.647***
BIC	28144.73	21818.83	37622.1	32875.99	31928.5	32876.47
N	6,910	6,910	11,941	11,941	11,941	11,941

*$P < .05$, **$P < .01$, ***$P < .001$

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Table 4 | Magnitude of extra annual electricity-based CO_2 emissions associated with stranded assets under a 1.5 °C scenario

	Annual electricity-based CO_2 emissions triggered by potentially stranded assets in million metric tonnes	Annual electricity-based CO_2 emissions associated with stranded assets as a percentage of annual remaining carbon budget under a 1.5 °C scenario with 50% probability	Annual electricity-based CO_2 emissions associated with stranded assets as a percentage of annual remaining carbon budget under a 1.5 °C scenario with 66% probability	Extra electricity-based CO_2 emissions associated with stranded assets over the next 10 years as a percentage of remaining carbon budget under a 1.5 °C scenario with 50% and 66% probabilities
World	12.08	0.21%	0.28%	2.1–2.8%
China	3.09	0.19%	0.26%	1.93–2.6%
United States	2.78	1.12%	1.61%	11.2–16.1%
India	.48	0.02%	0.04%	0.21–0.35%
Russia	1.38	.84%	1.19%	8.4–12%
Japan	.001	0.0010%	0.0013%	0.010–0.013%

of the carbon regime. In fact, the United States and Russia stand to lose the most profits from the physical stranding of assets[12] and their power plants are older, on average, (30.3 and 30.6 years, respectively) than those in other countries (25.5 years).

Discussion

Past research on the green paradox has emphasized reactions on the supply side, whereby fossil fuel companies accelerate the extraction of carbon reserves, leading to a reduction in current fossil fuel prices and, in turn, an increase in CO_2 emissions. While there is ample evidence that suppliers extract more fossil fuels and sell them at cheaper prices in anticipation of stronger environmental policies, there is less support for the idea that price decreases result in more CO_2 emissions, which has cast doubt on the green paradox thesis. In contrast, our study redirects attention to the demand side, positing that regulatory leniency and power plants' vested interest in their long-term fossil fuel contracts make plants more willing to burn fossil fuels earlier and thus are the mechanisms that produce the green paradox. In keeping with our argument that at-risk fossil fuel assets give government actors a financial incentive to relax environmental standards, results show that plants emit more carbon pollution in countries where vast amounts of fossil fuel reserves would be stranded under the Paris Agreement. And in keeping with our other argument that at-risk reserves motivate contractually constrained plants to speed up the processing and burning of their purchased inputs, findings indicate that stranded assets and plants' capacity utilization rates positively interact, causing plants to further increase their emissions. While the extra amount of carbon released each year due to the stranded asset effect is moderate, its cumulative impact on the electricity sector's remaining carbon budget could be significant in certain key countries. In addition to encouraging more theory building on the green paradox, therefore, our study's findings suggest that if important policy-making communities are to develop effective transition strategies, they, too, must pay greater attention to the demand side of fossil fuel consumption.

An important topic for future research is whether the effect of stranded fossil fuel assets on plants' emissions is strengthening over time[33]. The volume of emissions from the effect could dwindle as the fossil fuel sector shrinks. Or it could grow if more fossil fuel reserves are discovered through new production technologies. Additional research is also needed on the mechanisms we have theorized linking the key independent variable to the dependent variable. Although stranded assets' direct and interactive effects on power plants' CO_2 emissions can be plausibly explained by countries' regulatory leniency and plants' vested interest in their long-term fossil fuel contracts, measures of these concepts are needed to determine to what extent they, as variables, mediate the observed effects of stranded assets in a causal chain of relationships[34].

Methods

We constructed a global dataset that contains information on 11,941 individual power plants operating in 2009 and 2018, including their CO_2 emissions, technical specifications, the characteristics of the country in which a plant is located, and each country's expected value of stranded fossil fuel reserves under 1.5 °C and 2 °C climate stabilization scenarios. Our unit of analysis is the individual power plant where large volumes of carbon are most often burned and released into the environment. (The countries of the power plants analyzed here are listed in Supplementary Table 2 and are responsible for 88% of the world's electricity-based CO_2 emissions). We focus on plants' environmental performance between 2009 and 2018 because it is when most international climate treaties have yet to be fully enforced and, therefore, it is well suited for assessing whether polluters will emit carbon at higher levels in anticipation of what treaty enforcement will do to the future value of fossil fuel assets.

Our data on plants' emissions are drawn from an updated version of the 2009 Carbon Monitoring for Action (CARMA) file, the most widely used bottom-up inventory for allocating power plant CO_2 emissions[35]. The 2018 edition of CARMA draws on three data sets: plant-level emissions reports from the United States, European Union, Australia, Canada, and India; global plant- and company-level data from Platt's World Electric Power Plants Database; and country-specific power production data from the International Energy Agency (IEA). For non-reporting plants, CARMA estimates emissions using a statistical model fitted to data for the reporting plants and detailed data from the other two sources on plant-level engineering specifications. Details on this estimation procedure can be found in Grant, Mitova, and Zelinka[26].

Dependent variable

This study's dependent variable is power plants' CO_2 emission levels, defined as the annual tonnes of carbon emitted to the atmosphere. Because of this variable's skewed distribution, we apply a logarithmic transformation to it. To assess changes in plants' environmental performance, we include in our regression models (explained below) a lagged endogenous measure of our dependent variable for the year 2009.

Key independent variable

Our measure of potentially stranded assets is taken from Mercure et al.[25]. Specifically, we use their estimates of the value of total unburnable coal, gas, and oil reserves (measured in millions of 2020 euros) that would be left in the ground in each country in 2050 if the stringency of existing climate/energy policies were increased and new policies that can reasonably be expected were implemented that together would achieve a median global warming of 1.5 °C ("Net-zero CO_2 globally in 2050") compared to a scenario where energy markets grew at their expected rates and current policies and technologies essentially remained the same until 2050 and generated a median global warming of 3.5 °C ("Investment expectations"). These data are discounted by 6 percent by the authors of this data source to put greater value on near-term reserves. Because of this variable's skewed distribution, we apply a logarithmic transformation to it. (Because this variable has zeros for some countries, we add a constant (.1) to each case before transforming it.) Since this variable compares reserves produced*prices between baseline and climate stabilization scenarios, emissions do not enter into its estimation. Therefore, our key independent variable is not inherently highly correlated with our dependent variable. It is important to note that although our unit of analysis is the individual power plant, our key independent variable (potentially stranded assets) is measured at the national level. We do not measure the effects of stranded fossil fuel assets on the value of individual plants' infrastructure assets in large part because there is a lack of disclosure about the current carrying value of operational power plants, which makes estimating facilities' future carrying value even more problematic[27].

To determine the relative magnitude of the stranded assets effect (see Table 4), we compare the total annual tonnes of carbon released by (the world's or a nation's) plants in response to at-risk assets to the remaining annual carbon budgets of the world's and individual nations' electricity sectors. To calculate the total annual tonnes of electricity-based CO_2 emitted due to the assets effect (for the world or an individual nation), we multiplied the coefficient for the effect of stranded assets on CO_2 emission level for all plants operating in 2018 (see Supplementary Table 3) by the million euros of at-risk assets (in the world or a nation). Annual carbon budgets for electricity sectors were calculated as follows: for the world, we multiplied its remaining carbon budget in 2018 according to the Intergovernmental Panel on Climate Change Intergovernmental Panel on Climate Change (IPCC)[31] by the percentage of its 2018 CO_2 emissions stemming from the electricity sector. For individual nations, we first divided the world's remaining carbon budget in 2023 into a budget per person and assigned a budget to a country based on its population[36]. We next multiplied each country's budget by the percentage of its CO_2 emissions in 2018 from electricity. Having calculated these two sets of budgets, we then divided each by 32, which is the number of years from 2018 to 2050, the year targeted by the Paris Agreement for bringing global energy-related carbon dioxide emissions to net zero and giving the world an even chance of limiting the global temperature rise to 1.5 °C. Finally, to judge the relative magnitude of the CO_2 emitted by plants in response to at-risk assets, we divided annual emission totals for the world and individual nations due to the stranded asset effect by their respective annual remaining budgets, which gives the percent of a budget depleted due to the stranded asset effect.

Other predictors

Our models control for whether a plant's primary fuel is coal or gas using dummy variables for each (1 = yes), a plant's electrical capacity, its age (in years), its heat rate, its capacity utilization rate (percentage of potential output that was produced), and changes in a plant's capacity utilization rate between 2012 and 2017. Each of these plant-level measures, which past engineering research suggests may influence a plant's environmental performance[37], is taken from the World Electric Power Plants Database. Models also include controls for macro-level factors that past research suggests[38] could shape plants' CO_2 emissions, including national gross domestic product (GDP) per capita in constant US dollars, national population change (2012 to 2017), and percentage of a nation's power capacity that depends on fossil fuels. All three measures are taken from the World Bank. To account for a country's fossil fuel imports and exports, we use Mercure et al.'s data on fossil fuel supply and demand to calculate the ratio of fossil fuel supply to fossil fuel demand. A value of 1 would imply that a country produces as much as it consumes. A value of 1.1 would imply that a country produces 10% more than it consumes, suggesting that it is a net exporter. Because several countries improved their electricity sectors' emissions during the period of study[39], we also account for this development using a dummy variable for whether a plant is in a country whose electricity sector reduced its aggregate emissions between 2009 and 2018 (1 = yes). We also control for three factors tracked by the International Energy Agency (IEA): a nation's total number of electricity-related climate policies, whether a plant is subject to an emissions trading scheme (1 = yes), and the levelized cost of electricity using solar PV that captures how renewable costs have developed unevenly across countries. Each of the controls is lagged one year to ensure it is not influenced by plants' environmental performance in 2018.

Finally, to rule out the possibility that the statistical effect of stranded assets on power plants' CO_2 emissions is due to an omitted variable bias, we also constructed measures of changes in national coal, oil, and gas prices using available data for a subset of countries and proxy information for the others. With respect to coal prices, the IEA provides steam coal prices for electricity generation for 11 OECD countries. Steam coal prices for electricity generation for six non-OECD countries (Australia, China, Colombia, Indonesia, Russia, and South Africa) are also available on national websites. Together, these 17 countries cover 5333 of the plants in our sample. We applied regional steam coal prices for Northwest Europe and Pacific Asia (from Argus/McCloskey's Coal Price Index Report) to countries with missing data in those regions and steam coal prices for Australia, the largest exporter of thermal coal, to the remaining countries. With respect to oil prices, the IEA provides the prices of heavy oil used in electricity generation for 5 OECD countries that cover 9838 of the plants in our sample. Among these countries, the correlation between this price and another reported by the IEA – the retail price of oil – is fairly strong (.651). Hence, we used the latter as a proxy for the other 25 OECD countries that the IEA reports oil's retail price. For the rest of the countries in our sample, we used Brent's global price of crude oil as a proxy. Finally, the IEA provides the price for natural gas used in electricity generation for 10 OECD countries that cover 3387 of the plants in our sample. Among these countries, the correlation between this price and another reported by the IEA – the retail price of natural gas – is quite strong (.91). Therefore, we used the latter (from S&P Global Platts) as a proxy for the other countries in our sample. We measured changes in these three fuel prices between 2012 and 2017 or the years shortly before and after the Paris Agreement was signed in 2015 when, according to the green paradox thesis, suppliers of fossil fuels would be motivated to lower their prices.

We conducted several tests to determine whether our proxies were reasonable. We compared results using the full sample to samples that only included countries with available price data for steam coal, heavy oil, and natural gas used in electricity generation (Supplementary Table 4). We also estimated models that used the absolute prices of coal, oil, and gas in 2017 instead of changes in those variables as well as compared regressions using primary fuel prices with those using proxies. Results were consistent across all specifications – none of the fuel prices exerted a statistically significant effect on plants' CO_2 emissions. This coupled with the fact that our proxy measures are not endogenous and do not inject additional information into our models suggests that they are reasonable ones.

Modeling strategy

Decision-making is often done by power plants collectivity or within the utility that owns them. It is also the case that power plants owned by the same parent company can be located in different sub-national areas, some of which are also in different countries. And because parent companies, sub-national areas, and countries can have different understandings of the threat posed by carbon pollution, individual plants from different companies, sub-national areas, and countries may be variously impacted by potentially stranded fossil fuel assets and emit carbon at different levels. Unfortunately, controlling for the possible random effects of companies, sub-national areas, and countries in a single-level regression model would introduce wrong standard error estimates as residuals (i.e., observations in the same group) tend to be correlated.

Therefore, to account for the cross-nested nature of our data, when conducting our regression analyses of power plants' carbon emissions, we use a hierarchical linear model with three random intercepts (one for countries, one for sub-national areas (first-level administrative divisions)[40], and another for parent companies)[41]. These models are increasingly used throughout the social and behavioral sciences to model causal effects[42]. Unlike classical, non-hierarchical approaches, which analyze cases drawn from random samples, HLMs account for whether data were collected using a stratified design (e.g., plants within utilities), adjust for unmeasured covariates not addressed by panels (e.g., a single, unobserved trait of a plant that is constant over time), and capture treatment group variation (e.g., how the effect of at-risk assets depends on whether plants are located in particular countries, sub-national areas, and companies). Formally expressed, our model is shown as Eq. (1):

$$\mathbf{y}_{jk} = \mathbf{X}_{jk}\beta + \mathbf{Z}\frac{(4)}{jk}\mathbf{u}\frac{(4)}{jk} + \mathbf{Z}\frac{(3)}{jk}\mathbf{u}\frac{(3)}{jk} + \mathbf{Z}\frac{(2)}{jk}\mathbf{u}\frac{(2)}{jk} + \epsilon_{jk} \quad (1)$$

The reader will note that i is not explicitly added to Eq. (1) as an index. This is because the variables shown are all vectors, and i is assumed to represent the number of observations for each (j, k). It follows that for $i = 1,\ldots, n_{jk}$ first-level observations nested within $j = 1,\ldots, M_{jk}$ second-level groups, which are nested within $k = 1,\ldots, M$ fourth-level groups. Group j, k consists of n_{jk} observations, so y_{jk}, $\mathbf{x}_{jk}$, and ϵ_{jk} each have row dimension n_{jk}. $\mathbf{z}\frac{(4)}{jk}$ is the $n_{jk} \times q_4$ design matrix for the fourth-level random effects $\mathbf{u}\frac{(4)}{k}$, $\mathbf{z}\frac{(3)}{jk}$ is the $n_{jk} \times q_3$ design matrix for the third-level random effects $\mathbf{u}\frac{(3)}{jk}$, and $\mathbf{z}\frac{(2)}{jk}$ is the $n_{jk} \times q_2$ design matrix for the second-level random effects $\mathbf{u}\frac{(2)}{jk}$. Furthermore, assume that $\mathbf{u}\frac{(4)}{k}$, $\mathbf{u}\frac{(3)}{jk}$, $\mathbf{u}\frac{(2)}{jk}$, and ϵ_{jk} are independent. The beta coefficient (β) only appears in the **X** variable, but not the **Z** variable, as **Z** variables are predictors for the random effects, and there are no so-called betas for random effects. The various variables in the model each have a beta coefficient.

With this four-level mixed effect model, the predictors for the fixed equation are treated equally regardless of which level they are defined and whether they vary in some higher level only. Because there is not the same number of plants in each parent company and, therefore, as is the case with other unbalanced data, the actual sampling distributions of the test statistics are unknown, our model approximates these sampling distributions using the method recommended by Kenward and Roger[43]. All analyses were conducted in Stata.

Data availability

With the exception of information on plants' characteristics and countries' fuel prices, which require paid subscriptions to their sources, the data that supports the findings of this study is available on request from the corresponding author Don Grant (dogr2184@colorado.edu). Source data are provided with this paper.

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Author contributions

D.G. conceptualized and supervised the study. D.G. and T.H. acquired the data. D.G. and T.H. analyzed and visualized the data. D.G., T.H., A.J., and W.L. interpreted the data. D.G. drafted the work. D.G., T.H., A.J., and W.L. reviewed and edited the manuscript. D.G., A.J., and W.L. received external funding for the project. A.J. and W.L. paid the APC.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Don Grant.

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