Reply to "Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power," by Sovacool et al. (2020)

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Abstract

In a recent paper, Sovacool et al. (2020) undertake a cross-sectional regression analysis to test associations between different clean energy deployment patterns and national carbon dioxide (CO_2) pollution levels. The authors report that deployment of nuclear energy does not tend to associate with significantly lower carbon emissions, while renewable energy does. Here we critically review the paper's claims and methods and perform a reanalysis, including both a revised cross-sectional analysis and a more statistically powerful panel data analysis. We find the paper's claim that renewables are "on balance evidently more effective at carbon emissions mitigation" than nuclear power is not supported by the paper's empirical findings. Instead, addressing several methodological issues found in Sovacool et al. (2020) and employing the same data sources and time periods, we find that nuclear power and renewable energy are *both* associated with lower per capita CO_2 emissions with effects of similar magnitude and statistical significance.

Abstract

In a recent paper, Sovacool et al. (2020)[1] undertake a cross-sectional regression analysis to test associations between different clean energy deployment patterns and national carbon dioxide (CO_2) pollution levels. The authors report that deployment of nuclear energy does not tend to associate with significantly lower carbon emissions, while renewable energy does. The paper's

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[1]Sovacool, Benjamin K., et al. 2020. "Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power." *Nature Energy* 5.11: 928-935.

finding calls into question a widely held understanding that electricity generated from nuclear power can displace generation from carbon-intensive fossil fuel generation. Here we critically review the paper's claims and methods. We conclude that the paper's core finding is based on a misinterpretation of statistical hypothesis testing and is highly sensitive to influential outliers included in their sample. We also perform a reanalysis using the paper's data sources, including both a revised cross-sectional analysis and a panel data analysis. These analyses find that nuclear and renewable energy deployment are *both* associated with reductions in national carbon emissions, and at similar orders of magnitudes and levels of statistical significance, invalidating Sovacool et al. (2020)'s central claim.

As an initial matter, it is notable that the paper does *not* find a positive correlation between nuclear generation shares and emissions per capita – indicating that nuclear power deployment is associated with greater emissions. The paper actually finds a negative correlation between nuclear generation and emissions, albeit one that does not rise to a standard level of statistical significance. However, with a sample size of only 30 "nuclear countries", this is not surprising. Unless one designs a statistical test with sufficiently high power, a failure to reject a null hypothesis (e.g. a failure to establish an effect that is significantly different from zero) should not be treated as evidence that the null hypothesis is valid (e.g. that the effect *is* actually zero). With a larger sample size of "renewable countries" (n=117 and 123 in Timeframe 1 and 2 respectively) and correspondingly greater statistical power, the paper is able to establish a statistically significant negative correlation between renewable energy deployment and emissions. Thus the paper's central claim that nuclear is ineffective at reducing emissions while renewable energy is more effective appears to be a misinterpretation of statistical hypothesis testing and an artifact of the relatively greater statistical power of the larger "renewable countries" sample.

Putting aside this fundamental issue, the paper additionally hypothesizes that a national focus on nuclear power "crowds out" renewable energy deployment, thus explaining the supposedly negligible effect of nuclear power on emissions. To support this hypothesis, the paper describes an observed negative association in the production shares of the two resources. However, this claim does not follow logically: even if it turns out that renewables and nuclear have historically displaced one another at certain times, this does not say anything definitive about the potential effectiveness of nuclear at reducing emissions. To suggest an analogy, renewable energy can also displace nuclear generation – e.g. as in Germany, where retirement of nuclear power has been offset by growth of renewable energy. Yet everyone should agree that renewable generation can alternatively displace fossil generation and reduce CO_2 emissions in other contexts. In short, nuclear and renewables can sometimes be substitutes, but this does not demonstrate that one is better at reducing emissions than the other.

The paper's statistical analysis also exhibits several methodological limitations:

First, by using cross-sectional data (comparisons between countries during a given time period) instead of panel data (country-level observations over time), the paper neglects a considerable amount of observable variation that can be used to improve statistical power and make stronger inferences.

Second, the paper only includes a single control variable in these cross-sectional regressions: GDP per capita. National decisions to invest in renewable energy or nuclear are structured by complex economic, social and political debates. Myriad other unobserved factors could simultaneously shape these investment decisions and national carbon emission levels, biasing the papers' regression coefficients of interest. The paper does not establish that the observed correlation is robust to these likely confounders.

Third, the paper chooses to assess the lagged effect of nuclear and renewable shares of generation (e.g. the mean generation share over the period 1990-1999 in Timeframe 1 and 2000-2009 in Timeframe 2) on CO_2 emissions per capita five years later (e.g. the mean over 1999-2004 for Timeframe 1 and 2005-2014 for Timeframe 2), rather than contemporaneous measures. This may introduce bias in the estimated effects; when estimating lagged effects, one needs to assume a positive time dependence on these generation shares. While in most places renewable generation shares have been trending up over time, the same cannot be said for nuclear generation shares. If some countries reduce their nuclear share over time and this leads to increases in current emissions, then the lagged nuclear share may show positive or no correlation with current emissions for those countries.

Fourth, the use of per capita emissions as the paper's single control variable risks creating outlier observations, particularly due to the small number of nuclear countries and the large magnitude of differences in per capita GDP across countries. In a cross-sectional analysis with small sample size, results are highly sensitive to outliers and sampling choices. The papers' analysis includes the complete set of low-income countries, a set of countries that have low CO_2 per capita and minimal nuclear. This choice appears to establish a weaker correlation between nuclear and low per capita emissions, but likely reveals only that many poorer nations have lower emissions per capita due to greater reliance on agriculture and informal economic activities.

In light of these limitations, we augment the analysis in Sovacool et al. (2020) to address these issues and to highlight the sensitivity of the paper's results to particular choices in study design.

We first retain the paper's cross-sectional data designations – nuclear countries for Timeframes 1 and 2 (Nuc-TF1 and Nuc-TF2, respectively) and renewable countries for Timeframes 1 and 2 (Ren-TF1 and Ren-TF2, respectively). We alter the paper's original analysis in two ways. First, instead of breaking up the time frames such that the renewable and nuclear shares are the average over the first several years of the time frame and the CO_2 emissions per capita comes from the average of the last several years of the time frame, we use the average of CO_2 emissions per capita, renewable and nuclear shares, and GDP per capita over the entire time frame. In this way, we capture more contemporaneous measures of CO_2 emissions and renewable and nuclear generation. Second, we consider additional data set restrictions where we drop low GDP per capita countries (GDP per capita < \$2000) to avoid developing country outlier points that skews the relationship between nuclear generation and CO_2 emissions.

Results from these estimations are shown in Table 1. Here we find that using averages across the entire time frame instead of lagged nuclear and renewable still results in a negative but statistically insignificant parameter estimate for nuclear generation shares in the first time period (see Nuc_TF1). In the second time period (Nuc_TF2), this negative correlation between nuclear generation shares and per capita CO_2 is significant at the 10% confidence level. Additionally, when we remove the low income countries, we find negative and statistically significant effects of nuclear generation shares on CO_2 emissions per capita (at 5% confidence level) in both time periods. As reported in Table 1, this simple reanalysis highlights the effect of influential data points (outliers) on these relatively small samples. This specification shows that both nuclear and renewables deployment are associated with similar carbon emissions reductions (within one standard deviation) and at a statistically significant level.

Next, we consider an alternative approach with greater statistical power. We construct a panel data set, which retains and exploits variation across time within each country. This approach also controls for any unobserved time-invariant confounders at the national level (country fixed effects), such as fixed resource endowments, and any time-variant confounders common across all countries within a given year (year fixed effects), such as global economic shocks or commodity or fuel price changes. These controls reduce potential omitted variable bias. We collect annual data on CO_2 emissions, nuclear and renewable generation, and GDP per capita by country for the years 1990 – 2014, using the same data sources as Sovacool et al. (2020). We then conduct a country and year fixed effect regression as follows:

$$CO2_{it} = \beta_1 Renew_{it} + \beta_2 Nuclear_{it} + \beta_3 GDP_{it} + \alpha_i + \gamma_t + \epsilon_{it} \quad (1)$$

	Nuc-TF1		Nuc-TF2	
Nuc	-0.0368	-0.0719**	-0.0459*	-0.0644**
	(0.0261)	(0.0282)	(0.0233)	(0.0244)
Renew	-0.0724*	-0.0683*	-0.0669*	-0.0644*
	(0.0385)	(0.0387)	(0.0359)	(0.0362)
GDP	0.000218***	0.000160**	0.000144***	0.000114**
	(6.31e-05)	(6.44e-05)	(4.12e-05)	(4.43e-05)
Obs.	30	23	30	25
R^2	0.389	0.332	0.389	0.345

	Ren-TF1		Ren-TF2	
Nuc	-0.0153	-0.0433**	-0.0163	-0.0362*
	(0.0184)	(0.0192)	(0.0200)	(0.0214)
Renew	-0.0496***	-0.0641***	-0.0486***	-0.0609***
	(0.00833)	(0.0142)	(0.0111)	(0.0152)
GDP	0.000294***	0.000231***	0.000191***	0.000158***
	(3.65e-05)	(4.28e-05)	(2.02e-05)	(2.24e-05)
Obs.	117	57	123	80
R^2	0.610	0.483	0.472	0.376

Notes: The dependent variable in all cases is CO_2 emissions per capita measure used in Sovacool Nuc-TF1 and Nuc-TF2 are specifications using "Nuclear" countries from time frames 1 and 2. Ren-TF1 and Ren-TF2 are specifications using "Renewable" countries from time frames 1 and 2. The first and third columns include the full set of countries. The second and fourth columns exclude low-income countries with GDP per capita < \$2000. *, **, and *** denote statistically significant results at the 10, 5, and 1% levels, respectively. Standard errors are heteroskedasticity-robust and are given in parentheses below the parameter estimates. "Obs" denotes number of observations.

Table 1: Cross-sectional Data Results

	Nuc	Ren-TF1	Ren-TF2
Nuc	-0.779***	-0.827***	-0.765***
	(0.107)	(0.122)	(0.108)
Renew	-1.082***	-1.133***	-0.898***
	(0.144)	(0.172)	(0.0636)
GDP	1.66e-06	3.41e-06**	-2.02e-06
	(1.29e-06)	(1.34e-06)	(1.54e-06)
Obs.	744	672	2,818
R^2	0.681	0.713	0.401

Notes: The dependent variable in all specifications is country-level annual CO_2 emissions from electricity and heat per capita. "Nuc" refers to the specification using the "Nuclear" countries. "Ren-TF1" and "Ren-TF2" refer to the "Renewable" countries from time frames 1 and 2, respectively. *, **, and *** denote statistically significant results at the 10, 5, and 1% levels, respectively. Standard errors are heteroskedasticity-robust and are given in parentheses below the parameter estimates. "Obs" denotes number of observations.

Table 2: Panel Data Results

where $CO2_{it}$ is CO_2 emissions from the electric and heat sector per MWh of generation in country i in year t, $Renew_{it}$ is the renewable generation share, $Nuclear_{it}$ is the nuclear generation share, GDP_{it} is the GDP per capita, α_i is a country fixed effect, and γ_t is a common year fixed effect. The final term ϵ_{it} is a mean-zero error term. We estimate this equation for the nuclear- and renewable-country groupings that were used by Sovacool et al. (2020). Results from this estimation are presented in Table 2. Here we consistently show a negative and statistically significant effect of nuclear generation shares on CO_2 emissions intensity of electricity and heat production. Renewable electricity is also statistically correlated with lower emissions intensity and at similar magnitude (within one standard deviation) as nuclear.

Finally, we also conduct a sensitivity analysis to test the robustness of our results to potential unobserved confounders, following a method to test for the potential impact of omitted variable bias described by Cinelli and Hazlett (2019).[2] We focus on the strongest empirical specification we have: our panel analysis of the link between nuclear energy generation and carbon pollution (see Table 2). We report the results of this sensitivity analysis in Figure 1, where we show that even an omitted variable that is three times as predictive of emissions as GDP would do little to undermine our finding that nuclear energy is associated with lower carbon emissions in a country. This is evidence that the directional effect of nuclear generation on emissions reductions is not only intuitive but also causally robust.

[2]Cinelli, Carlos, and Chad Hazlett. "Making sense of sensitivity: Extending omitted variable bias." *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 82.1 (2020): 39-67.

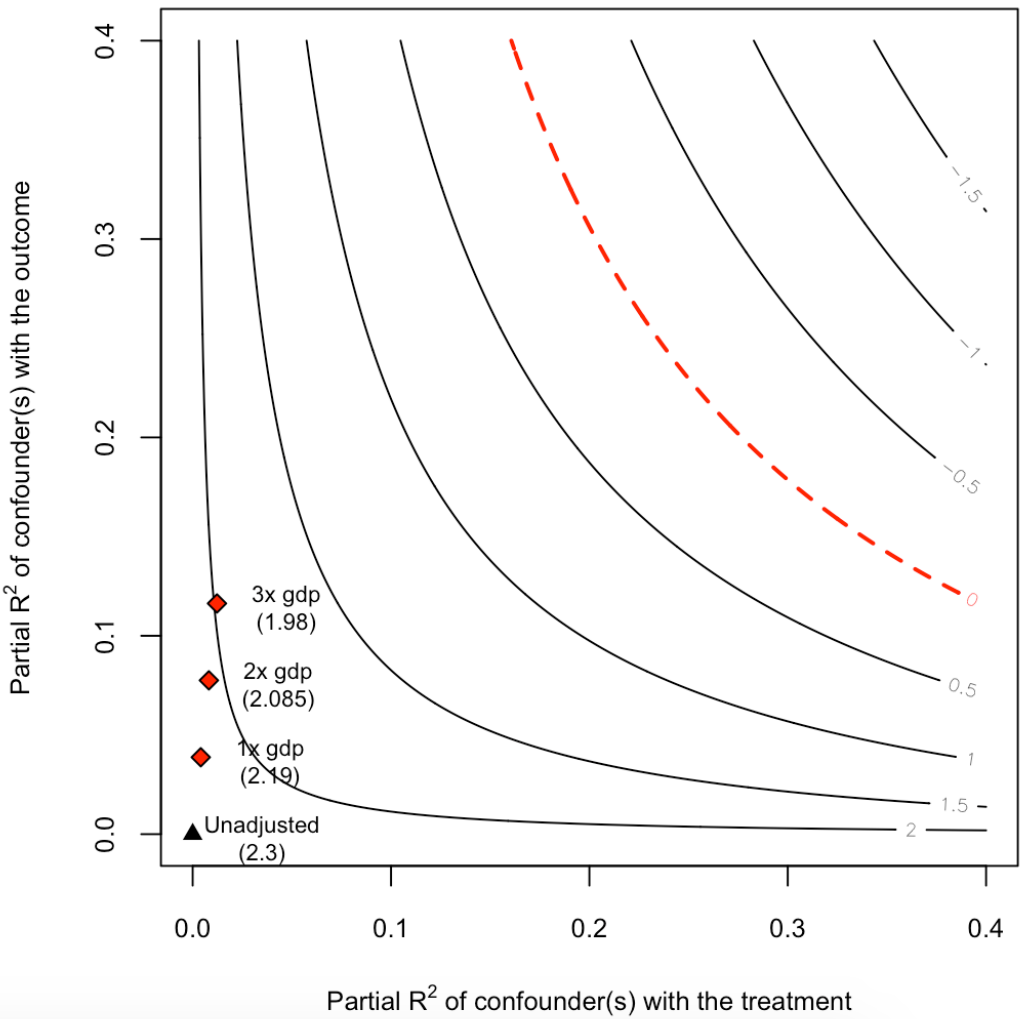

Figure 1: The contours in Figure 1 show the effect estimate, based on panel data analysis, as adjusted for varying possible degrees of confounding. Confounding is indexed by the proportion of residual variance in nuclear generation (the treatment) it can explain (on the horizontal axis) and the proportion of residual variance in carbon pollution it explains (vertical axis). The dashed line shows combinations of these two strengths at which confounding explains away the entire effect, making the adjusted estimate zero. Of particular note are the benchmark bounds (diamonds). These show how confounding "as strong as" (able to explain as much of the treatment and outcome residual variation as) the observed covariate (GDP) would alter the estimate. Even confounding three times as strong as GDP would not shift causal interpretation of the result (e.g. move the diamond to the top right of the red dashed line).

In sum, there are serious limitations in the Sovacool et al. (2020) analysis, which call into question the sweeping policy implications advanced by the authors. For instance, the paper's claim that renewables are "on balance evidently more effective at carbon emissions mitigation" than nuclear power is not supported by the paper's empirical findings. Instead, addressing several methodological issues found in Sovacool et al. (2020) and employing the same data sources and time periods, we find that nuclear power and renewable energy are *both* associated with lower per capita CO_2 emissions with effects of similar magnitude and statistical significance. In short, our empirical analysis strongly confirms the broad consensus of international organizations and national governments that nuclear power and renewable electricity alike can contribute to decarbonization and climate mitigation objectives.

Author Contributions

All authors critically reviewed the Sovacool et al. (2020) paper and contributed to writing this manuscript. HF and MM performed reanalysis of the cross sectional and panel data.