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Research article

When are fossil fuels displaced? An exploratory inquiry into the role of nuclear electricity production in the displacement of fossil fuels

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ABSTRACT

We explore how renewable electricity production influences nuclear energy and fossil fuel use in the electricity sector for 109 nations from 1960-2015 and how such patterns change over time. We find that although a one-unit increase in the number of kWh produced from renewable sources does not appear to displace an equivalent number of kWh from fossil fuels, such an increase is associated with an equivalent reduction in the number of kWh drawn from nuclear sources between 1960 and 2015. However, further analyses indicate that there has been a trend toward displacement of fossil fuel sources by renewables, as well as an attenuation of the displacement of nuclear sources by renewables, since the late 1990s in nations with the capacity for nuclear electricity production. These findings suggest that *social, political, and economic processes may prevent renewables from being deployed such that they* decarbonize the existing electricity grid, especially outside of the 31 nations capable of producing electricity from nuclear energy sources.

1. Introduction

Escalating consequences of climate change and the continued growth of greenhouse gas emissions from global electricity production has highlighted the urgent need to replace fossil fuels with other energy sources. Clearly, an energy transition is required to avert the most extreme global warming, which must entail a fundamental transformation of the global energy system (Smil, 2010, 2016; Sovacool, 2016; Sovacool and Geels, 2016). A key question is: does increasing electricity production from various non-fossil energy sources reliably lead to a reduction of fossil fuel use? To address this question, we assess how non-hydro renewable energy sources influence the use of fossil fuels and nuclear power in the electricity sectors of nations by analyzing cross-national time-series data. We explore the extent of such displacement for all nations— as well as among nations capable of producing electricity from nuclear sources— between 1960 and 2015 and how such trends are changing in the years following 1997. Our findings indicate that, though there does appear to be some displacement of fossil fuels in nuclear capable nations, across all nations little displacement has occurred.

There may be reason to be optimistic about the potential of renewable energy technologies since, due to their declining cost, growth in renewable energy production has outpaced total energy consumption since 2012 (UNSEC, 2019). On the surface this observation appears to suggest that, on average, renewables are starting to replace other sources of electricity production across the globe. Yet, previous research has also suggested that non-fossil sources of electricity production have largely failed to substantially displace fossil fuel sources in the past. York (2012) found that nations that had experienced more growth in non-fossil fuel energy sources (including hydro, nuclear, wind, and solar) since 1960 use only slightly less fossil fuels than do nations that did not substantially expand non-fossil energy sources, controlling for demographic and economic factors. Indeed, in the electrical sector, the average patterns across nations from 1960 to 2009 indicated that it took about 10 units of non-fossil energy to suppress one unit of fossil energy. This result implies that growth in non-fossil energy production is typically used to expand total energy consumption, rather than displace fossil energy use. Similarly, Greiner et al. (2018) found that, based on analysis of cross-national times-series data, nations that expanded natural gas use typically did not appreciably reduce coal use. More generally, a growing body of research suggests that we should be cautious in assuming that the introduction of a new technology, resource, or product will lead to the displacement of a previously existing, comparable technology, resource, or product (York, 2017, 2021; York and Bell, 2019; Longo et al., 2019). Rather, it is often

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the case that new energy sources, technologies, and products are added on top of existing ones, rather than in place of them, so that they enable more overall consumption.

For instance, between 1960 and 2015 global electricity production increased by 437.12% (EIA, 2020). In that time, fossil fuels never accounted for less than 51.47% of the global energy mixture used to generate electricity, while two of the most prominent non-fossil electricity sources – non-hydro renewables and nuclear – have never independently surpassed 6.8% and 17.6% of the sources of electricity generation in a given year, respectively (World Bank World Development Indicators, 2020). It is well acknowledged that reliance on fossil fuels in electricity production is one of the primary drivers of anthropogenic carbon dioxide emissions and, thereby, climate change. Indeed, it is estimated that in 2010 electricity and heat production accounted for 25% of anthropogenic CO_2 emissions (IPCC, 2014) – an estimate that grew to 42% by the year 2017 (IEA, 2020). Despite the large increase in electricity production since 1960, and the electricity sector's growing share of anthropogenic emissions, there is also a widespread desire to increase global electricity production capacity further still, as processes of electrification have been rolled out unevenly – deepening social and economic inequality within and across nation-states (McGee and Greiner, 2019). Great progress has been made to this end, with the estimated global share of people with access to electricity reaching 89% in 2017. The remaining 11%, however, is representative of over 840 million people who still lack access to even the most basic electricity provision (UNESC, 2019).

For decades the World Bank and the United Nations have worked in tandem to mitigate global climate change and alleviate extreme poverty around the world through the *Sustainable Energy for all Initiative* (United Nations (U.N.), 2020; World Bank, 2021). The goal of this effort is to eradicate extreme poverty and mitigate environmental harm by decoupling economic growth from environmental degradation. It is argued that the consumption and production of sustainable electricity is a path to reaching this goal by 2030. As such, one approach to this initiative is bringing affordable and sustainable electricity to the roughly 1 billion people who currently live off of electrical grids and rely on solid fuels, such as wood, charcoal, animal and crop waste, and coal, to cook or heat their homes. A number of scholars have explored the extent to which economic growth can be decoupled from environmental degradation through the goals set forth by this initiative. For example, York and McGee (2017) found that increasing renewable electricity consumption within nations from 1960-2012 did not decouple economic growth from CO_2 emissions, and instead resulted in a “tighter coupling between emissions and GDP per capita.” Similarly, Thombs (2017) found that economic growth becomes “increasingly coupled” to CO2 emissions in nations with higher levels of renewable energy consumption. Previous work (McGee and Greiner, 2019) also finds that renewable sources of electricity fare better at reducing CO2 emissions over time within nations when income inequality is higher, suggesting that the dual goals of the *Sustainable Energy for all Initiative* may be contradictory.

Further, recent work presented by the Intergovernmental Panel on Climate Change suggests that global emissions must begin to slow by 2030 if we are to have a reasonable chance of meeting the goals of the Paris Climate Accord (IPCC, 2018). Thus, the question of if, and to what degree, renewables are displacing, rather than simply adding to, other energy sources is of great importance. Recent research outside of the displacement literature has addressed this issue by exploring the extent to which carbon emissions are reduced in nations that rely more on nuclear or renewables – finding that renewables are more effective to this end, but also that renewables and nuclear may tend to “crowd each other out” (Sovacool et al., 2020). Using the displacement modeling approach, the present research aims to address questions such as these as well. To explore if and how the presence of multiple non-fossil energy sources for electricity production come to bear on fossil fuel displacement, or the decarbonization of the electricity sector more directly, we use World Development Indicator data (World Bank World Development Indicators, 2020) on national electricity generation from nuclear, fossil fuel, and non-hydro renewable sources for 109 countries for which data were consistently available to construct tobit random effects panel regression models. Using this modeling approach, we explore three specific questions. First, we examine the extent to which the growth of non-hydro renewable electricity generation served to displace generation from fossil fuels between 1960 and 2015 (although data are not available for all years for all nations). Second, we explore if renewables have tended to displace nuclear power in that period, exploring if these sources might indeed be crowding one another out rather than primarily suppressing fossil fuels. Finally, we examine the extent to which average displacement of fossil fuels and nuclear by renewables has changed among (1) all nations and (2) nations capable of nuclear electricity production from 1997 to 2015, the period during which renewables began to be more rapidly deployed.

2. Methods and analytic technique

The general logic of the models is to use as the dependent variable the amount of electricity from either fossil fuels or nuclear power, include various factors that have been established in the literature as the main drivers of electricity consumption as control variables (discussed below), and have the amount of renewable electricity generation as the key independent variable. This is a displacement model as developed by York (2012), where the coefficient for renewables has a straightforward interpretation. If renewables displace fossil or nuclear energy on a one-for-one basis, the coefficient should be -1, indicating that for each unit of renewable energy that is generated, one less unit of electricity from fossil or nuclear power is produced (controlling for other factors that would affect the scale of electricity use). A value between 0 and 1 indicates that there is partial displacement. A value of 0 indicates growth in renewable electricity has no effect on fossil or nuclear power.

We estimate left (0) censored tobit regression models with random effects. Tobit models allow for the estimation of latent values through a process of random sampling from available data. Here, doing so allows for the estimation of underlying nuclear generation potential. In other words, tobit modeling enables the estimation of a likely propensity for nuclear electricity production value for nations which had no nuclear electricity production capacity in the observed data (Woolridge, 2016) (Note that in the supplementary materials, and in Figure 2, we present results for models that are limited to nuclear producing nations and find that results are consistent across approaches.) Such a technique is particularly useful for the question at hand, as a good deal of nation-years had no nuclear electricity production. We note, however, that the random effects procedure does not account for unobserved contemporaneous and extemporaneous factors relevant to the central questions raised in this study. To ensure that such factors were not leading to bias in our results, we present alternate models where fixed effects estimators for nation and year were included in tobit regression analyses. The results of these models are consistent with those presented here, and can be found in tables S1and S2 of the supplemental materials. Where table S1 presents results for tobit models with fixed effects estimators for unit and years that explore the displacement effect of renewables on fossil fuels sources of electricity production, and table S2 presents results of the same modeling approach applied to explore the displacement coefficient of renewables on nuclear sources of electricity production. We focus discussion on random effects tobit models since the inclusion of fixed effects estimators can lead to bias in likelihood estimates for tobit models. We use the “xttobit” command with the “ll (0)” option in Stata MP 15.1 to run all tobit regressions. Results displayed here are also robust to the use of fixed effects panel regression models with robust standard errors and binary estimators for period effects. Results of fixed effects analyses can be found in table S3 of the supplementary materials document. We use the command “xtreg” with the options “fe robust” in Stata MP 15.1 in order to carry out fixed effects regression procedures. The general structure of the random effects tobit panel regression models used to produce the results in Table 2, including control variables which we discuss below, is as follows:

$$y_{it}^{*} = \beta_0 + \beta_1(Renewables_{it}) + \beta_2(GDPpc_{it}) + \beta_3(GDPpc_{it}^2) + \beta_4(Urban_{it}) + \beta_5(Manufacture_{it}) + \varepsilon_{it} \quad [1]$$

Such that:

$$y_{it} = \begin{cases} 0, \ if \ y_{it}^{*} \le 0 \\ y_{it}^{*}, \ if \ y_{it}^{*} > 0 \end{cases} \quad [2]$$

where: y_{it}^{*} is a latent dependent variable, y_{it} is the dependent variable being calculated (i.e. kWh of electricity produced from fossil or nuclear fuel sources) in the *i*th nation of year *t*; $GDPpc_{it}$ is the value of GDP per capita in 2010 U.S. dollars for the *i*th nation of year *t*; $GDPpc_{it}^2$ is the value of the quadratic term for GDP per capita in 2010 U.S. dollars for the *i*th nation of year *t*; $Urban_{it}$ is the value of the percentage of the population living in urban areas for the nation *i* in year *t*; $Manufacture_{it}$ is the value of value added from manufacturing as a percent of total GDP in the *i*th nation during year *t*; and ε_{it} is the residual term for nation *i* in year *t*.

While the general structure for the fixed effects panel regression model with period estimators and robust standard errors used to produce results presented in Table 3 can be expressed as:

$$y_{it} = \beta_0 + \beta_1(Renewables_{it}) + \beta_2(GDPpc_{it}) + \beta_3(GDPpc_{it}^2) + \beta_4(Urban_{it}) + \beta_5(Manufacture_{it}) + \beta_6(Year_t) + \beta_7(Renewables_{it})(Year_t) + \mu_i + \varepsilon_{it} \quad [3]$$

Where: y_{it} is the dependent variable being calculated (i.e. kWh of electricity produced from fossil or nuclear fuel sources) in the *i*th nation of year *t*; $GDPpc_{it}$ is the value of GDP per capita in 2010 U.S. dollars for the *i*th nation of year *t*; $GDPpc_{it}^2$ is the value of the quadratic term for GDP per capita in 2010 U.S. dollars for the *i*th nation of year *t*; $Urban_{it}$ is the value of the percentage of the population living in urban areas for the nation *i* in year *t*; $Manufacture_{it}$ is the value of value added from manufacturing as a percent of total GDP in the *i*th nation during year *t*; $Year_t$ is a linear, annual measure of time; μ_i is a control for unit specific, extemporaneous effects; and ε_{it} is the residual term for nation *i* in year *t*.

Considering the long time period of observation used in this study, we also take a number of steps to consider the possibility of non-stationarity and the cointegration of variables. First, we perform Fisher-type unit root tests on the 109 panels included in the models presented here for all demeaned variables. The Fisher-type test is appropriate for the present data structure, as it allows for unit root tests on panels that are not strongly balanced and that have time-series gaps. The results of this test indicate that the supposition that unit roots are present in all panels is false in all cases, with the exception of electricity produced from renewable sources which was found to have unit roots in all panels. Among all other variables, we find that the high inverse normal Z statistic is for electricity produced from fossil fuel sources, which has a value of -7.5618 and a p-value of 0.0000. Choi's (2001) work suggests that the Z statistic provides the best estimation of stationarity in practice. Still, we note that the inverse chi-squared (P), inverse logit (*L), and the modified inverse chi-squared (Pm) statistics are all in agreeance in all cases as well, with the inverse normal statistic reported above, and have p-values of 0.0000 for the sample of 109 nations used in this study. As only one of the variables used in our sample is of the classification I (1), or non-stationary, it is not possible for cointegration of the variables included in the analyses to be present.

The large set of panels, or countries, incorporated in the analyses presented here also raises concerns about the presence of slope heterogeneity. To ensure that the presence of slope heterogeneity is not biasing outcomes we perform two sensitivity analyses. First, we replicate tobit random effects regression models using a tobit random coefficients model structure. Such a model allows for random slopes to be accounted for in variables of interest. In addition, we replicate fixed effects analyses using a random coefficient modelling approach with years nested within units. Results of these sensitivity tests, with some minor exceptions, are consistent with those reported here, and can be found in tables S4 and S5 of the supplementary material. Finally, we examine the potential influence of cross-sectional dependence by performing sensitivity analyses using fixed effects panel regression models with Driscoll-Kraay calculated standard errors, as Driscoll-Kraay standard errors have been shown to perform well in the presence of cross-sectional dependence (Hoechle, 2007). Results of these analyses are available upon request

To produce Figures 2 and 3, which we discuss in the Results section below, we rely on estimations from fixed effects panel regression models with robust standard errors and period estimators presented in Table 3. Figures 2 and 3 allow for further illustration of the estimated change in renewable displacement coefficient magnitudes from 1997 to 2015. Figure 2 displays this information for fossil fuels for all nations with data available, while Figure 3 displays this information for both nuclear and fossil fuels in nuclear capable nations. In both figures we plot the derivative of the interaction function at each year between 1997 and 2015. We focus on the period 1997 as it was at this point that significant changes in the percentage of electricity drawn from non-hydroelectric renewable fuel sources are observable within our sample. Thus, point estimates in Figures 2 and 3 represent the differentiation of the interaction function for each year for which there are observations. As there is no substantive difference between the *average* displacement effects of non-hydroelectric renewable electricity production on nuclear or fossil sources when analyses are constrained this way, we choose to focus on the larger sample of nation-years (i.e. the period 1960 to 2015) in models that do not consider time-interaction effects.

All data are drawn from the WDI database (World Bank World Development Indicators, 2020), which provides information on all variables used here from 1960 to 2015. We include all available nation-years in our analyses. Our sample is representative of roughly 95% of global GDP, 80% of global population, and 72% of global electricity consumption in 2010. The two dependent variables used in analyses presented here are per capita kWh of electricity from nuclear and per capita kWh from all fossil fuel sources at the national level. The dependent variable for kWh of electricity from fossil fuel sources per capita is the aggregate of kWh of electricity per capita created from fossil fuel sources included in the WDI database– natural gas, oil, and coal. The dependent variable used in model 2 of Table 2 and model 3 of Table 3 represents kWh of electricity produced from nuclear sources per capita. The primary independent variable of interest is kWh of electricity drawn from renewables per capita, excluding hydroelectric methods of production. Here, then, renewable energy sources are: solar photovoltaic, solar thermal, geothermal, tide, wind, industrial waste, municipal waste, and a number of biofuels. Models presented here also include controls for the percent of the population residing in urban spaces, the percentage of GDP that is attributable to manufacturing, GDP per capita and a quadratic term for GDP per capita which allows the relationship to vary curvilinearly. In addition to analyses presented here, we explored models including electricity consumption per capita (kWh) and an age dependency ratio to control for changes in demand for electricity and the age structure of the population. Such models that we could estimate were robust to findings presented below. We focus on models without the age structure control or electricity consumption per capita (kWh) as tobit models with binary controls for year and nation fail to converge when these controls are included. Descriptive statistics for all variables are presented in Table 1, while the approximate Pearson's correlation values of the covariates are presented in Figure 1. Selected sensitivity analyses are presented in the supplementary materials.

3. Results

Results of our analyses can be found in Table 2, Table 3, figure 2, and figure 3. In model 1 of Table 2 we examine the extent to which an additional one kWh of electricity produced from renewable sources serves to displace one kWh of electricity produced from fossil fuels, net of

Table 1. Descriptive statistics (N = 2254).

Variables	Mean	Median	SD	Min.	Max.
Renewable electricity per capita (kWh)	249.67	34.91	1,035.36	0.00	16,241.78
Fossil fuel electricity per capita (kWh)	1,893.99	894.26	2,236.37	0.03	12,613.94
Nuclear electricity per capita (kWh)	607.22	0.00	1,462.54	0.00	8,907.70
GDP per capita (2010 U.S. Dollars)	$17,139.24	$7,697.14	$197,32.66	$187.52	$111,968.40
Manufacture (percent of GDP	16.37	16.12	5.57	1.23	39.12
Percent Urban (Percent of total population)	64.12	67.46	19.67	10.78	100.00
Population ages 15–64 (percent of total population)	63.20	64.77	6.08	46.99	85.41
Electric power consumption per capita (kWh)	4,069.31	2,014.18	5,485.89	22.76	54,799.18

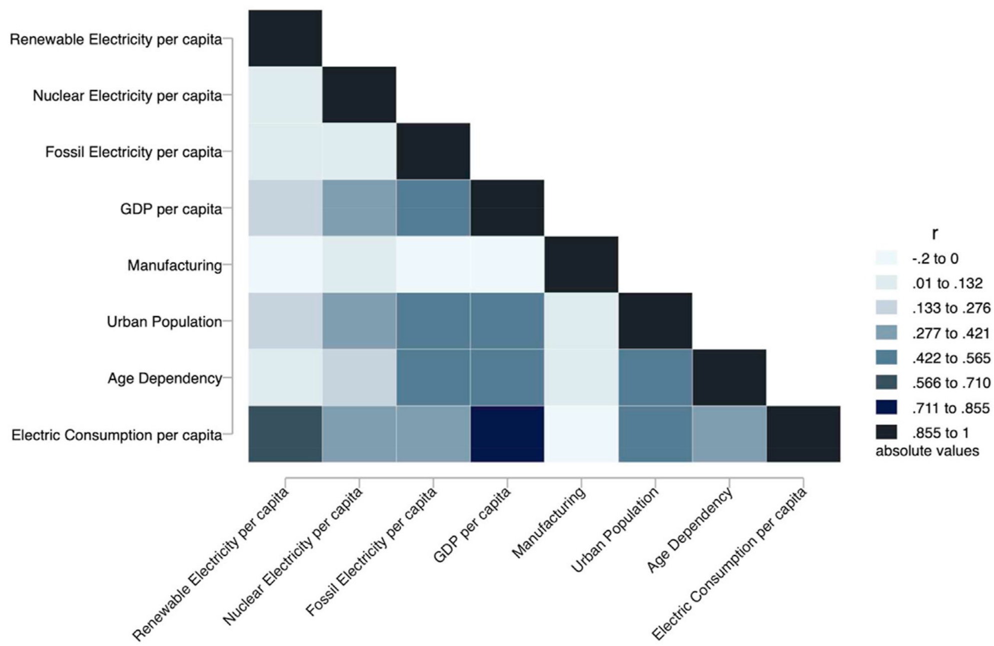

Figure 1. Pearson's correlation matrix for all co-variates. All data for Figure 1 drawn from the World Bank World Development Indicators (2020) database. Figure 1 displays results of Pearson's correlation analysis for all variables included in analyses presented below and in the appendix.

controls. Results suggest that, over the period of study, there was a statistically significant but very modest displacement of fossil fuels by renewables in the electricity production sector. Specifically, a one unit increase in kWh per capita from renewable sources is associated with about .193 kWh per capita reduction (i.e., the coefficient is -.193) in fossil fuel sourced electricity, with a 95% confidence interval for displacement of between .150 and .235 kWh (see Table 2). The results of this analysis are roughly consistent with previous research into the matter, which found non-hydro renewables did not significantly displace fossil fuels (York, 2012). This finding suggests that fossil fuel-based electricity production has only been marginally displaced by renewable production in the period explored. Notably, the renewable electricity displacement coefficient is significantly different from -1, which indicates that unit for unit displacement of fossil fuel electricity by renewables clearly has not occurred.

In model 2 we turn to our second question— if renewable electricity is not serving to displace fossil fuels to a large degree, is it displacing something else? More precisely, might there be some competition between nuclear and renewables? The results from model 2 indicate that each additional unit of electricity produced from renewable sources is associated with a 1.456 kWh per capita reduction of electricity drawn from nuclear sources. This displacement coefficient (−1.456) is significantly different at the .05 level (two-tailed test) from both 0 and -1. This result suggests that, net of other factors known to influence the production of electricity at the national level, the introduction of renewable sources of electricity is associated with a reduction in the use of nuclear sources. The large displacement effect may suggest that many nations are actively eliminating nuclear while also promoting the adoption of renewables. Results presented in Table 2 are robust to several alternative modeling approaches, including tobit regression with fixed effect estimators for nation and year, and fixed effects regression with robust standard errors and binary controls for period effects. The results presented here are also robust to the inclusion and exclusion of controls presented in the table below– as well as inclusion of controls for electricity consumption per capita and age dependency, limitation of analyses to the years following 1990, and the exclusion of some potentially anomalous cases.

In Table 3, and Figures 2 and 3 we present results of explorations into the average change of the renewable displacement coefficients for both fossil fuels and nuclear sources between 1997 and 2015 among all nations, as well as among nations that produce electricity from nuclear sources alone. In model 1 of Table 3 it can be seen that, across all nations, renewables are not serving to displace fossil fuel sources. Further, as seen in model 1 of Table 3, across all nations there is no statistically significant interaction between time and the displacement coefficient for renewables. To better understand this finding, we turn to Figure 2, where it can be seen that displacement coefficient of renewables is not statistically distinguishable from 0 at any point in the 1997 to 2015 time period, though, as Figure 2 shows, there is a tendency for the coefficient estimates to move toward displacement. Put differently, while there is no

Table 2. Tobit random effects panel regression models of estimated displacement of fossil fuel (kWh) (Model 1) and nuclear (kWh) (Model 2) electricity production (kwh per capita) by non-hydro renewable electricity production.

Variables	Model 1- Fossil Fuels	Model 2- Nuclear
Renewable electricity per capita (kwh)	-0.193*** † [-.235, -.150] (.021)	-1.456*** [-1.697, -1.285] (.122)
GDP per capita (2010 U.S. Dollars)	0.101*** [.087, .115] (.006)	0.320*** [.279, .362] (.021)
GDP per capita^2 (2010 U.S. Dollars)	-4.58×10^{-7}*** [-5.86×10^{-7}, -3.31×10^{-7}] (6.49×10^{-8})	-2.33×10^{-6}*** [-2.82×10^{-6}, -1.83×10^{-6}] (2.54×10^{-7})
Percent Urban (Percent of total population)	21.977*** [17.166, 26.788] (2.454)	-52.107*** [-70.38, -33.829] (9.325)
Manufacture (percent of GDP)	13.378*** [5.467, 21.289] (4.03)	-45.845*** [-65.751, 25.938] (10.156)
Constant	-617.900	-4780.527
Nation-years/Nations	2254/109	2254/109
Uncensored/Left censored observations	2254/0	664/1590

Notes: Results based on panel data for nations for which data is available between 1960 and 2015. Renewable electricity coefficients represent estimated change in kWh per capita of electricity produced using fossil fuel (model 1) and nuclear (model 2) sources associated with a 1-unit change in kWh per capita of electricity produced from renewables. Findings are robust to inclusion and exclusion of age dependency ratio.
†Significantly different from -1 at the .001 alpha level (two-tailed test) (Shown only for renewable electricity covariate).
*Significantly different from 0 at the .05 alpha level (two-tailed test).
**Significantly different from 0 at the .01 alpha level (two-tailed test).
***Significantly different from 0 at the .001 alpha level (two-tailed test).
Standard errors are reported in parentheses. The lower and upper bounds of 95% confidence intervals are reported in brackets. All data drawn from the World Bank World Development Indicators (2020) database.

displacement of fossil fuels by renewables as of 2015, it might be seen as hopeful that the estimates are moving in a direction that may be interpreted as indicating that displacement may occur in the future.

In models 2 and 3 of Table 3 we present results of analyses of the trajectory of renewable electricity consumption displacement coefficients for both fossil fuel and nuclear sources, respectively, between 1997 and 2015 in nations which have produced some electricity from nuclear energy sources. In model 2 it can be seen that there is a negative, statistically significant interaction between the renewable displacement coefficient and year— which suggests that, over time, there is a tendency for renewables to become more effective at displacing fossil fuels. On the other hand, in model 3 we can see that in nuclear producing nations the interaction between renewables and year yields a coefficient that is statistically significant and positive, suggesting that renewables are less associated with the displacement of nuclear fuel sources as time passes.

To better illustrate the meaning of these results, we turn to Figure 2. There it can be seen that renewable displacement coefficient estimates for fossil fuel sources have been declining over time. Specifically, by the year 2012 a 1-unit increase in kWh drawn from renewables is associated with a reduction in kWh of electricity drawn from fossil fuels that is statistically distinguishable from 0, and is not statistically distinguishable from -1. In other words, by 2012 it would appear that there is some meaningful displacement of fossil fuel sources in nations that are also producing electricity from nuclear sources. Conversely, Figure 2 and the results of model 3, Table 3 also suggest that, over time, the magnitude of the association between increases in kWh per capita of electricity produced using renewables and kWh per capita of electricity drawn from nuclear is diminished. This suggests that, in nations that have at least three energy sources to draw electricity from (i.e. fossil fuels, renewables, and nuclear) the deployment of renewables may indeed be crowding out

Table 3. Fixed effects panel regression models with robust standard errors of estimated displacement of fossil fuel (models 1 and 2) and nuclear (model 3) electricity production (kwh per capita) by renewable electricity production, with nation-state fixed effects estimators and a linear, annual control for year. Results of model 1 were used to produce Figure 2. Results of models 2 and 3 were used to produce Figure 3.

Variables	Model 1- Fossil fuels (all nations)	Model 2- Fossil fuels (limited to nuclear producing nations)	Model 3- Nuclear (limited to nuclear producing nations)
Renewable electricity per capita (kwh)	32.979 [-40.343, 106.302] (36.987)	115.295*** [51.414, 179.175] (31.278)	-26.518* [-47.201, -5.835] (10.127)
GDP per capita (2010 U.S. Dollars)	0.125* [.016, .233] (.054)	0.242* [.011, .474] (.113)	0.084 [.-.006, .175] (.044)
GDP per capita^2 (2010 U.S. Dollars)	-3.17×10^{-7} [-1.48×10^{-6}, 8.43×10^{-7}] (5.85×10^{-7})	-1.65×10^{-6} [-4.08×10^{-6}, 1.24×10^{-6}] (9.42×10^{-7})	-8.93×10^{-7}* [-1.72×10^{-6}, -7.08×10^{-8}] (4.03×10^{-7})
Percent Urban (Percent of total population)	72.837*** [38.536, 107.137] (12.403)	94.549** [33.899, 155.198] (51.736)	-37.556 [-124.259, 49.145] (42.454)
Manufacture (percent of GDP)	28.525 [-15.185, 72.237] (22.049)	59.746 [-45.913, 165.405] (51.736)	13.059 [-15.948, 42.066] (14.203)
Year	-35.298*** [-56.392, -14.204] (10.640)	-27.568 [-65.901, 10.763] (18.769)	14.457 [-12.005, 40.920] (12.457)
Renewable electricity per capita (kwh) * Year	-0.016 [-.052, .020] (.018)	-0.057*** [-.089, -.025] (.015)	0.012* [.002, .023] (.004)
Constant	65776.04	45973.86	-25382.37
Nation-years/Nations	1444/108	471/31	471/31
R^2	0.16	0.37	0.26

Notes: Results based on data for all nation-years for which data is available between 1997 and 2015. Renewable electricity coefficients represent estimated change in kWh per capita of electricity produced using fossil fuel (model 1 and 2) and nuclear (model 3) sources associated with a 1-unit change in kWh per capita of electricity produced from renewables. Findings are robust to inclusion and exclusion of age dependency ratio and GDP per capita^2.
†Significantly different from -1 at the .001 alpha level (two-tailed test) (Shown only for renewable electricity covariate).
*Significantly different from 0 at the .05 alpha level (two-tailed test).
**Significantly different from 0 at the .01 alpha level (two-tailed test).
***Significantly different from 0 at the .001 alpha level (two-tailed test).
Standard errors are reported in parentheses. 95% confidence intervals are reported in brackets. All data drawn from the World Bank World Development Indicators (2020) database.

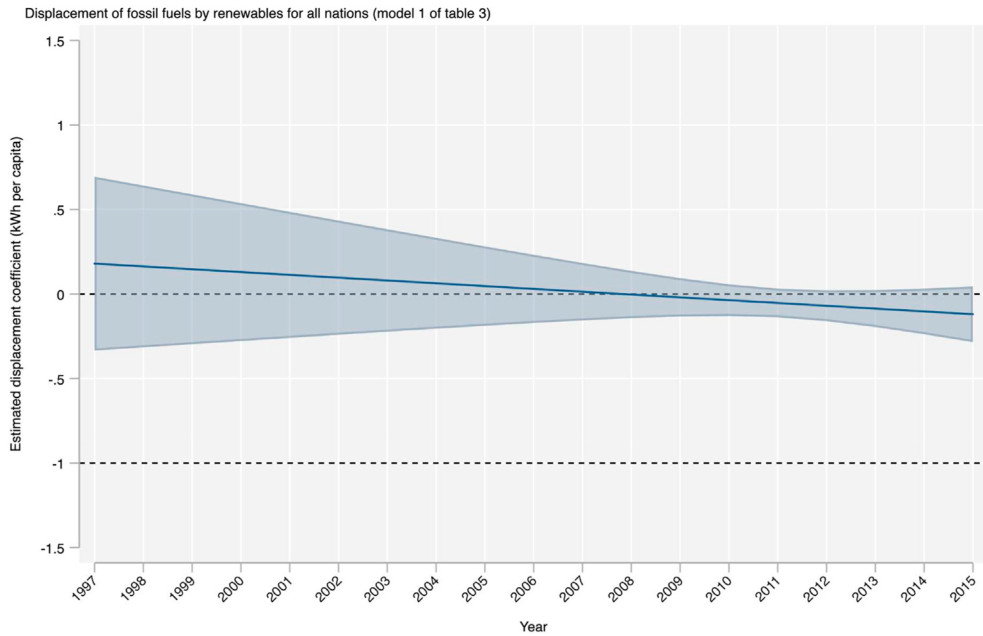

Figure 2. Change in displacement coefficients for fossil fuel electricity sources from 1997 to 2015, for all nations. All data for Figure 2 drawn from the World Bank World Development Indicators (2020) database.

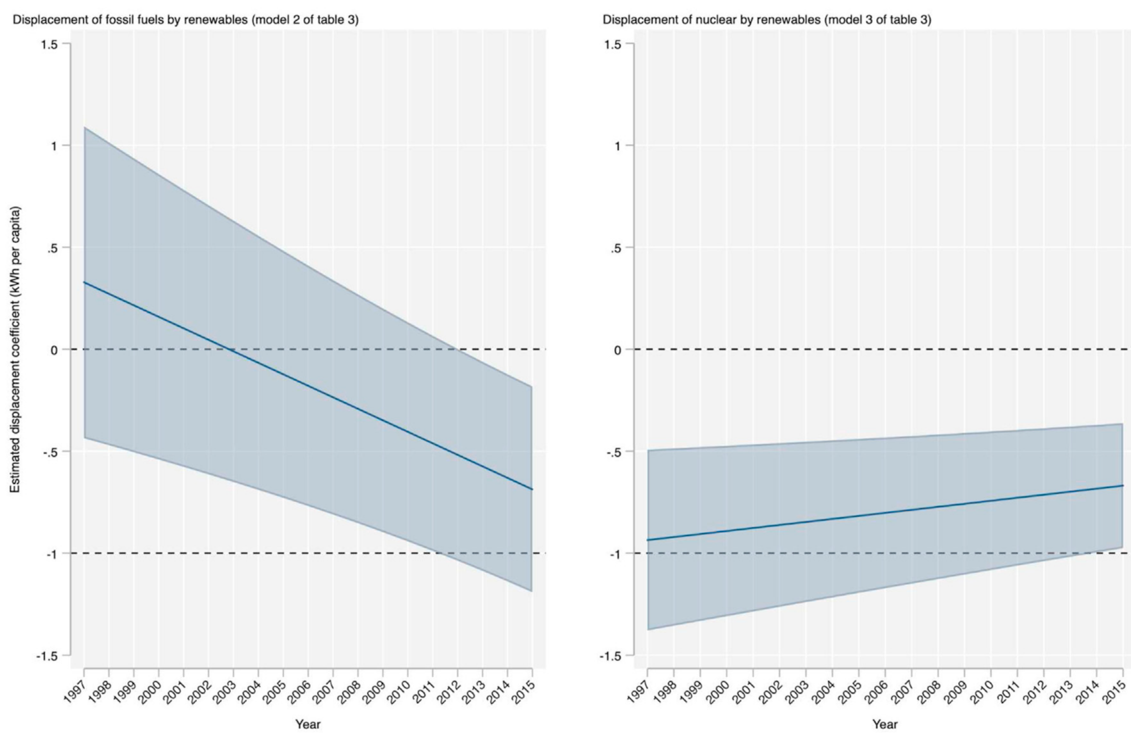

Figure 3. Change in displacement coefficients for fossil fuel and nuclear electricity sources from 1997 to 2015, constrained to nuclear capable nations. All data for Figure 3 drawn from the World Bank World Development Indicators (2020) database.

other sources of electricity generation. Further, it appears that in such nations the competition between fossil fuels and renewables may be intensifying over time, while competition between nuclear and renewables is diminishing. It could be the case that this signals a preference among decision-makers for non-fossil sources of electricity in nations that have a viable alternative with which to meet baseload demand (e.g. nuclear). However, for nuclear sources the upper bounds of 95% confidence intervals is well below 0, which indicates that the associative tendency for increases in renewable electricity production to draw down nuclear production remains— as of 2015. We note that these results are robust to the exclusion of Germany as well, which began deliberately reducing its reliance on nuclear sources of energy production in 2011 in response to the Fukushima-Daiichi disaster (Wittneben, 2012).

4. Discussion

It may be the case that these results are reflective of the difficulties that polities and decision-makers confront when attempting to balance

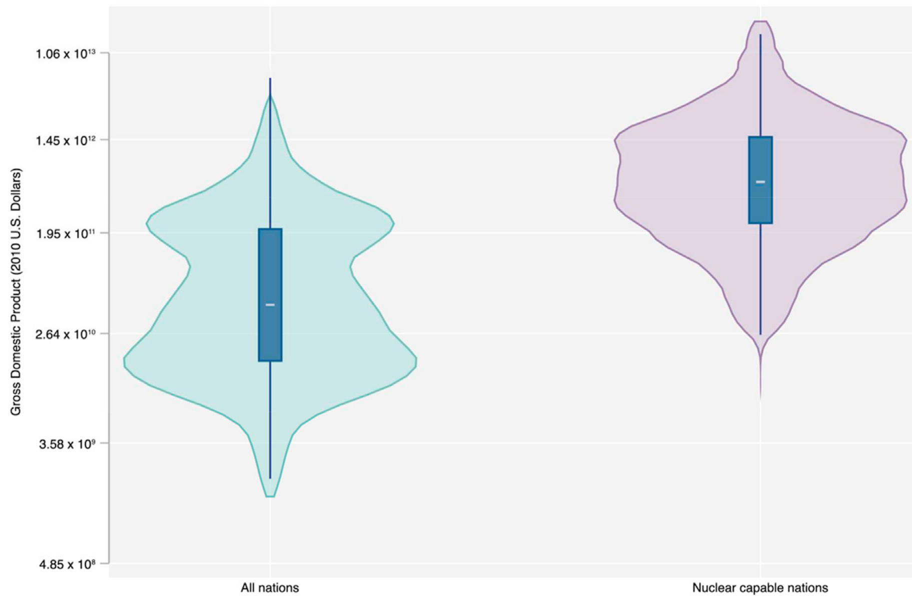

Figure 4. Distribution of GDP (2010 U.S. Dollars) for all nations and for nations that produce electricity from nuclear fuel sources. All data for Figure 4 drawn from the World Bank World Development Indicators (2020) database.

concern over the different risks societies face from nuclear power (e.g., meltdowns, long-term storage of radioactive waste) and fossil fuels (e.g., climate change and pollution). The results may also be due in part to the differential power of different actors in the energy sector, where fossil fuel companies are highly capitalized and politically influential. While we can only speculate as to the causal mechanisms underlying the associations we identify here, it appears that renewable sources of electricity have begun to displace fossil fuels in nuclear producing nations, although only very modestly. Displacement is taking place for nuclear sources of electricity as well, though less intensively as time passes. However, as Figure 2 and model 1 of Table 3 demonstrate, the incipient success of fossil fuel displacement in nations that use nuclear energy to produce some proportion of their electricity is not shared by the majority of nations included in our analysis. Across the 108 nations included in model 1 of Table 3 a displacement paradox is observed, in that the growing presence of renewables is not associated with a reduction of kWh per capita of electricity drawn from fossil fuels.

Taken together these results suggest that the addition of renewable sources of electricity production has not served to decarbonize electricity production processes globally, but rather has served to limit the socio-ecological risks, and fiscal costs, of both fossil fuel and nuclear electricity production in the nations that are energy rich enough to have all three sources of energy to use in electricity production processes. What's more, while non-hydro renewables appear to be in effective competition with nuclear and, more recently, fossil fuels in nations that have some capacity for nuclear electricity production— thereby reducing the likelihood of experiencing the negative social and environmental harms that are associated with nuclear energy use and moving away from forms of development that contribute to anthropogenic environmental change— they have yet to reduce *the world's* reliance on fossil fuels in the electricity production sector. These results suggest that *infrastructural path dependency, and broader policy contexts, including cross-national inequalities,* have largely insulated fossil fuels from competition with alternative sources of electricity production outside of those nations that enjoy the wealth and geopolitical standing required in order to acquire and manipulate nuclear energy fuel sources and technologies. To that end, Figure 4 shows a clear disparity between the distribution of wealth, as measured by GDP in 2010 U.S. Dollars, between the sample of all nations included in the analysis and nations capable of producing electricity from nuclear energy sources. Indeed, such an understanding is supported by the findings of previous research into the social, economic, and political dynamics of nuclear electricity production, which has suggested that it offers few concrete improvements to social stability, or the technological or economic efficiency of electricity production and distribution infrastructures. Rather, such investments offer geopolitical advantages by creating the space to manage the possibility for research of weapons technology (Ramana and Zia, 2014) and primarily serve to expand the risk of nuclear weapons proliferation instead of mitigating climate change– even when aimed at the most advanced nuclear energy technologies (Makhijani and Ramana, 2021). While we do not intend to suggest this is the cause of the observed disparity in displacement effects between such nation groups, it is suggestive of advantages that national wealth may yield when trying to navigate choices about electricity production infrastructures. As previous research into energy poverty suggests (McGee and Greiner, 2019), it may be the case that attempts to address poverty, underdevelopment, and to expand access to electricity— such as the *Sustainable Energy for all Initiative*— make nations with greater economic inequality and impoverishment more likely to use new energy sources to expand access to reliable electricity infrastructures rather than to reduce the reliance on already extant fossil fuel electricity production facilities. Incorporating additional considerations regarding the role played by inequality in the establishment and transition of electricity infrastructures may be a useful and productive direction for future inquiry into energy displacement.

We stress that these findings should not be taken to mean that non-hydro renewables sources of electricity cannot or will not displace fossil fuel sources of electricity in the rest of the world. Indeed, the renewable industry is still relatively early in its development, and it is entirely possible that incipient technologies such as cost-effective grid-scale batteries (Lamy et al., 2014) or innovative policy interventions that disincentivize the use of fossil fuels might change these dynamics, and make the associations observed in nuclear producing nations more ubiquitous in the years following the analyses presented here. Such potentialities are of fundamental importance if we are to successfully decarbonize the electricity production sector. However, the findings presented here indicate that globally such a transition has yet to begin, and that the efficaciousness with which renewable fuel sources displace fossil fuel sources is not independent of considerations of cross-national inequality related to energy access and international development.

5. Conclusion

Since fossil fuel use is a key driver of climate change (and various other environmental problems), it is clear that the world must transform its energy systems so that there is a transition away from fossil fuels. Such a transition will require expansion of alternative energy sources, especially those with the lowest environmental impacts, such as non-hydro renewables. However, we should not assume that merely expanding renewables will necessarily suppress fossil fuels, without concerted efforts to ensure that they do, since a growing body of research suggests that historically new energy sources have, for the most part, been used to expand energy consumption, rather than replace established energy sources (i.e., all energy sources have typically grown simultaneously, rather than new ones taking the places of others). For renewables to truly help curtail the climate crisis, they must *replace* fossil fuels, not simply allow for continued growth in energy consumption.

To assess what track the world is currently on, here we analyzed cross-national time-series data for 109 nations from 1960-2015 to examine how the production of non-hydro renewables affects fossil fuel use and nuclear power in the electrical sector. We found that renewables have had only a very modest effect on fossil fuel use, where on average it took an increase of five units of renewable energy to displace one unit of fossil energy. However, we also found that rising production of renewables was effective at suppressing nuclear energy, where each unit of renewable energy displaced slightly more than one unit of nuclear production. These results together suggest one of the reasons renewables are not effective at suppressing fossil fuels is that they are typically used in place of nuclear energy. However, in additional analyses, which focus on more recent years (1997–2015), the period in which non-hydro renewables have come to play a growing role in the global energy supply, and only the 31 nations that do produce nuclear energy, we found that over time renewables have become more effective at displacing fossil fuels (although still far from a one-to-one displacement) and less effective at displacing nuclear power. This change may be because it is only over the past two decades or so that many nations have taken the threat of global climate change seriously and begun to take actions to support a transition away from fossil fuels and toward renewables. Further, these results may reflect the different roles that new energy sources play in social and economic development in societies that do and do not have access to nuclear energy, where nuclear capable nations that have achieved expansive electrification may use renewables to displace fossil fuels, while nations with a more limited energy mixture use these new sources of electricity to expand the grid, rather than displace already existing sources. Broadly, these findings suggest that it is important to not assume that technological developments on their own will lead to environmental improvements. Rather, concerted political effort may be necessary for technologies, such as those involved in renewable energy production, to fulfill their potential to replace environmentally harmful technology, such as those connected with fossil fuel use.

Declarations

Author contribution statement

Patrick Trent Greiner: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Richard York: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Julius Alexander McGee: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request

Declaration of interest statement

The authors declare no conflict of interest.

Additional information

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