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ANALYSIS

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Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power

Benjamin K. Sovacool[1]✉, Patrick Schmid[2], Andy Stirling[1], Goetz Walter[2] and Gordon MacKerron[1]

Two of the most widely emphasized contenders for carbon emissions reduction in the electricity sector are nuclear power and renewable energy. While scenarios regularly question the potential impacts of adoption of various technology mixes in the future, it is less clear which technology has been associated with greater historical emission reductions. Here, we use multiple regression analyses on global datasets of national carbon emissions and renewable and nuclear electricity production across 123 countries over 25 years to examine systematically patterns in how countries variously using nuclear power and renewables contrastingly show higher or lower carbon emissions. We find that larger-scale national nuclear attachments do not tend to associate with significantly lower carbon emissions while renewables do. We also find a negative association between the scales of national nuclear and renewables attachments. This suggests nuclear and renewables attachments tend to crowd each other out.

While it is unmistakable that climate change mitigation must occur, it is less clear which particular strategies, infrastructures and practices offer the greatest potential in the energy sector. Pacala and Socolow argued more than a decade ago that a series of 'stabilization wedges' would enable humanity to maintain quality of life while avoiding catastrophic climate change[1]. They discussed more than a dozen such potential wedges ranging from energy efficiency and fuel switching from coal to natural gas to the advanced deployment of renewable electricity, nuclear power, and carbon capture and storage[1]. Other studies similarly note the importance of renewable energy and nuclear power in climate mitigation pathways and/or for achieving energy systems with net-zero emissions[2–5].

As we near three decades of dedicated climate protection interventions in many countries' energy strategies, we closely examine in this paper the extent to which scales of national attachments to either nuclear power or renewables associate with each other, and with effective aggregate reductions in national carbon emissions. Despite many contingencies and complexities, this offers a first-order test of conventional background assumptions that each strategy is comparably effective, and without notable opportunity costs or antagonistic effects on other strategies.

Accordingly, this paper uses regression analyses to interrogate relevant and consistent global datasets extending over 25 years and 123 countries, and to test interconnected hypotheses related to carbon emissions reduction with nuclear power and renewable energy, as well as one about crowding out and technological lock-in. One core finding is that countries with nuclear power attachments do not tend to have significantly lower levels of national carbon emissions. A second core finding is that lower levels of carbon emissions do associate more strongly with the relative scales of national attachments to renewable energy than with nuclear attachments. In other words, it is renewable (more than nuclear) attachments that tend to be associated in practice with significantly lower levels of carbon emissions. This is in line with recent work such as that of Jin and Kim, who find, using data from a sample of 30 countries, that "nuclear energy does not contribute to carbon reduction unlike renewable energy"[6]. A third core finding is that the scales of nuclear and renewable attachments tend to vary negatively with each other. This is broadly consistent with a finding that nuclear and renewables commitments crowd each other out. We then rigorously test and seek to validate these findings through further multiple regression analyses as well as an investigation of possible moderating effects. Note that the carbon-emission trends observed may not occur because of the choice between renewable or nuclear energy; the choice might be one result of a broader policy programme that leads to less carbon emissions (or does not).

The nuclear climate mitigation hypothesis

Emphasizing the widely discussed carbon emissions abatement potential of nuclear power, the nuclear climate mitigation hypothesis holds that the relative scale of national attachments to nuclear electricity production will vary negatively with carbon emissions. In simpler terms, emissions are expected to decline the more a country adopts nuclear electricity supply. Elements of this proposition are prominent in both energy policy and the academic literature[7–12]. For instance, the International Energy Agency includes nuclear power as one of its select 'low-carbon technologies' and argues that if the world is to see a 50% drop in energy-related CO_2 emissions, then nuclear energy must expand rapidly to where it reaches 1,200 gigawatt electrical (GWe) of installed capacity in 2050, when it also becomes the single largest source of electricity that year[13]. Achieving this level of nuclear capacity would require about US$4 trillion of additional investment, larger than any other source of electricity[13].

[1]Science Policy Research Unit (SPRU), School of Business, Management, and Economics, University of Sussex, Sussex, UK. [2]ISM International School of Management, Munich, Germany. ✉e-mail: B.Sovacool@sussex.ac.uk

Table 1 | Correlations between research variables on carbon emissions and electricity pathways

	Timeframe 1 (1990–2004)					
	Nuclear countries ($n = 30$)			Renewable countries ($n = 117$)		
	CO_2 emissions per capita (tons)	GDP per capita (US$)	Nuclear electricity production (%)	CO_2 emissions per capita (tons)	GDP per capita (US$)	Nuclear electricity production (%)
GDP per capita (US$)	0.52**			0.69**		
Nuclear electricity production (%)	0.12	0.32		0.31**	0.38**	
Renewable electricity production (%)	−0.26	0.08	−0.30	−0.47**	−0.16	−0.29**
Renewable electricity production (%), GDP per capita excluded (partial correlation)			−0.34			−0.25**
	Timeframe 2 (2000–2014)					
	Nuclear countries ($n = 30$)			Renewable countries ($n = 123$)		
	CO_2 emissions per capita (tons)	GDP per capita (US$)	Nuclear electricity production (%)	CO_2 emissions per capita (tons)	GDP per capita (US$)	Nuclear electricity production (%)
GDP per capita (US$)	0.51**			0.61**		
Nuclear electricity production (%)	−0.04	0.22		0.21*	0.31**	
Renewable electricity production (%)	−0.23	0.10	−0.23	−0.38**	−0.12	−0.25**
Renewable electricity production (%), GDP per capita excluded (partial correlation)			−0.26			−0.22*

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$.

The renewables climate mitigation hypothesis

The renewables climate mitigation hypothesis holds that the relative scale of national attachments to renewable electricity production will vary negatively with carbon emissions. In simpler terms, emissions are expected to decline the more a country adopts renewable electricity supply. This hypothesis is grounded in the wide diversity of renewable technologies and resources across different national circumstances and core competencies, such that most nations are able to achieve high levels of renewable energy contribution to electricity supply, and many achieve a surplus. For example, Jacobson et al. argue that 139 countries around the world can meet all of their energy needs with wind-, water- and solar-based energy systems[14]. Bogdanov et al. similarly depict a 100% global renewable electricity system that can be achieved by 2050 and provide low-carbon electricity without social disruption[15]. With the current unprecedented pace of technology development and cost reduction in many renewable energy-storage and grid-management technologies[16,17], it is clear that the picture over time is rapidly becoming more favourable for strategies based on renewable energy[18]. Perhaps reflecting this unfolding paradigm change, local commitments to push for 100% renewable energy systems at the scale of cities and regions—54 counties and eight US states have mandated a transition to 100% renewable electricity—are also accelerating investment in batteries, flexible storage and demand management[19].

The crowding out hypothesis

Our final hypothesis, the crowding out hypothesis, is that the relative scale of nuclear attachments will tend to associate negatively with renewables attachments, and vice versa. In simpler terms, the two options show a tendency to mutual exclusion, and each creates lock-ins or path dependencies that crowds out the other.

There exists no shortage of candidates for the kinds of mutual incompatibility, reciprocal tension and active antagonism that might (in one direction or another) serve to drive this crowding out. Take the configuration of electricity transmission and distribution systems, for instance. It is well recognized that a grid structure optimized for larger-scale centralized power production (like much conventional nuclear power) will tend on balance to make it more difficult, time-consuming and costly to introduce small-scale distributed power (like many renewables). The same is true of the associated norms, protocols, contracts, and operating codes and expert cultures necessary to make these structures work[20]. Likewise, although the limited relevant history of existing electricity systems around the world makes this more uncertain, it is probably the case on each of these points that the reverse may also be true (that is, that optimization around renewables would impede nuclear).

In broadly comparable ways, finance markets, regulatory institutions and employment practices structured around large-scale, base-load, long-lead-time construction projects for centralized thermal generating plants will not handle so well a multiplicity of much smaller, short-term, distributed initiatives, and vice versa. The particular necessity with nuclear power of elaborate governance arrangements around potentially catastrophic safety risks, security against attack, long-run waste management and safeguarding against proliferation also tends to sideline resources and attention from other options[21]. On the other hand, the erosion by renewables of the funding base for these expensive arrangements will tend to raise the unit costs falling on nuclear power. Finally, whatever the detail may be of particular interdependencies, the undoubted military connections and security repercussions displayed by nuclear power but not renewables mean (depending on context) that each will tend to be favoured under contrasting political circumstances and perspectives, thus introducing another mutual tension[22]. Indeed, there is a wider sense in which nuclear power and renewables each reflect 'technological aesthetics' that are valued by contrasting socio-political communities, such that whatever the operational merits may be judged to be, either will incur the antagonism of the constituency associated with the other[23].

Table 2 | Results of multiple regression analyses for carbon emissions and electricity pathways

	Timeframe 1 (1990–2004)				Timeframe 2 (2000–2014)			
	Nuclear countries ($n=30$)		Renewable countries ($n=117$)		Nuclear countries ($n=30$)		Renewable countries ($n=123$)	
	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	0.27**		0.48***		0.26**		0.38***	
GDP per capita (US$)		0.52**		0.69***		0.51**		0.61***
Step 2	0.00		0.00		0.02		0.00	
GDP per capita (US$)		0.54**		0.67***		0.54**		0.61***
Nuclear electricity production (%)		−0.05		0.05		−0.16		0.02
Step 3	0.11*		0.13***		0.11*		0.10***	
GDP per capita (US$)		0.61**		0.65***		0.60**		0.59***
Nuclear electricity production (%)		−0.18		−0.05		−0.25		−0.05
Renewable electricity production (%)		−0.36*		−0.38***		−0.34*		−0.32***
Step 4	0.12		0.05***		0.09		0.03*	
GDP per capita (US$)		0.66***		0.71***		0.57**		0.61***
Nuclear electricity production (%)		−0.22		0.08		−0.29		0.04
Renewable electricity production (%)		−0.24		−0.35***		−0.26		−0.31***
Moderator GDP × nuclear		−0.37*		−0.28***		−0.31		−0.18*
Moderator GDP × renewable		0.01		−0.06		0.05		−0.08
Total	0.51**		0.66***		0.48**		0.50***	

ΔR^2 is the increase of the coefficient of determination between the different steps of the regression. 'Moderator GDP × nuclear' refers to the variable that originates from the product of 'GDP per capita' and 'Nuclear electricity production (%)' from above, and 'Moderator GDP × renewable' refers to the variable that originates from the product of 'GDP per capita' and 'Renewable electricity production (%)'. For all four conducted hierarchical regression analyses, CO_2 emissions per capita (tons) is the dependent variable. β is the coefficient of linear regression for the respective independent variable. ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$.

Historical carbon emissions reductions

With our three hypotheses thus grounded in the long-standing literature on energy choices and technology dynamics more widely, we then proceeded to design and execute a research strategy to offer a rigorous and tolerably robust first-order picture of this important field (Methods). Results of our empirical analysis are displayed in Table 1 and Table 2. Table 1 shows bivariate and partial correlations of our research variables per country sample and timeframe. Table 2 shows the results of four hierarchical regression analyses conducted, with CO_2 emissions as the dependent variable. Based on this research design, our analysis does not confirm the nuclear climate mitigation hypothesis. On the other hand, it does confirm the renewables climate mitigation hypothesis, and partially confirms the crowding out hypothesis. Even as a first-stage result with a need for further confirmatory and interrogating research, this holds important practical implications.

Rejection of nuclear climate mitigation hypothesis

It is interesting, given the intense debates with which this paper began, that we were unable to confirm the hypothesis that the relative scale of national attachments to nuclear electricity production will vary negatively with carbon emissions. As Table 2 indicates, when analysing the general influence of relative nuclear electricity production as independent variables on CO_2 emissions per capita, we do not observe significant effects. For both country samples and in both timeframes, step 2 of the hierarchical regression analyses does not provide any significant increase in R^2. The slope parameter of relative nuclear electricity production also never reaches significance.

An additional result regarding this hypothesis is shown in step 4 of the conducted regression analyses: the effect of nuclear electricity production on CO_2 emissions per capita is significantly moderated by gross domestic product (GDP) per capita in three of four conducted regression analyses (once, it misses the significant level by a very small margin). Figure 1 shows that in countries with a high GDP per capita, nuclear electricity production has a negative effect on CO_2 emissions (that is, emissions decline), while in countries with a low GDP per capita, the reverse is true: there, nuclear electricity production seems to have a positive effect on CO_2 emissions (that is, emissions rise).

Confirmation of renewables climate mitigation hypothesis

Approaching our renewables climate mitigation hypothesis in an exactly symmetrical way to the corresponding nuclear hypothesis, we did confirm that the relative scale of national attachments to renewable electricity production will vary negatively with carbon emissions. When analysing the influence of relative renewable electricity production as an independent variable on CO_2 emissions per capita in Table 2, we observe that step 3 of all conducted hierarchical regression analyses shows a significant increase in R^2 (medium effect sizes). The corresponding β coefficients are always negative and reach significance in all timeframes and country samples. This negative effect of renewable electricity production on CO_2 emissions (lower emissions) does not seem to be moderated by GDP per capita: the corresponding moderator effect in step 4 fails to reach significance in all conducted regression analyses.

Partial confirmation of crowding out hypothesis

Our final hypothesis was that the relative scale of national nuclear attachment will tend to be associated with a lower level of renewables commitment, and vice versa. As Table 1 indicates, we partially confirm this hypothesis. The corresponding correlation coefficients are always negative, and equal small to medium effect sizes. Importantly, the coefficients do not change much when the effect of GDP per capita is excluded (partial correlation). However, the correlations only reach significance in the renewable country samples,

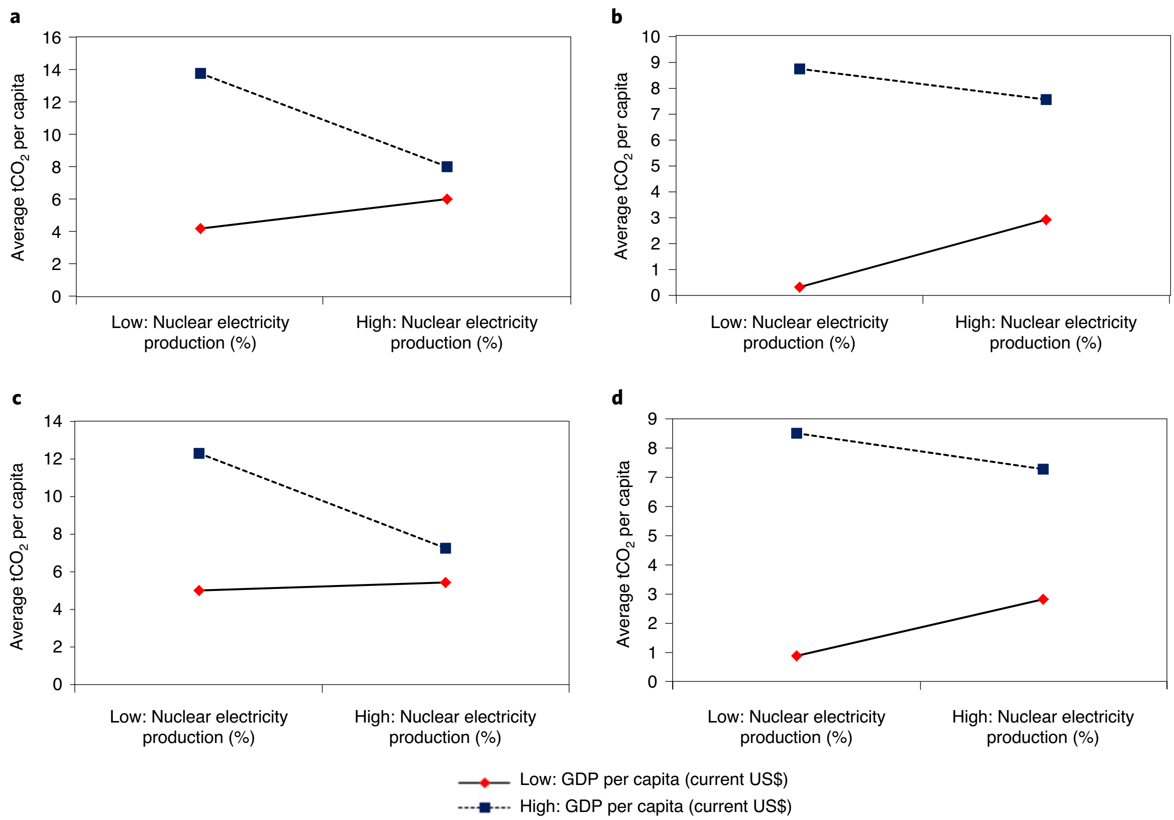

Fig. 1 | Graphical display of the moderating influence of GDP per capita on the effect of nuclear electricity production on CO_2 emissions. **a**, Nuclear countries in timeframe 1. **b**, Renewable countries in timeframe 1. **c**, Nuclear countries in timeframe 2. **d**, Renewable countries in timeframe 2. Timeframe 1 is 1990–2004, and timeframe 2 is 2000–2014. Nuclear countries includes all countries that have at least some nuclear electricity production per timeframe. Likewise, renewable countries pursue at least some production from renewable electricity. The solid and dotted lines together with their coloured endpoints represent regression lines between nuclear electricity production (%, independent variable) and CO_2 emissions per capita (average kilotons, dependent variable). Low and high with respect to nuclear electricity production and GDP per capita are understood as follows. A low value of nuclear electricity production means average value minus one standard deviation. Likewise, a high value means plus one standard deviation. Low for the GDP regression line means the regression line originating from the multiple regression with a low value of the GDP (as described). High for the GDP regression line is analogous. In **c**, the corresponding β parameter for the moderator GDP × nuclear variable does not reach a statistically significant level (as seen from Table 2).

and not in the nuclear country samples, possibly due to smaller sample sizes in the latter group. The bivariate relationships between nuclear and renewable electricity production per sample and timeframe are displayed in Fig. 2.

In the category 'renewable country', we address those countries that pursue renewable energy, and the degree to which they do so. In 'nuclear country', we address those countries that pursue nuclear power. The two categories obviously partly overlap (Supplementary Table 2). The negative nature of this correlation suggests that higher political, institutional or infrastructural attachments or wider cultural attachments to either nuclear power or renewable energy tend to associate with a lower attachment to the other technology. An interpretation of the asymmetry in this negative correlation may simply reflect substantive factors or some feature of the more encompassing nature of the 'renewable country' as compared with the 'nuclear country' category.

Contextualizing diverging nuclear and renewable pathways

What might explain these patterns? We posit possible technological, policy and social considerations.

Technologically, nuclear systems have been prone over the past few decades to greater construction cost overruns, greater delays and longer lead times than renewable energy projects. One dataset of real construction time data from 273 electricity projects over a fifty-year period shows a 90-month average lead-time for nuclear power, compared with a 40 month average for solar and wind. The finding that nuclear (and hydro) are more prone to cost overruns holds true even when normalized to scale, per unit of megawatt electrical installed. Thus, per dollar invested, the modularity of renewables projects offers quicker emissions reductions than do large-scale, delay-prone nuclear projects (Fig. 3)[24]. Solar energy even has a mean average cost underrun as a percentage of expected budget. The costs of nuclear waste, especially management of long-term waste at permanent geologic repositories, are—like the costs of periodic accidents[25,26]—not reflected in these construction costs, and would further add to the lifetime cost of nuclear power plants in ways that further erode their economic competitiveness[27].

Furthermore, renewables tend to display higher rates of 'positive learning', where increased deployment results in lower costs and improved performance[28], especially for wind farms[29] and solar energy parks[30]. This contrasts with the experience of nuclear power in France, which has been prone to 'negative learning'[31], rising costs or reduced performance with the next generation of technology. Similarly, a historical examination of the nuclear reactor fleet in the United States noted two broad problems: dependence on operational learning, a feature not well suited to nuclear capital investment; and

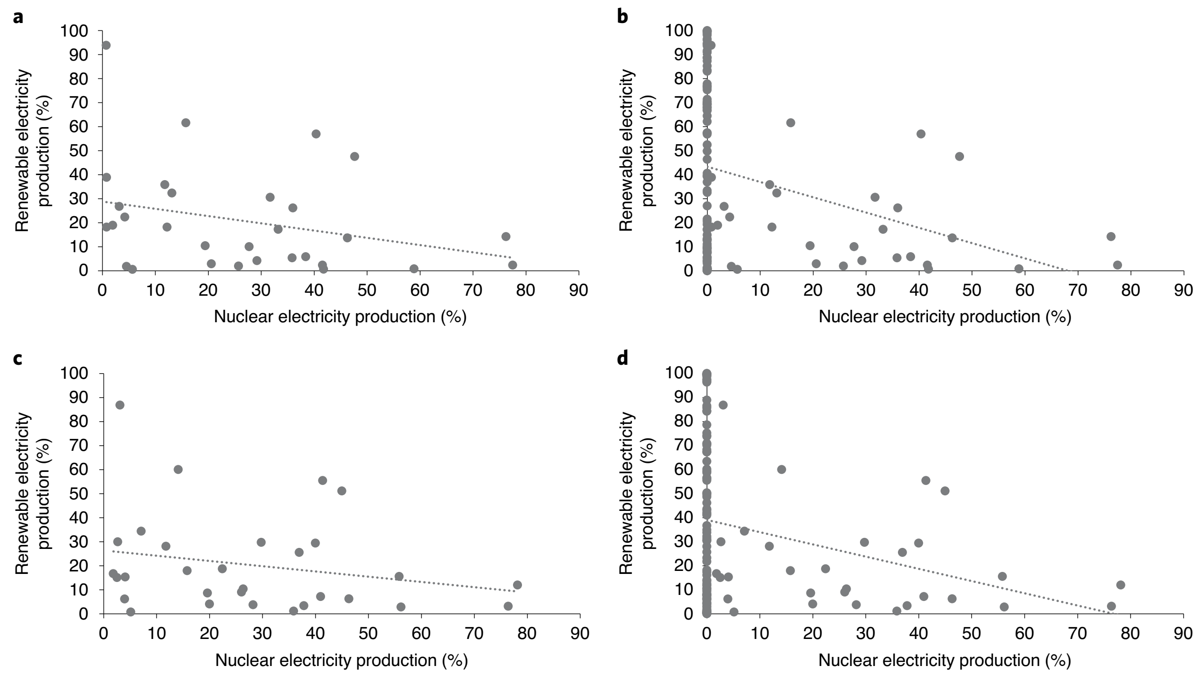

Fig. 2 | Graphical display of bivariate relationships between nuclear and renewable electricity production. a, Nuclear countries in timeframe 1. **b**, Renewable countries in timeframe 1. **c**, Nuclear countries in timeframe 2. **d**, Renewable countries in timeframe 2. Timeframe 1 is 1990–2004, and timeframe 2 is 2000–2014. Nuclear countries includes all countries that have at least some nuclear electricity production per timeframe. Likewise, renewable countries pursue at least some production from renewable electricity. The displayed points represent the data points. The dotted line represents the simple regression line between nuclear electricity production (%, independent variable) and renewable electricity production (%, dependent variable).

difficulty in standardizing units, including the idiosyncratic problems of relying on large generators whose specific site requirements do not allow for mass production[32], unlike most renewables.

In terms of policy, after each of the serious incidents or accidents at Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011) for example, regulatory requirements were substantially tightened for both operational and under-construction nuclear reactors. Each time, this regulatory ratcheting[33] had important impacts on equipment needs, construction designs, labour and materials, resulting in salient and unexpected price increases, longer shutdowns and delays to ongoing projects. Other than large hydroelectric dams, where some major failures were experienced in the 1970s and 1980s, no other source of renewable electricity is subject to such catastrophic accident risks or consequent regulatory ratcheting. Research on the governance of nuclear safety, the risk of possible future accidents and the politicized nature of reactor safety assessments all strongly suggests that such unexpected failures and accidents will continue well into the future[25,26,34].

Finally, wider social factors may also work against nuclear energy, and for renewable energy, facilitating faster acceptance, permitting and deployment[35–37]. Public attitudes typically afford greater attention than does much policymaking to some distinctive features of nuclear infrastructures, perceiving nuclear tendencies to be connected to weapons of mass destruction, and to be polluting, risky and technocratic[38]. Some research has even shown that nuclear accidents have severe psychological or psychosocial impacts alongside their environmental or technical ones[39], resulting in stigmas associated with the technology. Moreover, nuclear waste facilities in particular often lack a 'social license' to operate in many regions[40]. Renewables, on the other hand, have the opposite image, with higher levels of public acceptance, even when accounting for 'not in my backyard' sentiments in some communities[41]. For example, a survey in the United Kingdom shows higher levels of acceptance for further investment in renewable energy (two-thirds of the public support it) compared to nuclear power (only one-third of the public support it)[42]. One study explicitly asking respondents to choose between the two found 'discriminatory levels of public support' with 77% of a representative national sample preferring the increased deployment of renewable energy technologies to new fossil-fuel or nuclear power stations[43].

Limitations and future work

Although only an initial study, we believe the findings discussed here to be sufficiently clear and robust to be considered directly salient to current policy debates on carbon emissions reduction strategies in the energy sector.

Nonetheless, it is a limitation that this study aggregates nuclear and renewable electricity technologies. We treat both nuclear power and renewable energy as a consolidated reference class for the purposes of our analysis. This framing allows us to achieve a requisite expansiveness and symmetry of scope—to encompass in a balanced way the full diversity of options currently available in electricity system planning and policymaking. However, it involves a coarse-grain lumping together of all types of nuclear reactors, fuel cycles and respective institutional and geographical socio-political settings, as well as the radically divergent forms of renewable technology, even though these differ by resources, institutions, endowments and capabilities across contexts[44]. Based on the available data, a subnational or fuel cycle analysis is not possible yet for either nuclear power or renewables. We strongly encourage agencies related to nuclear and renewable energy (for example, the Nuclear Energy Agency, World Nuclear Association, International Atomic Energy Agency and International Renewable Energy Agency) to begin to collect this form of data so that future research can explore and build on it. Second, our analysis has focused exclusively on carbon mitigation efficacy—the relative empirical propensities of nuclear

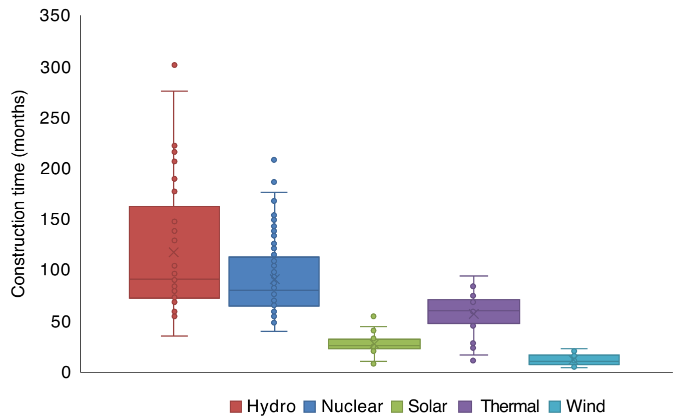

Fig. 3 | Construction lead times and opportunity costs for nuclear and renewable power plants. The mean construction time in months is shown for various sources of electricity supply, based on data from the literature[47]. The full range of the data is shown, with some nuclear reactors taking far more than 10 years (120 months) to construct. The dots represent actual data points for real construction costs from projects, and the whisker lines the maximum and minimum values without outliers. The central box shows the interquartile range including the median (line in the middle of each central box) as well as the upper and lower quartiles (the remainder of the box).

and renewable sources of electricity supply to associate with contrasting scales of carbon emissions. Therefore, the scope of analysis is incomplete and potentially skewed with respect to a wider array of concerns. These include issues such as economic costs, integrated resource planning, reliability, lifecycle impacts, risk profiles, waste management, and ecological, political and security impacts. Future work ought to consider a broader spectrum of attributes across nuclear and renewable energy systems, among which carbon emissions represent only one (albeit compelling) issue.

Third, although we confirm the presence of some degree of mutual crowding out between nuclear and renewable energy, we are unable (based on this initial analysis) to say which side of the dynamic matters most in which ways, or exercises the greatest net effect. More specifically, we can say very little about the particular kinds of mechanism that are more or less important or about the spatial or material drivers and implications that lie behind this. In itself, this wide scope for further questioning does not negate the salience of the result that the crowding dynamic may lead to perverse effects, given the parallel finding that renewable-based strategies are evidently generally associated with lower national carbon emissions than are nuclear-based strategies.

Fourth, our study focused only on renewables and nuclear power, when of course many other energy service options are available for generating electricity and modulating demand, in particular fossil fuel with carbon sequestration infrastructures and energy efficiency gains. Again, future research could explore the comparative carbon-emission mitigation efficacies across this wider array of strategic options.

Fifth and last, our data extend only up to 2014 (incorporating time lags), and our analysis is merely correlative. While we deem it logical that nuclear and renewable electricity production might show similar relations in later years with CO_2 emissions, our design does not test this. Nor, of course, can it be assumed that past data is predictive of future developments.

Thus, while our study can be viewed as a starting point for robust research on the topic of nuclear power, renewables and lock-in, it is not meant to be a finishing point. It is an anomaly that the strong claims in favour of particular technologies with which this paper began, have for so long remained so under-researched. We encourage others to address this gap in their future research.

Conclusions and policy implications

Notwithstanding these future possible orientations for research and limitations, our present conclusions are clear. Crucially, renewable energy strategies are, to an evidently noteworthy degree, associated with lower levels of national carbon emissions. Equally salient, the general climate change mitigation rationales for new nuclear investments are called into question. This, in turn, raises the important finding that nuclear and renewable strategies evidently tend to display such meaningful mutual tensions or antagonisms that one of them tends to crowd the other out. This confirms the widespread literature reviewed earlier, holding that the two broad approaches coexist only uneasily.

When taken together with the finding that renewables seem importantly more positive for carbon abatement worldwide, important adverse implications arise for nuclear power. As nuclear is the evidently less generally favourable of the two broad carbon-emission abatement strategies, a tendency of nuclear not to coexist well with its renewable alternative does (all else being equal) raise doubts about the opportunity costs of investments in nuclear power rather than renewable energy. The direction of the cost and learning trends discussed here intensifies this point.

Given the current state of climate debates internationally, it is troubling that nuclear and renewable energy pathways appear (both historically and, here, empirically) to display such mutual tension. It appears that countries planning large-scale investments in new nuclear power are risking the suppression of greater climate benefits from alternative renewable energy investments. That the converse may also be true (with renewables tending to suppress nuclear investments) is evidently less important, because it is renewable strategies that are on balance evidently more effective at the mitigation of carbon emissions.

In a world where the averting of catastrophic climate disruption is so imperative, energy diversity can play many crucial roles in achieving carbon-emission mitigation, but diversity comes in many forms and modes[45]. The challenge is not one of doing everything in directions conditioned by any entrenched interest, but about societies rigorously, democratically and deliberately choosing what to do. In light of this analysis, the implication for electricity planning is that diverse renewables are generally proving, in the real world, to be crucially more effective than nuclear power at reducing climate disruption.

Methods

Data sources and description. Because we wanted to use data that were both rigorous (subject to internal peer review) and also accessible (open to the public for others who may want to verify our results), we used World Bank and International Energy Agency data for our analysis. This includes data on nuclear electricity production per year and country (per cent of total electricity output); renewable electricity output per year and country (per cent of total electricity output); GDP per capita in current US$ (GDP divided by midyear population); and CO_2 emissions per year and country (metric tons per capita), defined as "carbon dioxide emissions … stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring"[46].

We chose to include GDP per capita as a control variable since we deemed it one of the most influential confounding variables when testing our hypotheses (see also Jin and Kim[6]). Regarding the dependent variable in the nuclear climate mitigation and renewables climate mitigation hypotheses, we chose carbon emissions from fossil fuels and industry to capture the electricity and industrial applications of nuclear power and renewable electricity sources. Both nuclear and renewables are large sources of process heat or energy for industry. For example, nuclear is a major potential energy source for industrial applications relating to desalination, refining and hydrogen manufacturing. Renewables as a whole, especially bioenergy and solar energy, provide district heating, process heating, residential space heating and cooling. Hydroelectricity in particular is a primary energy source for aluminium electrolytic plants as well as industrial irrigation and agricultural processing. This convinced us it was best to select a metric that tracked

emissions across electricity, heat and industry, which is what our data choice does. It seems a nice middle ground between electricity only (excluding other sectors of energy use) or national carbon footprints as a whole (too general for analysis).

With our choices made, we collected relative data rather than absolute data in order to reduce potential distortion effects due to confounding variables such as country size and population per country. Metric characteristics of all research variables per sample and timeframe are displayed in Supplementary Table 1. We proceeded to utilize multiple forms of data analysis to test the hypotheses as rigorously as possible.

Regression model. Regarding the nuclear climate mitigation and the renewable climate mitigation hypotheses, we conducted four hierarchical regression analyses with CO_2 emissions as the dependent variable. In the first step of all regression analyses, only the control variable GDP per capita was added to the model. In the second step, nuclear electricity production was included. In the third step, we added renewable electricity production. And in the fourth and last step of the hierarchical regression analysis, we included two possible moderator variables, namely an interaction term between GDP per capita and nuclear electricity production, as well as an interaction term between GDP per capita and renewable electricity production. All independent variables were z-standardized before being added to the model.

We did four hierarchical regression analyses because we split the data into two timeframes (1990–2004 and 2000–2014) and two samples (nuclear countries and renewable countries, defined below) as a triangulation method. Timeframe 1 was measured as follows: It was tested whether the mean of the years 1990 to 1999 of the independent variables had an effect on the mean of the years 1995 to 2004 of the dependent variable. Accordingly, Timeframe 2 tested whether the mean of the years 2000 to 2009 of the independent variables had an effect on the mean of the years 2005 to 2014 of the dependent variable. The lag of five years between the independent and dependent variables was chosen since it allowed optimal use of the available data (renewable energy figures were only recorded since the 1990s), and it allowed for a more directional interpretation of our correlative dataset (higher electricity production per technology influences CO_2 emission levels five years later). This appreciation of a lag was further grounded in the idea that nuclear or renewables would not necessarily result in immediate emission reductions; they could take time, and the temporal nature of our analysis also enabled us to look at five-year increments (rather than one-year increments) to help even out the data and avoid outliers.

'Nuclear countries' included all countries that have at least some nuclear electricity production per timeframe. Likewise 'renewable countries' pursue at least some renewables. Countries for which we did not have values in the given timeframes were omitted. Countries included per analysis are listed in Supplementary Table 2. If the same effect occurs in both timeframes and both samples, it is less likely that patterns are caused by random factors.

Regarding the crowding out hypothesis, we used a similar approach. However, since the research design sought a bidirectional correlation between renewable and nuclear electricity production (rather than a directional effect), we used the same years for both variables per timeframe (1990–1999 and 2000–2009), and used Pearson's coefficient of correlation r as statistical procedure. Similar to the other two hypotheses, we did the analysis multiple times, due to different timeframes and different country samples. Per sample and timeframe, we tested the crowding out hypothesis two times—once as simple bivariate correlation and once as partial correlation while controlling for the effect of GDP per capita.

For all analyses, the significance level was set on 5% (two-tailed). We treat $r = .10$ ($R^2 = .01$) as a weak effect, $r = .30$ ($R^2 = .09$) as a moderate effect and $r = .50$ ($R^2 = .25$) as a strong effect.

Potential criticisms and justifications. As always, there are limitations to these methods. Given the partisan nature of these debates, it is possible that other less-well-founded criticisms may be made. For instance, some may question a focus on national carbon emissions rather than looking at subsectors or emissions reductions. However, national-level emissions give more complete pictures of trends and accord better with this key locus of policymaking.

Some may question inclusion of countries with only small nuclear or renewable attachments (for example, the Netherlands for nuclear or France for renewables). However, our multiple linear regression method does directly address such issues of proportionality and scale.

Some may misconstrue our findings that we are mainly concerned with GDP (as it has the largest explanatory power via its coefficient of determination) and not with the influence of nuclear versus renewables. However, this is addressed by the four-stage model, which shows how GDP only explains (or moderates) so much. No claims are made that any effect explains 100% of emissions, but our results are consistent across two timeframes and two country classes (see Tables 1 and 2). In any case, the fact that a more expensive carbon mitigation option tends to associate more with higher GDP would itself be consistent with our overall findings.

Some may question our inclusion of hydroelectricity along with solar and wind under the category of renewable electricity. However, this inclusion is important given that hydropower is the world's leading source of renewable electricity; it competes directly with nuclear power over the provision of base-load power in many countries, and it is often pursued along with wind and solar as a portfolio.

Finally, some may misinterpret our findings as conveying causality. This is not the case, with our methods attuned to revealing correlations only (albeit statistically significant ones).

Data availability

All data generated or analysed during this study are included in this published article and its Supplementary Information.

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Author contributions

B.K.S. and A.S.: conceptualization; investigation; methodology; project administration; supervision; validation; writing, reviewing and editing of manuscript. P.S. and G.W.: conceptualization; data curation; formal analysis; methodology; validation; visualization; writing, reviewing and editing of manuscript. G.M.: writing, reviewing and editing of manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to B.K.S.