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Do alternative energy sources displace fossil fuels?

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A fundamental, generally implicit, assumption of the Intergovernmental Panel on Climate Change reports and many energy analysts is that each unit of energy supplied by non-fossil-fuel sources takes the place of a unit of energy supplied by fossil-fuel sources[1–4]. However, owing to the complexity of economic systems and human behaviour, it is often the case that changes aimed at reducing one type of resource consumption, either through improvements in efficiency of use or by developing substitutes, do not lead to the intended outcome when net effects are considered[5–9]. Here, I show that the average pattern across most nations of the world over the past fifty years is one where each unit of total national energy use from non-fossil-fuel sources displaced less than one-quarter of a unit of fossil-fuel energy use and, focusing specifically on electricity, each unit of electricity generated by non-fossil-fuel sources displaced less than one-tenth of a unit of fossil-fuel-generated electricity. These results challenge conventional thinking in that they indicate that suppressing the use of fossil fuel will require changes other than simply technical ones such as expanding non-fossil-fuel energy production.

The logic of my modelling approach is to control for the principal driving forces of national per capita demand for fossil-fuel energy (coal, oil and gas) and, to test for displacement, include in the models the amount of energy per capita from non-fossil-fuel sources (hydropower, nuclear, geothermal, solar, wind, tidal and wave energy, combustible renewables and waste) measured in the same units as energy from fossil-fuel sources. If, as is the common assumption, non-fossil-fuel energy displaces fossil-fuel energy proportionately, the coefficient for non-fossil-fuel energy should be approximately −1, meaning, controlling for demand, for each unit of non-fossil-fuel energy produced/consumed there should be one unit of fossil-fuel energy that is not produced/consumed. Partial displacement would be indicated by a coefficient between −1 and 0. A coefficient of 0 would indicate that non-fossil-fuel energy sources are simply added on top of fossil-fuel sources, without displacing them.

The displacement coefficients from four models are presented in Table 1 (full results are presented in the Supplementary Information). Models 1 and 2 examine electricity production (in kilowatt hours) per capita from fossil-fuel sources. In model 1, only gross domestic product (GDP) per capita (in inflation-adjusted US dollars) is included to control for demand, as data on it are available for most nations and most time points, giving broad coverage (132 nations, with data for many nations complete from 1960 to 2009), and also because economic production is generally considered the primary force driving energy use. As it is well established that the relationship between GDP per capita and energy use is not necessarily linear, the models are specified to allow for a nonlinear relationship. The displacement coefficient of −0.089 indicates that each kilowatt hour of non-fossil-fuel electricity that is generated displaces only 0.089 kWh of fossil-fuel-generated electricity. Therefore, to displace 1 kWh of fossil-fuel electricity requires generating more than 11 kWh (1/0.089 = 11.236) of non-fossil-fuel electricity.

In model 2, additional independent variables are added to further control for demand: urbanization (percentage of the population living in urban areas), including a specification to allow for a nonlinear relationship, manufacturing (percentage of GDP from the manufacturing sector) and the age-dependency ratio (the ratio of dependent-age people, that is, those under 15 and over 64, to non-dependent age people, that is, those 15–64 years of age)[10]. Including these extra control variables limits the coverage of the models owing to data availability, where 128 nations are included and most nations do not have complete data until the 1980s. Electricity production from non-fossil-fuel sources has a significant coefficient of −0.079, very similar to what was found in model 1. This coefficient indicates that close to 13 kWh (1/0.079 = 12.658) of non-fossil electricity are needed to displace 1 kWh of fossil-fuel electricity.

Models 3 and 4 examine the total national energy use (that is, electricity plus other uses) per capita from fossil-fuel sources (in kilotonnes oil equivalent). In model 3, where only GDP per capita is used to control for demand, the coefficient for energy use from non-fossil-fuel sources is −0.128, indicating that it takes nearly eight units (1/0.128 = 7.813) of non-fossil energy to displace one unit of fossil-fuel energy. Model 4 includes the additional control variables. Energy use from non-fossil-fuel sources has a significant coefficient of −0.219, the strongest coefficient of any model, but, nonetheless, very modest. This coefficient indicates that more than 4.5 units (1/0.219 = 4.566) of non-fossil-fuel energy are required to displace one unit of fossil-fuel energy.

In other versions of the four models I present here, I have tested whether the displacement coefficient varies over time by estimating the coefficient separately for each decade. The coefficients do not differ significantly across decades in any of the four models. I have also estimated models to assess whether the displacement coefficient varies with national affluence by estimating the coefficient separately for cases below the median GDP per capita value and those above it. The coefficients did not differ significantly across the two affluence categories for any of the four models.

I have also estimated models assessing whether the displacement coefficient is different for different types of non-fossil-fuel sources. For total national energy use, data availability limits the potential to disaggregate non-fossil-fuel sources, allowing for separation into only two categories: first, nuclear and non-combustible alternative sources, which represents non-carbohydrate energy sources, which do not emit carbon dioxide when generated (for example, hydropower, geothermal and solar power); and second, combustible renewables and waste, which includes biofuels. In versions of models 3 and 4, I substituted alternative and

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Table 1 | Non-fossil-fuel displacement coefficients for models of electricity production and energy use from fossil-fuel sources.

	Fossil-fuel electricity production per capita (kWh)		Fossil-fuel energy use per capita (kilotonnes oil equivalent)	
	Model 1	Model 2	Model 3	Model 4
Displacement coefficient for non-fossil-fuel energy sources per capita	−0.089*	−0.079*	−0.128*	−0.219*
Nations	132	128	132	128
Nation years	4,334	3,267	4,336	3,269

Results are based on statistical analyses of data from most nations of the world for 1960–2009. Each coefficient represents the effect on fossil-fuel use from the addition of one unit of energy from non-fossil-fuel sources. In models 1 and 3, energy demand is controlled for using GDP per capita. In models 2 and 4, energy demand is controlled for using GDP per capita, urbanization, manufacturing and the age-dependency ratio. *Statistically significant at the 0.05 alpha level (two-tailed test).

Table 2 | Nuclear, hydro and non-hydro renewable sources displacement coefficients for models of electricity production from fossil-fuel sources.

	Fossil-fuel electricity production per capita (kWh)	
	Model 5	Model 6
Displacement coefficient for nuclear energy per capita	−0.221*	−0.163*
Displacement coefficient for hydropower per capita	−0.099*	−0.086*
Displacement coefficient for non-hydro renewable sources per capita	0.048	0.018
Nations	132	128
Nation years	4,334	3,267

Results are based on statistical analyses of data from most nations of the world for 1960–2009. Each coefficient represents the effect on fossil-fuel use from the addition of one unit of energy from non-fossil-fuel sources. In model 5, energy demand is controlled for using GDP per capita. In model 6, energy demand is controlled for using GDP per capita, urbanization, manufacturing and the age-dependency ratio. *Statistically significant at the 0.05 alpha level (two-tailed test).

nuclear sources per capita and combustible and renewable sources per capita for the single non-fossil-fuel sources variable. The displacement coefficients for the two categories of energy were not significantly different from each other in either model, indicating that the models presented here with the single combined non-fossil-fuel sources variable are appropriate. Therefore, I do not present the results from the alternative models here.

More fine-grained data are available for sources of electricity, where non-fossil-fuel sources can be broken into three categories: nuclear; hydropower; and non-hydro renewable sources, which include wind, solar, geothermal, tides, biomass and biofuels. The displacement coefficients for these models are presented in Table 2. Model 5 controls only for GDP per capita, whereas model 6 controls for GDP per capita, urbanization, manufacturing and the age-dependency ratio. Model 5 indicates that nuclear power displaces more fossil-fuel electricity than other sources, but still not a substantial amount, with a coefficient of −0.221. Hydropower displaces less, with a coefficient of −0.099. Non-hydro renewable sources have a positive coefficient, indicating the opposite of displacement, but this coefficient is not significantly different from 0, indicating that renewables tend to simply be added to the energy mix without displacing fossil fuels. The differences among all three of these coefficients are statistically significant. Model 6 indicates a similar pattern, where nuclear power displaces the most fossil-fuel electricity, with a coefficient of −0.163, hydropower displaces less, with a coefficient of −0.086, and non-hydro renewables do not displace, with a non-significant coefficient of 0.018. In these models, the coefficient for nuclear power is significantly different from that of non-hydro renewables, but no other coefficients are significantly different from one another.

The lack of a significant displacement effect from non-hydro renewables is not necessarily that surprising, as they are such a small proportion of non-fossil-fuel energy sources (less than 4% of the world total). As they have, in general, been deployed only on a small scale, their potential to displace fossil-fuel use is hard to assess with confidence. Both nuclear and hydropower have significant, if only modest, displacement effects. Nuclear seems to displace somewhat more fossil-fuel use than hydropower does, although the difference between the coefficients for these two electricity sources is statistically significant only in model 5, not in model 6. The lower displacement coefficient for hydro power may stem from the fact that hydroelectric dams are often developed for many reasons, including flood control, irrigation and navigation, with the electrical output being merely one of the purposes. In contrast, nuclear power plants are typically developed primarily for electricity generation. In light of the fact that non-hydro renewables make up such a small proportion of non-fossil-fuel electricity sources, and that the difference in displacement effects between hydro and nuclear sources is ambiguous, the results from models 1 and 2, where all non-fossil-fuel electricity sources are combined, may best represent the general pattern.

Based on all of the results presented above, the answer to the question presented in the title of this paper—do alternative energy sources displace fossil fuels?—is yes, but only very modestly. The common assumption that the expansion of production of alternative energy will suppress fossil-fuel energy production in equal proportion is clearly wrong. The failure of non-fossil energy sources to displace fossil ones is probably in part attributable to the established energy system where there is a lock-in to using fossil fuels as the base energy source because of their long-standing prevalence and existing infrastructure and to the political and economic power of the fossil-fuel industry.

The clear implication of these results is that, if the pattern that has characterized energy use over the past five decades prevails in the future, massive expansion of non-fossil-fuel energy sources will be required to significantly suppress fossil-fuel use. This, of course, has serious environmental implications in light of the fact that non-fossil-fuel energy sources contribute to serious environmental impacts of their own. The recent disaster at the Fukushima Diachi nuclear plant in Japan is enough to highlight the risks associated with expanding nuclear power, without even considering the serious risks stemming from long-term nuclear waste disposal and the environmental damage caused by uranium mining[4]. Hydropower destroys river ecosystems and threatens the survival of anadromous fish and other aquatic species[11]. Solar voltaic power and wind power, although representing less serious environmental threats than nuclear power and hydropower, require large amounts of material, some of it toxic and energy-intensive to produce, as well as large areas of land to produce substantial amounts of energy[12]. In short, all energy sources have environmental costs.

Does this mean that alternative energy sources will be of little help in moving societies away from fossil-fuel use? Not necessarily. Of course all societies need energy. So, obviously, if societies are to stop using fossil fuels they must have other energy sources. However, the results from the analyses presented here indicate that the shift away from fossil fuel does not happen inevitably with the expansion of non-fossil-fuel sources, or at least in the political and economic contexts that have been dominant over the past fifty years around the world. One implication of these results is that direct suppression of fossil-fuel use (for example, by a carbon tax) is likely to be much more effective at reducing fossil-fuel use than simply expanding non-fossil-fuel energy sources. It is possible that non-fossil energy sources could more substantially displace fossil energy sources if they were deployed in a context where there were explicit policies aimed at reducing carbon emissions, such as in California where there is a goal of dramatically reducing carbon emissions over the coming decades[13]. The most effective strategy for curbing carbon emissions is likely to be one that aims to not only develop non-fossil energy sources, but also to find ways to alter political and economic contexts so that fossil-fuel energy is more easily displaced and to curtail the growth in energy consumption as much as possible. A general implication of these findings is that polices aimed at addressing global climate change should not focus principally on developing technological fixes, but should also take into account human behaviour in the context of political, economic and social systems.

Methods

I constructed fixed-effects panel models with the Prais–Winsten correction for first-order autocorrelation, using the nation as the unit of analysis and including dummy variables for each year to control for general period effects. This approach controls for any effects that are constant over the span of time examined for each nation, such as geographic and geological characteristics, and any effects that are constant across nations for a given point in time, such as international energy prices. I used cross-sectional time-series data on all nations for which they are available, for all years for which they are available from 1960–2009, from the World Bank's world development indicators[14]. Note that the data set of the world development indicators records data on Hong Kong separately from China, so Hong Kong is treated as a separate nation in this analysis. All reports of statistical significance or non-significance are based on a 0.05 alpha level with a two-tailed test. The dependent variable in models 1, 2, 5 and 6 was constructed by multiplying electricity production by the proportion of electricity production from oil, gas and coal sources and dividing by total population. The corresponding independent variable is the difference between electricity production from fossil-fuel sources and electricity production from all sources. The dependent variable in models 3 and 4 was constructed by multiplying energy use by the proportion of fossil-fuel energy consumption and dividing by total population. Note that for a small number of observations, the percentage of fossil-fuel energy consumption was recorded as slightly more than 100%. In these cases, it was set at 100%. The corresponding independent variable is the difference between fossil-fuel energy use and overall energy use. All models include linear and polynomial versions of GDP per capita, both a quadratic and a cubic term, so as to control for the nonlinear effects of GDP per capita on fossil-fuel use as precisely as possible. Likewise, models 2 and 6 include a linear and a quadratic version of urbanization. Model 4 was originally estimated with both a linear and a quadratic of urbanization, but as the quadratic version had a non-significant coefficient, the model was re-estimated with only the linear term. To test whether the displacement coefficient varies over time, I included interaction terms for the non-fossil-fuel energy sources variable by decade (that is, 1960–1969, 1970–1979 and so on). To test for whether the displacement coefficient varies with affluence, I included an interaction term for cases below the median from the largest sample (that for model 3) of GDP per capita (US$2,792). To test for whether the displacement coefficient varies across types of non-fossil-fuel sources, I replaced the single non-fossil-fuel variable with the variables described in text and used F-tests to determine whether they were significantly different from one another.

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Additional information

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