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Where are Fossil Fuels Displaced by Alternatives?

World-Systems and Energy Transitions

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Abstract

In light of ongoing and accelerating climate change driven by human combustion of fossil fuels, researchers have found evidence that national-level inequality influences whether nations are able to replace fossil fuels with alternative energies. This paper asks whether the inequality between nations also influences the rate at which nations replace fossil fuels. I use multilevel modeling techniques, World Bank data and data aggregated by Our World in Data for 146 nations from 1960–2021 to better understand the variation in national-level displacement of fossil fuels. Findings suggest there has been only partial displacement of fossil fuels at the global level during this period. In examining whether the variation in displacement of fossil fuels with alternative fuels at the national level can be described by lasting global inequality among nations, here measured by world-systems position, I find that semiperiphery nations displace fossil fuels at a higher rate on average as compared with core nations. This is further evidence for the importance of fossil fuel infrastructure and global inequality for implementing energy transitions to address climate change.

Keywords: Energy Transition, Multilevel Models, World-Systems, Displacement Paradox

Ongoing climate change is swiftly impacting the global environment along many dimensions, driven primarily by anthropogenic carbon dioxide emissions from burning fossil fuels. Debates about the nature and timing of the transition away from fossil fuels towards alternatives is varied and contentious; where technology, often presented as a natural outcome of affluence, is a contested tool for development and sustainability (Grubler, Wilson, and Nemet 2016; Smil 2016; Sovacool 2016; Sovacool and Geels 2016). Environmental sociology has often addressed the political economic drivers of increased greenhouse gas emissions (Rosa and Dietz 2012), adding to this wider discussion by highlighting paradoxes in technological transitions intended to combat climate change.

The purpose of this paper is to further describe displacement of fossil fuel generated electricity by non-fossil fuel generation. Previous work suggests that novel fuels intended to replace more carbon-intensive fuels do not do so proportionally, and these patterns may be influenced by domestic inequality (York 2012; Greiner, York, and McGee 2018; McGee and Greiner 2018). Given the linked systems of oppression which influence the continuation of within-nation inequality, particularly economic inequality and inequality between nations, this paper extends discussions of the links between energy development and social inequality by examining how fuel use within nations varies by world-systems position (Alderson and Pandian 2018). "World-systems position" has been used to describe lasting historical inequality among nations and regions, which has been connected to disparities of the environmental impact of global production and economic growth (Bunker 1985; Jorgenson 2006; Rice 2007; Wallerstein 2004). My main research questions are, does the rate of displacement of fossil fuels by alternative fuels vary by nation? And if so, what is the influence of world-systems position on this variation?

This paper uses a multilevel model (MLM) with random slopes and unstructured covariance using World Bank Development Indicators and data aggregated by Our World in Data from 1960–2021 (WDI 2022; Ritchie et al. [2020] 2022). I find that overall, fossil fuels are only partially displaced by alternative fuels across nations. Using a cross-level interaction with Clark's (2012) world-systems position classification, I find that fossil fuels are only partially displaced by alternative energies in core and periphery nations. However, there is evidence that fossil fuels are displaced by alternatives in semiperiphery nations, possibly due to semiperiphery nations using alternative energies like hydroelectricity to expand domestic energy use and increase economic activity. These findings are consistent with previous research and further our understanding of the patterns of global movement towards renewable energies (York 2012). This suggests that core nations, though in a dominant economic position at the expense of the wellbeing and environment of other nations, are not sole leaders in replacing fossil fuels with alternative energies. This paper expands upon the evidence of a displacement paradox, where novel technologies intended to have fewer environmental impacts often do not in fact replace higher impact technologies, but rather expand total consumption as additional technologies (York 2004, 2017; McGee 2015; York and Bell 2019).

Explanations for these findings either suggest why there *is* some estimated displacement in semiperiphery nations and why there *is not* some estimated displacement found in core or periphery nations. Domestic elites in semiperiphery nations may be promoting economic and energy development in opposition to the core rather than in alignment with the core in a form of resource nationalism. Large hydroelectric projects prevalent in some semiperiphery nations may be an example of this phenomenon. Path dependency, additions of renewable energy capacity replacing retired nuclear capacity rather than fossil fuels, and alternative energies like ethanol that are closely tied to fossil fuel use may all be explanations for a lack of evidence for average displacement in either core or periphery nations. Further research could clarify the mechanisms driving this pattern, as well as bring closer attention to periphery nations, here indistinguishable from core nations in terms of displacement rate. Critically, the drivers of between-nation inequality as measured by world-systems position likely overlap with drivers of expanded energy use displayed by the displacement paradox, thus further case study work is needed to continue to illuminate these historical connections.

Economic Growth, Modernization, and Energy Transition

At the intersection of environmental sociology and sociology of development is the question of whether affluence alone can lead to better environmental outcomes without further restructuring of our economic system or explicit and purposeful suppression of the causes of environmental harms. A better understanding of the dynamics of increased energy use and diversification of fuels will aid in understanding development in the time of climate crisis (York 2016). To appropriately describe the dynamics of the steep diversification of fuels since 1960, I examine below two distinct perspectives on technological development as well as existing research on the relationship between socioeconomic indicators and the effective implementation of new energy technologies.

Ecological modernization proponents argue ecological rationalization of social institutions will lead to reduced environmental impacts, and they demonstrate this through specific case studies of environmentally reflexive institutions. We are assured that while these shifts are not yet seen more broadly across nations or even across institutions, they mark a potential or perhaps underlying transition to more ecologically rational institutions (Mol and Spaargaren 2000). Sustainable production and consumption are framed as a luxury naturally developed with increased modernization leading to a dematerialized society. Closely related is the environmental Kuznets curve (EKC) which asserts that as GDP increases, environmental degradation will increase only to a certain point of affluence, then begin to decline to create an inverted U shape relationship between GDP and environmental degradation (Panayotou, Peterson, and Sachs 2000; Shahbaz 2013). Thus, at a certain point of affluence, nations will turn to the relative luxury of environmental sustainability and develop dematerialized economic growth. Both EM and EKC imply that new technology is developed at the correct point of affluence as a rational response to a stated need. In the context of transitions away from fossil fuels, this suggests that more affluent nations will be replacing fossil fuels at a greater rate than less affluent nations.

In contrast, a treadmill of production (ToP) perspective presents a different theory of technological change with respect to the environment. ToP suggests that in the context of the monopoly capitalist system, expanded production leads to the reinvestment of profit due to gains from economies of scale and increased industrial efficiency, leading to the increase in the scale of environmental degradation through environmental "withdrawals" (i.e., natural resources) and "additions" (i.e., waste) (Schnaiberg 1980). Profits are often reinvested in technological change, which increases the capitalization of production, in turn increasing the "productivity of labor" (Schnaiberg 1980: 228) and driving the treadmill to ever accelerated revolutions. The investment in technology, as a sunk cost, encourages further investment in these production pathways (Gould, Pellow, and Schnaiberg 2004). Thus, technology is a product of the production process in a cyclical sense, rather than as a product of affluence, political need or readiness.

Previous research has examined socioeconomic dynamics in the implementation of new energies. National energy history, including the level of historical reliance on fossil fuels, influences a nation's ability to grow renewable energies (Gellert and Ciccantell 2020; Hao and Shao 2021). For example, nations which have heavily invested in fossil fuel infrastructure like pipelines or extraction are less likely to move away from fossil fuels due to sunk costs of their investment; this concept is often termed path dependency. The effect of renewables on emissions may also fluctuate with time, possibly as new infrastructure takes hold or as global energy markets shift (Thombs 2018). There may be a threshold in the proportion of national energy use from renewables that needs to be achieved before renewables have a mitigating effect on carbon emissions (Chiu and Chang 2009). In asking whether increasing renewable energy generation decouples economic growth and carbon emissions, researchers have found mixed results which suggest different nations apply alternative fuel technology differently. Renewables may have their greatest mitigating effect on CO_2 emissions in low-income nations (Thombs 2017). One mechanism to explain this relationship is that renewables are replacing nuclear energy rather than fossil fuels in affluent nations moving away from nuclear energy (York and McGee 2017).

Energy Transitions Over Time

In this paper, alternative fuels include all non-fossil fuels: hydro, nuclear, biofuel (including waste and ethanol), and renewables such as solar, wind, and geothermal. Each of these alternatives to fossil fuels has specific material and political economic features which influence their substitutability in replacing fossil fuels in electricity generation. I discuss these features in more detail below and in the Results section. While an emphasis on energy transitions in the context of climate change has dominated contemporary discussions of energy transition, attention to fuels as substitutes for each other has a longer history (e.g, Fouquet and Pearson 2012; Smil 2017). It has been commonly stated that globally, energy transitions have happened before as the global economy shifted dominant energy regimes (e.g., oil overtaking coal as the globally dominant fuel). While these shifts have been between various fossil fuels or smaller scale technologies, this history suggests that energy transitions are not just possible but somewhat common.

However, this has not necessarily been the case at an aggregate level. Previous research shows that when one looks at the absolute use of all fuels rather than percentages of total use, no fuel but nuclear has experienced any significant decline in absolute use, but rather incumbent fuels persist alongside them (York 2012; Gellert and Ciccantell 2020). For example, the use of coal globally has continued to grow even as oil is the most commonly used fuel globally. The displacement paradox suggests that the introduction of new materials or technologies intended as substitutes to incumbent technologies do not always act as 1:1 substitutes and can even expand total consumption of resources through various mechanisms (York 2006, 2017; McGee 2015; York and Bell 2019).

We might not always expect the introduction of alternatives to replace incumbent fossil fuels, particularly in the earliest time periods of the 1960s and 1970s, included in the analysis below. However, the 1960s–1970s saw a rapid expansion of hydroelectricity and some nuclear in the global North, as well as the dual movement of the exporting of engineering regimes and the rise of post-colonial political and infrastructural projects in the global South, which served to spread large-scale energy projects like hydroelectric dams globally (McCully 2001; Bunker and Ciccantell 2005). Hydroelectricity remains the most prominent low-carbon source of electricity in the world and is often framed as a utopian project of sovereignty and abundant, cheap electricity (McCully 2001; e.g., Norwood 1981). Nuclear power similarly had a utopian veneer of abundant and cheap energy, and often still does in the context of climate change (e.g., Qvist and Goldstein 2019). These utopian visions have remained salient as advocates for hydroelectricity and nuclear power reframe these energies in response to growing environmental concern in the last decades of the twentieth century. Therefore, examining the dynamics of energy transitions with respect to fossil fuels needs the wider view beginning in the 1960s and 1970s to establish a better understanding how the dynamics of energy transitions have changed historically, especially given the renewed urgency of an existential crisis beyond geopolitical power struggle.

World-Systems Position, Inequality, and Energy Transition

There is a growing emphasis on better understanding the dynamics of social inequality in implementing energy regimes, reflecting a broader move towards integrating understandings of social inequality and environmental degradation (Boyce 1994; Pellow and Nyseth Brehm 2013). For example, previous work has linked national-level energy use to within-nation economic and gender inequality (McGee and Greiner 2018, 2019; McGee et al. 2020; Ergas et al. 2021). The integration of nations in the global capitalist economy link within- and between-nation inequality (Alderson and Pandian 2018). Given these previous findings linking domestic inequality with alternative energy implementation, between-nation inequality merits further investigation with respect to the dynamics of energy transition. In this paper, I turn my attention to between-country inequality using a measure of world-systems position.

World-systems theory builds on dependency theory, suggesting a core-periphery structure of the world-economy[1] to describe the international division of labor as well as the unequal international distribution of surplus profits (Chase-Dunn 1989; Wallerstein 2000). The relationship

[1] World-economy is hyphenated, as is world-systems, to indicate that much like the world-system, there are world-economic systems which may not encompass the entire globe geographically but constitute a cohesive system.

of core-periphery is one of exploitation and mutual constitution—one cannot exist without the other.

The semiperiphery has been a cause for debate—is it simply a way to denote some halfway point in the continuum of global national hierarchy, or a distinct position with qualitative differences from periphery and core nations (see Babones 2005)? The semiperiphery is presented as an intermediate position, both exploited by the core and exploiters of the periphery, with a mixed function in the world-economy. Semiperiphery nations have been theorized to have internal tensions between domestic ruling classes, divided between those benefiting from relationships with the core and those opposed via nationalism to exploitation by the core (Terlouw 1993, 2002). One strategy for nationalism may include resource nationalism and efforts by elites to install energy capacity which does not rely on global commodity trading over time (Kaup and Gellert 2017). There is an implication of autocratic control or non-democratic decision making in this process, though some previous research suggests democracies are more likely to invest in pro-environmental fuels (Swyngedouw 2015; Ramalho, Sequeira, and Santos 2018). World-systems theory provides a framework to focus on the relationship between global processes and national-level outcomes and has been used to assess drivers of greenhouse gas (GHG) emissions, air pollution, deforestation, and other socioenvironmental outcomes (Burns, Davis, and Kick 1997; Roberts, Grimes, and Manale 2003; Jorgenson 2006; Grant, Jorgenson, and Longhofer 2018; Mejia 2020).

While much empirical research using world-systems theory has been historical case studies or national-level studies, there has been critical quantitative cross-national work as well. Snyder and Kick (1979) used network blockmodeling to present an empirical measurement of a world-systems structure by examining the connections between nations based on diplomat exchange, military interventions, trade flows, and treaty memberships. They found evidence for distinct groupings and presented a classification of nations based on 1960s data. Clark (2012) presents an updated and exclusively economic empirical measurement of the core - semiperiphery - periphery structure of the world-system, also using network blockmodeling of total international trade flows. They show the core as dense and interconnected, both among core nations and to the periphery. Peripheral nations are isolated and connected almost exclusively with core nations—this sparseness facilitates and reflects the relative power of the core in trade relationships. The semiperipheral nations occupy a middling structural position in these trade networks—less densely connected than core nations, but more interconnected than the periphery.

World-systems position can offer a testable dimension of geopolitical power and may be an important factor in understanding national fuel mixes in a hierarchical nation-state system. Previous research has demonstrated that world-systems position moderates the relationship between economic growth and environmental harm using a multilevel modeling structure (Greiner and McGee 2018; Greiner 2022). This is a step towards better understanding past relationships between alternative energies and fossil fuels, given the landscape of global inequality and the relationship between exploitation and energy development (Alderson and Pandian 2018; McGee and Greiner 2020).

There are limitations to using world-systems position, as measured by Clark (2012), as an indicator of inequality between nations in a quantitative study. First, it relies on trade centrality and thus only includes economic dimensions of power differentials between nations. However, political dimensions such as military power, past colonial relationships, international finance, and participation in international governance all are important dimensions of power at the global level and remain uncaptured by this specific measure, besides the ways that these dimensions are reflected in trade relationships. Second, world-systems theory itself pushes back against reifying the nation-state as the most important unit for thinking about the world-system—the complexity of the world-economy penetrates nation-states through commodity chain links and internal peripheries such that patterns of inequality may not affect every person or industry within a nation in equal ways. Keeping these limitations in mind, this study uses this classification of "world-systems position" in an exploratory sense to better understand an underexamined factor in global energy transition.

This paper takes another look at describing the patterns of displacement or lack of displacement of fossil fuels at the cross-national level. I use multilevel modeling (MLM) techniques to tease out the variation in national-level displacement of fossil fuels and try to characterize possible patterns in national displacement across nations using world-systems analysis. I ask first, is there variation in energy transition at the nation-state level? If so, can the variation in displacement of fossil fuels with alternative fuels at the national level be described by their position in the world-systems? I use "world-systems position" as a descriptor of nations because this classification indicates trade centrality, which is linked to economic history and position in global networks of power. This may be a useful measure to describe different rates of displacement of fossil fuels because fuel use is deeply tied to these historical global power networks (Angus 2016; Malm 2016).

Data and Methods

This paper uses a two-level multilevel model (MLM) with random slopes, a modeling structure uncommon in the quantitative cross-national human ecology literature. This is in part due to the differences in how random and fixed effects models estimate error terms, stemming from their respective approaches to addressing sampling—typically fixed effects are preferred to random effects for panel data of nations (Rabe-Hesketh and Skrondal 2021). The models presented in the Results section were also run using fixed-effects panel regression with robust standard errors, and the findings were substantively the same. I use a MLM structure here to leverage the parsing of variance made possible by this modeling structure. The models estimated below have a two-level hierarchical structure, where level 1 are annual observations and level 2 are nation-states (see Figure 1).

MLMs are advantageous as they are intended to account for clustering, in this case observations within nations, as well as allowing for detailed parsing of variance. Variance is parsed by clusters, such that within- and between-cluster error terms can be examined independently.

Therefore, MLMs allow for greater options in investigating attributes of clustering to describe by what characteristics clusters, in this case of nations, may differ. Random slope models allow for each nation to have its own estimated coefficients of select independent variables, here the displacement coefficient, described further below. By adding level 2 (time-invariant, country) variables and cross-level interactions, we can characterize the variance in those national-level predicted displacement coefficients by world-systems position.

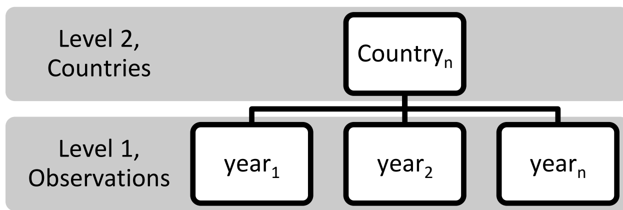


Figure 1: A Brief Sketch of the Hierarchical Structure of the Models Below[2]

Additionally, MLMs have been adopted in other social science research contexts to address issues of adjusting for numbers of observations within clusters, model parsimony, and ease of interpretation with respect to the interaction effects (Evans et al. 2018; Alvarez and Evans 2021). MLMs can be useful when addressing clusters with very different numbers of observations—given that data tracking for core nations, for example, has been more long-standing due to the international inequalities that are the very subject of this analysis, MLMs allow for the inclusion of nations with very few observations without presenting extreme estimates for these underrepresented groups, drawing their estimates towards the grand mean (Evans et al. 2018). Given the specific goal of this analysis to describe variation across nations grouped by world-systems position, I use MLM strategies. However, I would underscore that displacement coefficient estimates for nations, as described below, should not be over-interpreted and rather the analytical focus should be on the relative distribution of these scores and changes over time.

STATA was used for analysis using the command *mixed*. Data for this project was retrieved through the World Bank Development Indicators and data aggregated by Our World in Data for 1960–2021. The main dependent variable is fossil fuel-generated electricity in megawatts per capita. This is an aggregate of oil-, coal-, and natural gas-generated electricity. This dependent variable was calculated by multiplying the proportion of total electricity generation from fossil fuels by the total kilowatts of electricity generated per year, dividing by 1,000 to obtain megawatts, and dividing by total population for a per capita measure.

[2] Annual observations are clustered by nation.

I focus on electricity generation here, rather than all forms of energy use. Focusing on electricity excludes important economic sectors such as transportation and more traditional fuels and energy uses such as firewood. This paper takes a rather narrow look at the dynamics of substitution, which are most conceptually clear in the case of electricity generation. All fuels (including biofuels such as wood) are used to generate electricity in different places and times. The level of technological adaptation needed to generate electricity from different fuels, rather than to apply those fuels at the point of consumption in various activities, such as transportation, is quite different, meaning substitution of fuels to generate electricity is much easier than for other purposes. In other words, it is hard to substitute gasoline use for wind power without electricity as a common medium. Finally, given the contemporary emphasis on electrification as a strategy in and of itself to promote the substitution of fossil fuels, a better understanding of existing dynamics of the diversification of fuels for electricity generation can contribute to this discussion.

The main independent variable is all non-fossil fuel generation of electricity in megawatts per capita. This includes hydroelectricity, nuclear, wind, solar, and geothermal electricity generation by nation. This variable is generated by subtracting fossil fuel-generated electricity from total electricity production, dividing by 1,000 to again obtain megawatts, and dividing by total population for a per capita measure. The regression coefficient for this independent variable is the displacement coefficient, which is the metric of interest for this study. It describes the displacement, or replacement, rate of fossil fuels by alternative fuels holding other factors constant (York 2012).

Table 1: Descriptive Statistics by World-Systems Position[3]

Variables	**Overall**	**Core**	**Semiperiphery**	**Periphery**
Mean *GDP per capita (GDPPC) (2010 const. dollars)*	11,494 (15,439)	21,648 (18,396)	5,485 (6,222)	3,201 (6,360)
Minimum *GDP per capita (2010 const. dollars)*	156	295	401	156
Maximum *GDP per capita (2010 const. dollars)*	111,574	111,574	41,171	65,129
Mean *Fossil Fuel Electricity Generation per capita (megawatts)*	1.74 (2.62)	2.81 (2.54)	1.25 (2.96)	0.80 (1.88)
Min *Fossil Fuel Electricity Generation per capita (megawatts)*	0	0.01	0	0
Max *Fossil Fuel Electricity Generation per capita (megawatts)*	21.70	13.87	21.70	17.65
Groups *(nations)*	146	47	35	64
Observations *(nation-years)*	5,620	2,341	1,418	1,861

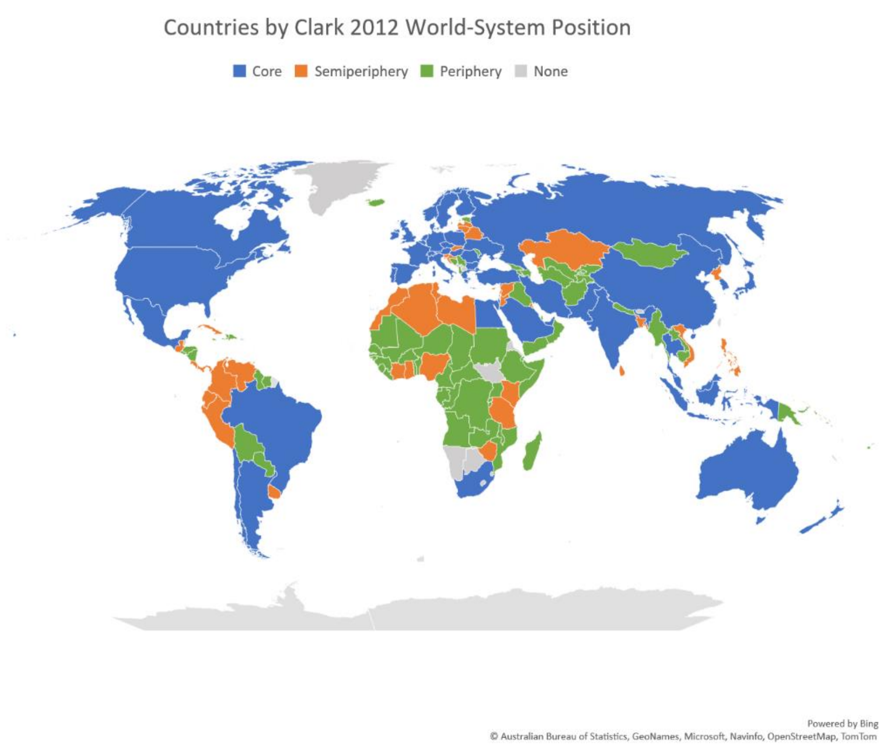
[3] Note: The standard deviation is in parentheses under each mean reported.

Displacement coefficients between 0 and -1 signify some level of displacement of fossil fuels with alternatives. For example, if the coefficient was -0.5, then it would take 2 megawatts per capita of alternative electricity generation to replace 1 megawatt per capita of fossil fuel electricity generation. If the coefficient is zero, this would indicate that alternative energies are added to total electricity generation on top of fossil fuels. Alternative electricity generation will also be the random slope variable, allowing for each nation to have a unique predicted displacement coefficient.

The controls for the full models use conventional controls in other human ecology and cross-national environmental sociology work on the drivers of CO_2 emissions: GDP per capita (in constant 2015 USD), percent of population in urban centers, and age dependency ratio (ratio of dependents to working age population) (Jorgenson et al. 2019). Quadratic terms are included for per capita GDP and urbanization to allow for nonlinear relationships.

Sensitivity checks were used to see if the substantive findings were consistent across smaller samples of the data. The sample was split at the median GDP per capita, and both analyses presented similar substantive results. The data used in the final modeling sequence does not include nations with populations smaller than one million.

Figure 2: Countries by Clark (2012) World-Systems Position



Source: Australian Bureau of Statistics

I use the world-systems classification system noted below. Due to missing data and available world-systems classification information, there are 146 nations included in the full model. Country classifications are displayed in Figure 2 and listed by country name in Table 2.

Table 2: World-Systems Position Measure National Classifications (Clark 2012)

Core (47)	Semiperiphery (39)	Periphery (62)
Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, South Korea, Malaysia, Mexico, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Saudi Arabia, Singapore, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, Ukraine, UAE, United Kingdom, United States	Algeria, Bahrain, Bangladesh, Belarus, Colombia, Costa Rica, Cote d'Ivoire, Croatia, Cuba, Cyprus, Iraq, Israel, Kenya, Kuwait, Ecuador, Ghana, Guatemala, Jordan, Kazakhstan, Kenya, Kuwait, Latvia, Lebanon, Libya, Lithuania, Morocco, Nigeria, Panama, Peru, Philippines, Slovak Republic, Slovenia, Sri Lanka, Syria, Tanzania, Tunisia, Uruguay, Vietnam, Zimbabwe	Afghanistan, Albania, Angola, Armenia, Azerbaijan, Benin, Bolivia, Bosnia and Herzegovina, Burkina Faso, Burundi, Cambodia, Cameroon, Central African Republic, Congo (Dem. Rep.), Congo (Rep.), Costa Rica, Dominican Republic, El Salvador, Equatorial Guinea, Estonia, Ethiopia, Gab on, Gambia, Georgia, Guinea, Guinea-Bissau, Haiti, Honduras, Iraq, Jamaica, Kyrgyz Republic, Laos, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Moldova, Mongolia, Mozambique, Myanmar, Nepal, Nicaragua, Niger, Oman, Papua New Guinea, Paraguay, Qatar, Rwanda, Senegal, Serbia, Sierra Leone, Somalia, Sudan, Togo, Trinidad and Tobago, Turkmenistan, Uganda, Uzbekistan, Yemen, Zambia

The equation for Model 3, the model of interest and a random slope cross-level interaction model with unstructured covariance, is as follows:

$$\begin{aligned} ffmw_{ti} = \beta_0 &+ \beta_1(alternatives_{ti}) + \beta_2(gdppc_{ti}) + \beta_3(gdppc_{ti}^2) + \beta_4(urban_{ti}) \\ &+ \beta_5(urban_{ti}^2) + \beta_6(agedep_{ti}) + \beta_7(semiperiphery_i) + \beta_8(periphery_i) \\ &+ \beta_9(semiperiphery_i)(alternatives_{ti}) + \beta_{10}(periphery_i)(alternatives_{ti}) \\ &+ \mu_{0i} + \mu_{1i}(alternatives_{ti}) + e_{0ti} \end{aligned}$$

$$Level\ 2\text{: } \begin{bmatrix} \mu_{0i} \\ \mu_{1i} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma_{u0}^2 & \\ \sigma_{u0u1} & \sigma_{u1}^2 \end{bmatrix}\right)$$

$$Level\ 1\text{: } [e_{0ti}] \sim N(0, \sigma_{e0}^2)$$

In this model μ_{0i} represents the nation-specific error term for the random intercept; μ_{1i} represents the nation-specific error term for the random slope, here alternative electricity generation per capita; e_{0ti} represents the error term for observations within nations. The covariance term is σ_{u0u1}. The included variables are as follows: $ffmw_{ti}$ indicates fossil fuel electricity generation per capita; $alternatives_{ti}$ indicates non-fossil fuel electricity generation per capita; $gdppc$ indicates GDP per capita; $gdppc_{ti}^2$ indicates the quadratic term for GDP per capita; $urban_{ti}$ indicates urbanization as percent of total population living in an urban area; $urban_{ti}^2$ indicates the quadratic term for urbanization; $agedep_{ti}$ indicates the age dependency ratio measured as a ratio of working-age population to dependent population (below age 15 or above age 65). The last two lines of the above equation indicate the distribution of error terms at each level, level 1 being the nation-year (within-nation variance), and level 2 being nations (between-nation variance).

From the above equation, nation-specific estimates of displacement can be found as follows:

$$\beta_1 + \beta_{10}(semiperiphery_i) + \beta_{11}(periphery_i) + \mu_{1i}$$

Given that world-systems position is a categorical variable, the precision weighted grand mean for core nations can be found as β_1, semiperiphery nations as $\beta_1 + \beta_9$, and periphery nations as $\beta_1 + \beta_{10}$. These are means across each world-systems position, weighted by the number of observations available within each nation. For national level estimates within each category, I add the random slope, country-specific error term μ_{1i}.

Results and Discussion

Results are displayed in Table 3. Model 1 looks at overall displacement across the full dataset, without restricting observations to those nations with a specified world-systems position.

I conducted a likelihood-ratio test against random intercept and random slope with structured covariance which suggested including unstructured covariance provided for a better model fit. Model 1's inclusion of unstructured covariance (σ_{u0u1}), where the slope and intercept are allowed to covary should that allow for a "better" fit model, suggests that nations converge at some level of fossil fuel electricity generation per capita at higher levels of alternative electricity generation, before perhaps diverging again. The clearest finding associated with unstructured covariance here is that there is a relationship between the displacement coefficient and the amount of fossil fuels used to generate electricity per capita when alternative fuel use is at zero. This may be consistent with path dependency, where greater investment in fossil fuel use within a nation may systematically structure national-level displacement of those fossil fuels by alternatives.

In Model 1, the displacement coefficient is less than zero though greater than negative one, suggesting there is partial displacement across all nations during this time period, on average.

Table 3: Results

Variables	**Model 1**	**Model 2**	**Model 3**
Level 1 Variables			
Displacement Coefficient	-0.79***	-0.77***	-0.38
Alternative Electricity Generation (MW per capita)	(0.18)	(0.18)	(0.26)
GDP per capita	2.17 $x10^{-4}$*** (4.96$x10^{-6}$)	2.18 $x10^{-4}$*** (4.98$x10^{-6}$)	2.18 $x10^{-4}$*** (4.98$x10^{-6}$)
GDP per capita quadratic	-1.84 $x10^{-9}$*** (5.21 $x10^{-11}$)	-1.85 $x10^{-9}$*** (5.22 $x10^{-11}$)	-1.85 $x10^{-9}$*** (5.22 $x10^{-11}$)
Urbanization	-0.09*** (0.01)	-0.09*** (5.30 $x10^{-3}$)	-0.09*** (5.29 $x10^{-3}$)
Urbanization quadratic	1.05 $x10^{-3}$*** (4.92 $x10^{-5}$)	1.05 $x10^{-3}$*** (4.92 $x10^{-5}$)	1.05 $x10^{-3}$*** (4.9 $x10^{-5}$)
Age Dependency Ratio	-0.03*** (1.23 $x10^{-3}$)	-0.03*** (1.23 $x10^{-3}$)	-0.03*** (1.23 $x10^{-3}$)
Level 2 Variables			
Core (reference)		-	-
Semiperiphery		0.34 (0.38)	0.73 (0.40)
Periphery		0.25 (0.33)	0.38 (0.28)
Ex-Soviet Nation	1.34*** (0.40)	1.24** (0.41)	1.31*** (0.41)
Cross-Level Interaction			
Core x Displacement Coefficient			-
Semiperiphery x Displacement Coefficient			-1.25** (0.44)
Periphery x Displacement Coefficient			-0.32 (0.41)
Constant	3.88*** (0.26)	3.69*** (0.33)	3.54*** (0.34)
Variance Terms			
σ^2_{e0}	0.3341974	0.3341796	0.3344327
σ^2_{u0}	3.177303	3.112305	3.090355
σ^2_{u1}	3.176875	3.150729	2.894727
σ_{u0u1}	-1.383533	-1.266949	-1.297836
Nation-years	5,620	5,620	5,620
Nations	146	146	146
****p<0.001; **p<0.01; *p<0.05*			

In Model 1, the estimated displacement coefficient suggests that across all nations, about 1.27 megawatts per capita alternative fuel generation would be needed to displace 1 megawatt per capita fossil fuel generation, on average.

Model 2 adds a level 2 (country-level) variable, world-systems position, to the random slope unstructured covariance model. Neither semiperiphery nor periphery coefficients are found to be significant at an 0.05 level, suggesting that nations across world-systems positions do not have a different overall average fossil fuel electricity generation per capita when fossil fuels are the only kinds of fuels used within nations. The displacement coefficient across all nations is once again significant at a 0.001 alpha-level; about 1.30 megawatts per capita alternative fuel generation would be needed to displace 1 megawatt per capita fossil fuel generation.

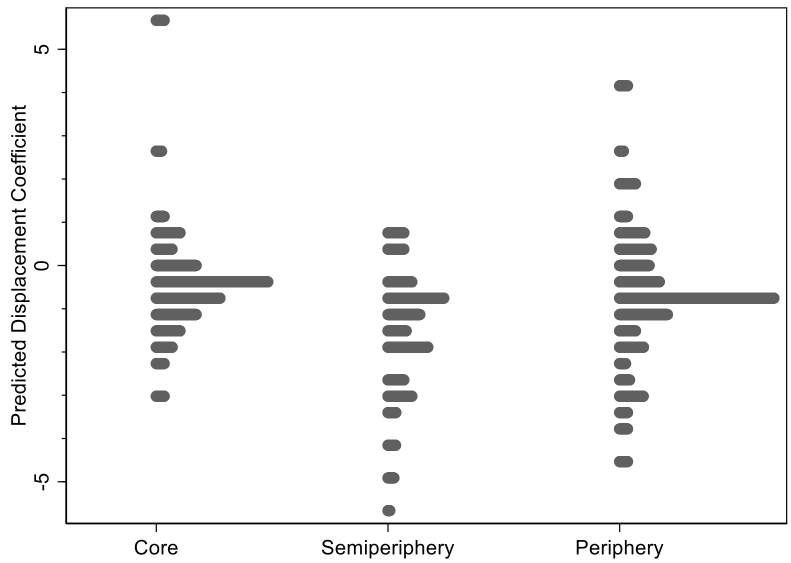
Model 3 adds a cross-level interaction effect between world-systems classification and the displacement coefficient, allowing each world-systems group to have a group average displacement rate. I conducted a likelihood ratio test between Models 2 and 3, the addition of the cross-level interaction provided for a better fit model.

Model 3 suggests that the semiperiphery has a statistically significant displacement coefficient distinct from the core on average, where fossil fuels in electricity generation are being displaced in semiperiphery nations by alternative fuels at a greater rate than in the core. The estimated displacement coefficient across semiperiphery nations is -1.25, suggesting alternatives replace fossil fuels in semiperiphery nations near a 1:1 ratio during this period. Meanwhile, periphery nations are not discernably different from core nations based on statistical significance, suggesting that periphery nations also only partially displace fossil fuels. Core nations have an estimated displacement coefficient of -.38, meaning about 2.63 megawatts per capita alternative fuel generation would be needed to displace 1 megawatt per capita fossil fuel generation in core nations, on average. This is lower than the estimated displacement rate across all nations in Model 1.

Figure 3 illustrates the distribution of predicted displacement coefficient (see equation above) of observations within each world-systems position. This figure shows the distribution for semiperiphery nation-years is set below (more negative) than core and periphery nation-years. However, there are nation-years in both the core and periphery with an estimated displacement coefficient around -1, suggesting that there are places and times where fossil fuels are being displaced 1:1 within these categories. Further parsing of national characteristics in future research may serve to explain some of this variation.

The greater displacement estimated for semiperiphery nations has several possible explanations. One may be path dependency—core nations have longer histories of and greater dependence on fossil fuels, while semiperiphery nations have laid down and continue to lay down electricity infrastructure later in time than core nations, and sometimes without early dependence on fossil fuels. Periphery nations may have similar pathways as the core due to being in more intensely exploitative economic relationships with the core than semiperiphery nations experience (Terlouw 2002). Peripheral nations experience a similar lock-in through exploitation and reliance on extractive industries flowing towards the core and semiperiphery, which prunes energy development pathways available to periphery nations (Bunker 1985). As a system of exploitation, the capitalist world-system consists of extractive relationships, originally articulated as predominantly between the core and periphery. Given the reliance on fossil fuels in the core, these extractive relationships are deeply permeated by fossil capitalism and the concomitant infrastructures and technologies endemic to fossil capitalism. Therefore, the periphery experiences underdevelopment, which raises the barriers to developing alternatives to a fossil fuel-based economy.

Figure 3: Dotplot Distribution of Predicted Displacement Coefficient by World-Systems Position, Based on Model 3.



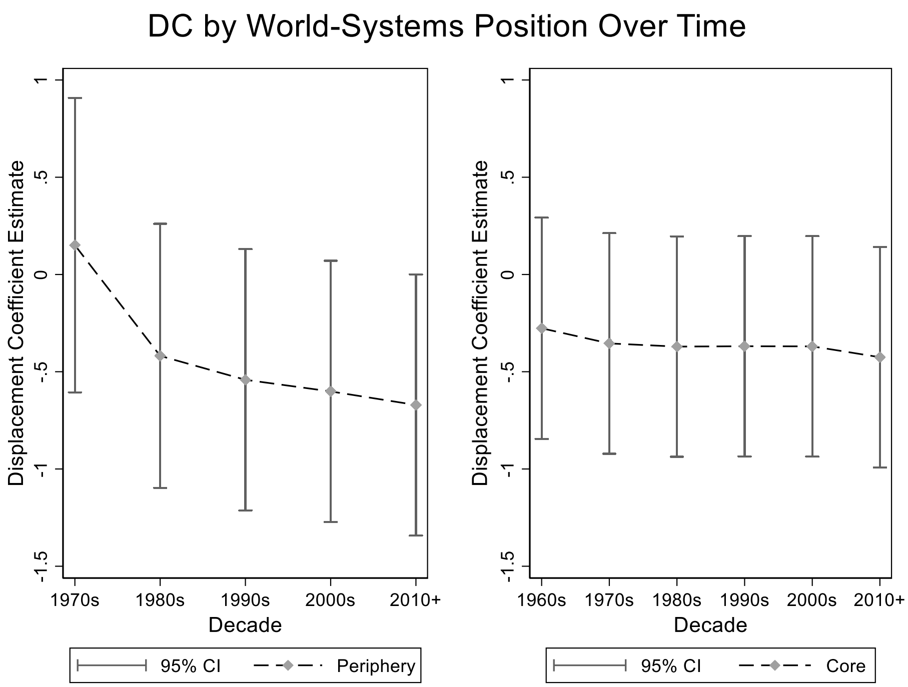
This is also consistent with some work on unequal ecological exchange (UEE), which argues that there are nations in deeply unbalanced trade and ecological relationships with economically powerful nations (Bunker 1985; Jorgenson 2006; Gellert, Frey, and Dahms 2017). The role of the semiperiphery and intermediary nations in general as both exploiters and exploited in the context of international trade has been a topic of debate within UEE research (e.g., Theis 2021). Given that the Clark (2012) world-systems measurement is reliant on trade relationships and indicates relative trade integration of nations as a system of classification, this connection seems an important consideration in the development of diversified fuel use.

Returning to the variation in domestic elites based on world-systems position may provide further explanation of displacement described here in the semiperiphery. The semiperiphery has been theorized as having a division in domestic elites between those whose interests, like most elites in the periphery, align with the core, and those elites whose interests lie in domestic development in an effort to disengage with an exploitative relationship with the core (Terlouw 1993, 2002). It may be that elites aligned with domestic interests have been successful, at least in some semiperiphery nations, in disengaging with core-dominated fossil economy through domestic projects. Given the expense and disruption of large energy projects like large hydroelectric projects, the involvement of the state and domestic elites is necessary and can be observed in many nations categorized as semiperiphery in this analysis in Eastern Europe and

Central and South America (e.g., Duarte-Abadía, Boelens, and Roa-Avendaño 2015; Martínez and Castillo 2016; Kappeler 2017). This explanation does not necessarily mean that the resulting energy resource nationalism will necessarily result in pro-environmental outcomes (e.g., Kaup and Gellert 2017; Shriver, Longo, and Adams 2020), but low-carbon energy resource nationalism may stand out when looking at the semiperiphery in aggregate.

Finally, another possible explanation for the disparity between world-systems positions is that some nations may be displacing alternative fuels, like nuclear, with newer alternative fuels seen as cleaner options (i.e., wind, solar) (York and McGee 2017; Greiner, York, and McGee 2022). This would also include biofuels, which include traditional fuels like wood. However, since this particular model is examining electricity generation, direct use of traditional fuels for activities such as cooking or heating will not be captured by this analysis. To what extent wood and other biofuels are being used to generate electricity, there may be a similar dynamic as with nuclear power. The replacement of nuclear power with other alternatives is a phenomenon generally associated with core nations such as Germany, which may explain the lack of displacement seen in core nations overall (Greiner et al. 2022).

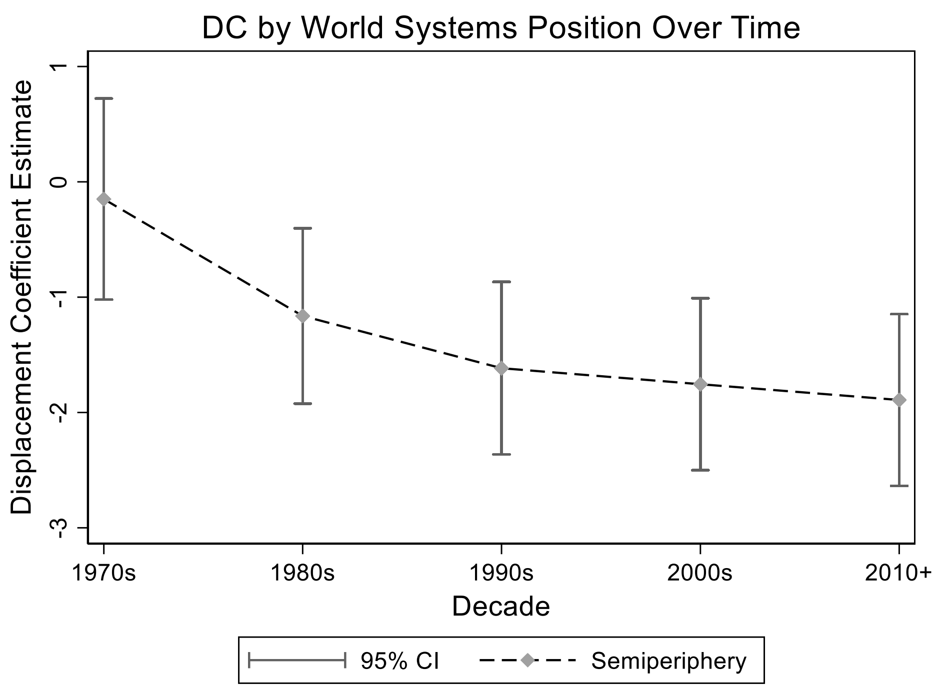
Figure 4: The Estimated Displacement Coefficient for Periphery and Core Nations Respectively with 95 Percent Confidence Intervals.



The Confidence Intervals Overlap, Indicating no Statistically Significant Change Across Time Within Each World-Systems Position, and No Statistically Significant Difference Between Core and Periphery Estimates.

There is further the question of the recent development of renewable energy, particularly hydroelectricity, solar, and wind in the past decade or two. Some might point to the drop in the price of solar as an indication of increased solar development and thus energy transition. However, the displacement paradox would suggest that the introduction of affordable alternatives does not always lead to the movement away from the original resource (York 2012, 2017; McGee 2017). While the estimate over the time period of available data across all nations and for core and periphery nations only shows partial displacement, perhaps there is improvement over the past decade or two. Was there a change in the estimated displacement coefficient over this time period? Below I offer a brief supplemental analysis addressing this question.

Figure 5: Estimated Displacement Coefficient for the Semiperiphery Over Time With 95 Percent Confidence Intervals.



The Estimates for the 1970s and 2010s Have a Statistically Significant Difference, Indicating Increasing Displacement Over Time in Semiperiphery Nations on Average.

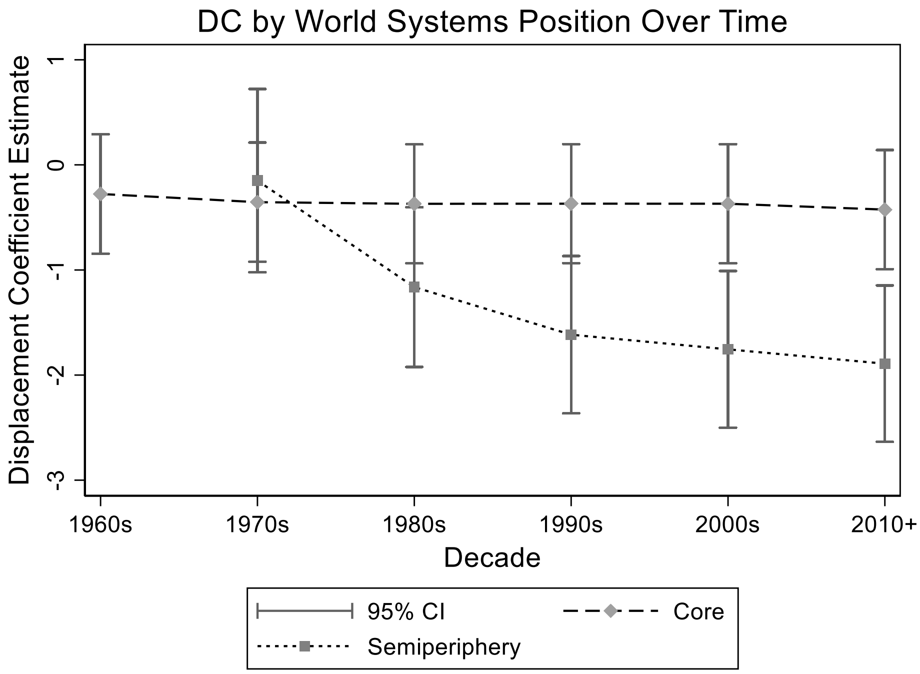
Figure 4 presents key results from this supplementary analysis, identical to Model 3 but with an added interaction with decade to the cross-level interaction between world-systems position and alternative electricity production. Figure 4 presents the estimated displacement coefficient for core and periphery nations each decade included in the analysis, with 95 percent confidence intervals. The confidence intervals overlap, both between core and periphery and across the time periods for each. Therefore, there is no evidence that the average displacement rate for core or periphery nations has changed over time in a statistically significant way. Additionally, there remains no statistically significant difference between core and periphery nations.

Figure 5 presents the displacement coefficient estimate for semiperiphery countries by decade with 95 percent confidence intervals. The confidence intervals for the 1970s and the 2010s (which includes 2020 and 2021) do not overlap, suggesting that there is some evidence that there is greater displacement in semiperiphery nations in the last decade than in the 1970s. This demonstrates some amount of change in semiperiphery nations, unlike core and periphery nations. This is inconsistent with the ideas of ecological modernization where the wealthiest of nations will implement pro-environmental technologies first.

Figure 6 presents the estimated displacement coefficient for semiperiphery and core nations over time with 95 percent confidence intervals. The confidence intervals overlap from the 1970s, 1980s, and 1990s, but begin to diverge in the 2000s. This suggests that semiperipheral nations were indistinguishable from core nations in a statistically significant sense until the 2000s. Though the investment in renewable energies like wind and solar began in earnest in the 2000s, there isn't evidence in this particular analysis that the core has employed these investments to reduce fossil fuel use.

The results of this supplementary analysis suggest that there is no evidence of change in displacement since the 1960s in core or periphery nations. Given that the 1960s were before the Paris Agreement (2015), Kyoto Protocol (1997), or the UN Framework Convention on Climate Change (1992), this lack of change is particularly alarming (Strandsbjerg Tristan Pedersen et al. 2021). The change in estimated displacement in semiperiphery countries aligns with the global boom in hydroelectricity construction of the 1980s and 1990s, including many projects funded by the World Bank and massive state investment (McCully 2001).

Figure 6: Estimated Displacement Coefficient for Core and Semiperiphery Nations. The Two World-Systems Positions Diverge Beginning in the 2000s.



Conclusion

These results present some evidence in contradiction with research suggesting core nations invested in renewable and low-carbon energies are replacing fossil fuels with these alternatives. It pushes us to look further into the conditions under which nations are able to effectively reduce their use of fossil fuels in favor of alternatives. For example, though Germany has developed an extensive transition program with *Energiewende*, this growth in renewable production has mostly replaced retired nuclear power production and coal mining in Germany has accelerated (Smil 2016; Greiner et al. 2022). The Fukashima-Daiichi disaster in 2011 and current fears for the safety of nuclear plants in Ukraine may extend the trend of new installation of renewables replacing politically unfavored nuclear energy, though the embeddedness of nuclear industry members in government and wider industry may limit the spread of the movement away from nuclear (Dreiling et al. 2019).

There are a few mechanisms which may contribute to this relationship. First, the economic inequality between nations is found to be associated with some level of domestic inequality (Alderson and Pandian 2018). World-systems theory suggests that this relationship is not just in the sense that nations at different levels of development have a corresponding or linear relationship with domestic inequality (i.e., less-developed nations are more unequal domestically, or vice versa, and will become more equal with development). Rather, as the whole of the world-system is the appropriate unit of analysis, domestic income inequality in one nation cannot be independent of domestic income inequality in another nation, either through commodity chain links, historical relationships, or economic embeddedness (Mahutga, Kwon, and Grainger 2011).

Second, there may be an amount of resource nationalism motivating the investment in alternatives which nations may use to disengage from the fossil fuel commodity trade and protect or grow national sovereignty (Kaup and Gellert 2017). Semiperipheral nations include many nations invested in hydroelectricity and other large alternative energy projects to grow electricity generation capacity without necessarily increasing fossil fuel use (e.g., Martínez and Castillo 2016; Kappeler 2017; Israel and Herrera 2020). Given the semiperiphery is conceptualized as nations which often have tensions between domestic elite who either align with core nations or push against them through nationalist policies, resource nationalism may be one strategy of the latter group and lead to greater levels of displacement. This tension may not always lean towards movement away from fossil fuels, though that might be the case here (Sovacool et al. 2022).

This paper gives attention to the dynamics of geopolitical power and historical global inequalities in the structure of energy transitions. Though transitions are often treated as a technical problem with a solution rooted in entrepreneurship and capitalist innovation (Goldstein 2018), there are structural constraints and persistent contradictions which influence pathways towards averting climate catastrophe.

Limitations of this study include data availability and the constraints of world-systems classifications. Testing other dimensions of global inequality unbounded by this limitation would provide a broader view of the relationship between structural inequality and energy transitions. Future research can deepen this thread by investigating further dimensions of geopolitical power, including perhaps colonial history, domestic inequality, and specific trade relationships. This quantitative work can serve as support alongside case studies and detailed qualitative work to further describe the influence of global inequality in systemic change, particularly in the crucial case of eliminating fossil fuel use.

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