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LETTER

The effects of economic and political integration on power plants' carbon emissions in the post-soviet transition nations

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Abstract

The combustion of fossil fuels for electricity generation, which accounts for a significant share of the world's CO_2 emissions, varies by macro-regional context. Here we use multilevel regression modeling techniques to analyze CO_2 emissions levels in the year 2009 for 1360 fossil-fuel power plants in the 25 post-Soviet transition nations in Central and Eastern Europe and Eurasia. We find that various facility-level factors are positively associated with plant-level emissions, including plant size, age, heat rate, capacity utilization rate, and coal as the primary fuel source. Results further indicate that plant-level emissions are lower, on average, in the transition nations that joined the European Union (EU), whose market reforms and environmental directives are relevant for emissions reductions. These negative associations between plant-level emissions and EU accession are larger for the nations that joined the EU in 2004 relative to those that joined in 2007. The findings also suggest that export-oriented development is positively associated with plant-level CO_2 emissions in the transition nations. Our results highlight the importance in macro-regional assessments of the conjoint effects of political and economic integration for facility-level emissions.

Introduction

Recent estimates suggest that the combustion of fossil fuels for the production of electricity accounts for nearly a fourth of global anthropogenic CO_2 emissions [1]. Emissions from the electricity generation sector could increase substantially in coming decades [2], given the growing energy demands and concomitant increases in the number of power plants throughout the world, especially in nations where fossil-fuel burning power plants account for a large proportion of the electricity generation sector [3]. And more broadly, analyses suggest that for the majority of the world's nations, growth in the use of renewable forms of energy has been unsuccessful so far in adequately 'displacing' fossil-fuel energy consumption [4].

With these factors in mind, an emerging body of research on fossil-fuel power plants seeks to identify how facility-level characteristics and broader contextual factors, such as national development, political circumstances and openness to the global economy, are associated with CO_2 emissions at the plant level. Many of these studies involve the analysis of large datasets of fossil-fuel burning power plants in nations throughout the world [5–7], while some instead focus on plants within just one nation, such as the United States [8–10].

Analyses of power plants in nations throughout the world provide an important lens for assessing relatively broad-based socioenvironmental relationships [6], while studies within one nation allow for more nuanced assessments of sub-national conditions

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that might influence plant-level emissions [8, 11, 12]. As important, we suggest, is a type of middle-level approach that is generally absent so far [13, 14], where studies are conducted of CO_2 emissions from plants within a macro-region that might consist of multiple nations that share similar sociohistorical characteristics. Country-level analyses of various human drivers of greenhouse gas emissions and other environmental outcomes have highlighted notable macro-regional differences [15–18]. Further, sustainability scientists have argued that such regionally-oriented research could aid in the creation of more effective climate change mitigation approaches, and therefore should be more prevalent in the synthesis reports and other activities of scientific bodies and policy organizations [19].

One such region that has been the focus of socioenvironmental research in recent years is the 25 'transition' nations located in Central and Eastern Europe and Eurasia. Subsequent to the collapse of the Soviet Union, in the early 1990s these countries began transitioning away from centrally planned economies with few connections to the global economy [20–22]. The recent studies on socioenvironmental relationships in these transition nations largely focus on how economic and demographic conditions influence country-level outcomes, including national CO_2 emissions. Consistent with cross-national studies on large samples of nations throughout the world [23, 24], population size and economic development are both found to increase national-level emissions in the transition nations [25, 27], while world-economic integration, such as increased exports, has been found to be associated with higher levels of CO_2 emissions in these nations as well [28, 29]. Public opinion research suggests that on average, individuals in the transition nations express higher levels of environmental concern than individuals in other regions of the world, and such concerns could be partly resulting from the unintended environmental problems associated with energy-intensive, export-oriented development [30].

With few exceptions (i.e. Azerbaijan, Moldova, Tajikistan, Uzbekistan) these nations have all increased their per person electricity consumption in recent years as they pursue various pathways of development to enhance their collective human well-being [31–33]. According to the World Bank (http://databank.worldbank.org/data/home.aspx, accessed July 21, 2016), average electric power consumption in the 25 transition nations increased from 3169 kilowatt hours per capita in the year 2003 to 3648 kilowatt hours per capita in the year 2013 (the most recent year for which these data are currently available for all 25 nations), higher than the global averages of 2491 kilowatt hours per capita (in 2003) and 3104 kilowatt hours per capita (in 2013).

For many of these nations, the transition away from centrally planned economies was followed by accession into the European Union (EU). The Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, and Slovenia joined the EU in the year 2004, while Bulgaria and Romania joined in the year 2007. As of mid-2016, Albania and Macedonia are candidate countries for EU membership.

Prior to the post-communist transition, environmental policies in the region were relatively weak and pollution levels remained high [27, 34]. However, with EU accession, new Member States worked to harmonize national laws with existing EU environmental directives, and public officials, nongovernmental organizations, and energy policy consultants all played important roles in these efforts [35–37]. For example, a primary directive addressing CO_2 emissions was the establishment of the EU Emissions Trading System in 2005, followed by the 2009 package of EU climate and energy agreements, which set targets for greenhouse gas emissions.

In addition to the slate of environmental directives adopted by the new Member States, accession into the EU further opened up the new Member States' economies to global trade [33, 38], and higher levels of exports have been found to be associated with growth in national emissions in the transition nations due to the increased manufacture and production of goods destined for wealthier nations [28]. Nonetheless, given the scope of the constellation of EU environmental directives and policies related to climate change mitigation, energy efficiency, and other environmental sustainability concerns, we hypothesize that EU membership for transition nations should have an overall beneficial effect on lowering CO_2 emissions from fossil-fuel power plants within Member States. Thus, we expect plant-level emissions to be, *ceteris paribus*, lower in the transition nations that joined the EU than in those that did not. However, environmental policies are sometimes decoupled from environmental improvements on the ground [39], and in the case of EU accession, compliance would prove to be costly for the new Member States [35]. As a consequence, compliance with EU directives and significant environmental improvements were likely not immediate. Thus, we also expect plant-level emissions to be, on average, lower in the transition nations that joined the EU in 2004 relative to those that joined in 2007.

In this study, we use multilevel regression modeling techniques to analyze how facility-level characteristics and national-level factors are associated with CO_2 emissions levels for 1360 fossil-fuel power plants in the 25 transition nations in the year 2009, the most recent year in which these plant-level data are currently available. The facility-level characteristics include if the primary fuel source for the plant is coal relative to other fossil-fuels, plant size, plant age, capacity utilization rate, and heat rate. Consistent with past research on power plants [6, 8], we expect that plant-level CO_2 emissions will be positively associated with each of these characteristics. Many estimated

Table 1. Fossil-Fuel Power Plants in the 25 Transition Nations of Central and Eastern Europe and Eurasia, 2009.

Country	Number of Fossil-Fuel Power Plants	GDP Per Capita in Constant 2010 US Dollars	Population Size	Exports as Percent GDP
Albania	4	3928.341	2927519	29.601
Armenia	2	3054.826	2966108	15.474
Azerbaijan	16	5639.002	8947243	51.636
Belarus	31	5391.134	9507000	50.530
Bulgaria (Joined EU in 2007)	27	6794.657	7444443	42.415
Croatia	18	13707.935	4429078	34.523
Czech Republic (Joined EU in 2004)	73	19376.915	10443936	58.813
Estonia (Joined EU in 2004)	12	14283.454	1334515	60.805
Georgia	6	2753.546	3978000	29.739
Hungary (Joined EU in 2004)	66	12908.981	10022650	74.770
Kazakhstan	51	8573.773	16092701	41.838
Kyrgyz Republic	3	894.818	5383300	54.698
Latvia (Joined EU in 2004)	29	11533.606	2141669	42.603
Lithuania (Joined EU in 2004)	9	11550.569	3162916	51.939
Macedonia	6	4420.508	2058920	32.806
Moldova	13	1521.856	3565604	36.872
Poland (Joined EU in 2004)	286	12126.203	38151603	37.184
Romania (Joined EU in 2007)	52	8314.736	20367487	27.372
Russian Federation	528	10219.521	142785342	27.938
Slovakia (Joined EU in 2004)	36	15819.506	5386406	67.609
Slovenia (Joined EU in 2004)	23	23253.481	2039669	57.243
Tajikistan	1	714.477	7414960	15.146
Turkmenistan	10	4153.588	4978960	74.595
Ukraine	48	2834.343	46053300	46.375
Uzbekistan	10	1305.538	27767400	34.241

models also include plant-level CO_2 emissions in the year 2004 to account for the extent to which prior emissions levels influence their more recent CO_2 emissions levels [40].

In the analysis we include country-level measures that allow for assessing if EU membership, and duration of membership, might be associated with plant-level CO_2 emissions. As noted above, we anticipate that on average, emissions will be lower for fossil-fuel power plants in EU member transition nations than for plants in non-member transition nations, and that emissions in 2009 were likely lower, on average, for plants within transition nations that joined the EU in 2004 relative to plants in transition nations who joined the EU in 2007.

We also assess how national-level socioeconomic factors, which were found in prior research to increase country-level emissions for the transition nations, might be associated with plant-level CO_2 emissions [26, 27]. These national-level factors include level of economic development (measured as GDP per capita), total population size, and world-economic integration (measured as exports as a percent of total GDP, also referred to as export-oriented development). Prior research on fossil-fuel plants in nations throughout the world have also found some evidence indicating that population size and level of economic development influence plant-level emissions, with population size exhibiting a positive effect, and level of economic development exhibiting a negative effect [6, 7].

Methods

The sample

The analyzed sample consists of 1360 fossil-fuel power plants located within the 25 transition nations in Central and Eastern Europe and Eurasia. Table 1 lists the number of fossil-fuel power plants from our overall sample within each of the transition nations in the year 2009, if and when a nation joined the EU, and three country-level measures, which we describe below, that are included in the analysis. The average (mean) number of plants within each nation is 54.4, and ranges from a low of one plant in Tajikistan to a high of 528 plants in the Russian Federation. Poland has 286 plants, the second largest number of fossil-fuel plants in the transition nations, followed by the Czech Republic with 73 plants, Hungary with 66, and Romania with 52 plants. Among the bottom of the distribution, Tajikistan and Armenia have the least amount of plants (with 1 and 2, respectively), followed by Kyrgyz Republic with 3 plants, Albania with 4, and Georgia and Macedonia, both of which have 6 fossil-fuel plants within their borders.

Dependent variable

Our dependent variable is total pounds of CO_2 emitted by a plant in the year 2009, the most recent year for which these data are currently available. Because the CO_2 data are highly positively skewed, and consistent with past research on plant-level emissions [6, 8], we convert them into logarithmic form (base 10) for our statistical analysis. We obtained these data from the Center for Global Development's 'Carbon Monitoring for Action' (CARMA) database [41, 42], which is consistent with prior studies of plant-level emissions [5–7, 43–45]. CARMA assigns to each plant a unique Platts identification code, which enables researchers to obtain additional information gathered by Platts and other sources on characteristics of each plant.

Plant-level CO_2 emissions data are disclosed and publicly available for all fossil-fuel power plants in the United States as well as for the majority of plants in Canada, India, South Africa, and the European Union [42]. These publicly available data are in the CARMA database. For power plants where no public data are available, CARMA provides estimates for their emissions that are derived from statistical models fitted to the publicly available U.S. plant-level data. The estimated plant-level CO_2 emissions values = electricity generation * heat rate * CO_2 emission factor. For a more in-depth discussion of CARMA's estimation methodology, we refer readers to Ummel [42].

A comparison of the estimated values and the publicly available data for a sample of almost 3500 power plants, including approximately 800 plants with publicly available data from outside the United States [42], indicates that the CARMA estimates quite accurately capture broad differences among plants of various types and sizes (R^2 statistics over.90). And for any given plant in the CARMA database, it is estimated that the reported value is within 20 percent of the actual value in 75% of cases for annual CO_2 emissions [42].

As a validity check [7], we summed CARMA's plant-level emissions data for the fossil-fuel power plants in each of the 25 transition nations in Central and Eastern Europe and Eurasia, and then compared those values for each of the 25 nations with the International Energy Agency's (IEA) 2009 annual national measures of carbon dioxide emissions from fossil fuel combustion for the electivity production sector. These data are readily available in the 2011 online edition of the IEA Statistics' Report on CO_2 Emissions from Fuel Combustion. The Pearson's correlation for our summed measure of national CO_2 emissions from fossil-fuel power plants and the IEA's measure is 0.996 (N = 25, 0.001 level of statistical significance, two-tailed test). Nonetheless, it is important to acknowledge that much of CARMA's plant-level emissions data, particularly for facilities outside of the US, are estimates with some level of uncertainty and measurement error.

Level-one (facility-level) independent variables

In all models we include a dummy-coded measure for coal as the plant's primary fuel (coal = 1), which were obtained from Platts. The carbon content of coal varies by its moisture, but systematic information on the latter is not available for most plants, nor can it be readily estimated [6]. In an unreported sensitivity analysis, which we describe in the Results section, we also include a dummy-coded measure for natural gas as the plant's primary fuel. In models that include both the coal and natural gas dummy variables, liquid fossil-fuels as the plant's primary fuel is the reference category.

We include a measure of plant size, which specifically refers to full nameplate capacity in megawatt hours, and plant age, measured in years for the plant's oldest generator. We also include plant-level measures of capacity utilization rate (i.e. percent of potential output being produced) and heat rate of generation in terajoules per gigawatt hour (i.e. ratio of input fuel energy to output electrical energy). Heat rate is the inverse of a plant's thermal efficiency. Like the plant-level measures of primary fuel source, these data were obtained from Platts.

We note that electricity generation = plant size * capacity utilization rate, and electricity generation as well as heat rate are two of the factors used by CARMA when estimating CO_2 emissions values for plants that do not have publicly available emissions data [42]. As suggested by an anonymous reviewer, for heat rate, capacity utilization rate, and plant size, our multilevel model estimates are to some extent returning the regression model coefficients that went into CARMA's estimates of plant-level CO_2 emissions. Simply, one should fully expect that the coefficients derived from our multilevel models for each of these three measures will be positive and statistically significant. Nonetheless, with these caveats in mind, and consistent with other studies of plant-level emissions [6], we consider the inclusion of these particular level-one predictors to be important for purposes of reducing omitted variable bias, allowing for more valid coefficient estimates for the other independent variables included in the study.

In half of the ten estimated models we include total pounds of CO_2 emitted by a plant in the year 2004 (i.e. the lagged dependent variable, labeled 'lagged CO_2 emissions' in table 2) to account for the extent to which prior emissions influence current CO_2 emissions. These data are obtained from CARMA. Such an approach also allows us to partially capture other conditions from the past that might influence a plant's present emissions levels [40]. Like the 2009 measure, these 2004 emissions data are converted into logarithmic form (base 10) to minimize their skewness. For the models that include the lagged dependent variable, the overall sample size is restricted to 952 power plants, since 408 of the 1360 plants existing in 2009 did not exist in 2004.

Level-two (country-level) independent variables

In the first half of the estimated models, as a level-two predictor we employ a dummy-coded variable that indicates if a nation was a member of the European Union in 2009 (EU member = 1). In the second half of the estimated models we instead employ two dummy-coded variables that indicate if a nation joined the

Table 2. Multilevel Regression Models of CO_2 Emissions for 1360 Fossil-Fuel Power Plants in the 25 Transition Nations of Central and Eastern Europe and Eurasia, 2009.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10
Level-One Predictors										
Coal	.608***	.119***	.617***	.122***	.613***	.123***	.616***	.122***	.611***	.122***
	(.104)	(.048)	(.106)	(.050)	(.106)	(.049)	(.105)	(.049)	(.105)	(.049)
Plant Size	.001***	.001**	.001***	.001**	.001***	.001**	.001***	.001**	.001***	.001**
	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)	(.000)
Plant Age	.013***	.002**	.013***	.002**	.013***	.002**	.013***	.002**	.013***	.002**
	(.003)	(.001)	(.002)	(.001)	(.002)	(.001)	(.002)	(.001)	(.003)	(.001)
Capacity Utilization Rate	1.116***	.572***	1.123***	.572***	1.106***	.570***	1.124***	.572***	1.109***	.571***
	(.305)	(.151)	(.305)	(.151)	(.302)	(.149)	(.304)	(.151)	(.301)	(.149)
Heat Rate	.025**	.028***	.025**	.028***	.025**	.028***	.024**	.028***	.025**	.028***
	(.012)	(.009)	(.012)	(.009)	(.012)	(.009)	(.012)	(.010)	(.012)	(.009)
Lagged CO_2 Emissions (LG)		.838***		.838***		.837***		.838***		.837***
		(.070)		(.070)		(.070)		(.070)		(.070)
Level-Two Predictors										
EU Member			−.529***	−.139*	−.450**	−.189**				
			(.148)	(.088)	(.203)	(.104)				
Joined EU in 2004							−.625***	−.140*	−.820***	−.244*
							(.159)	(.107)	(.131)	(.158)
Joined EU in 2007							−.170***	−.134***	−.110	−.125**
							(.073)	(.046)	(.098)	(.062)
GDP Per Capita (LG)					−.334*	−.015			−.056	.017
					(.208)	(.099)			(.192)	(.113)
Population Size (LG)					.257*	−.005			.211*	−.012
					(.167)	(.078)			(.146)	(.070)
Exports as Percent GDP					.012***	.004**			.017***	.005**
					(.004)	(.002)			(.003)	(.002)
Constant	3.345***	.157	3.589***	.225	2.429**	.136	3.599***	.225	1.582*	.049
	(.225)	(.381)	(.204)	(.379)	(1.070)	(.776)	(.202)	(.381)	(1.029)	(.821)
Wald chi^2	454***	7340***	643***	8055***	789***	8849***	609***	8485***	799***	9030***
Number of Plants	1360	952	1360	952	1360	952	1360	952	1360	952
R^2	.472	.903	.568	.907	.575	.911	.583	.907	.606	.912

Notes: $^*p < .10$ $^{**}p < .05$ $^{***}p < .01$ (one-tailed tests); robust standard errors clustered by nation are in parentheses; LG denotes base 10 logarithmic form; R^2 statistics obtained using random effects model estimation techniques

European Union in the year 2004 (Joined EU in 2004 = 1) or in the year 2007 (Joined EU in 2007 = 1). For the 25 nations in the analysis, ten were members of the European Union in 2009, of which Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, and Slovenia joined in the year 2004, while Bulgaria and Romania joined in the year 2007.

In four of the estimated models we also include country-level measures of gross domestic product per capita (GDP per capita), total population size, and exports as a percent of total GDP as level-two predictors (all estimated for the year 2009). These data are obtained from the World Bank's online World Development Indicators database (http://databank.worldbank.org/, accessed April 14, 2016). The GDP per capita data, which are converted to logarithmic form (base 10) to minimize skewness, are measured in constant 2010 US dollars. The total population data, which are also converted to logarithmic form (base 10) to minimize skewness, are mid-year estimates and based on the de facto definition of population, which counts all residents regardless of legal status or citizenship. The exports data represent the value of all goods and other market services provided to the rest of the world as a percent of total GDP.

Univariate descriptive statistics and bivariate correlations for all variables included in the study are available from the lead author upon request.

Model estimation technique

We use the suite of 'mixed' commands in Stata software to estimate two-level random intercept models of plant-level CO_2 emissions [46–48]. Maximum likelihood estimation is employed to estimate the multilevel models, and for all models we estimate robust standard errors clustered by nation, which leads to relatively conservative tests of statistical significance [48]. A basic two-level random intercept model can be designated by the following [49, 50]:

$$y_{ij} = \beta_0 + \beta X_{ij} + \beta X_j + \mu_{0j} + \varepsilon_{ij}$$

The observation y_{ij} is for individual i (e.g. power plant) within cluster j (e.g. country), and the individuals (power plants) comprise the first level while the clusters (countries) comprise the second level of the model. β_0 represents the overall mean intercept, μ_{0j} represents the cluster-specific random intercept, βX_{ij} represents a vector of coefficients for level-one predictors, βX_j represents a vector of coefficients for level-two predictors, and ε_{ij} is the disturbance term.

The following equation is for the most fully saturated multilevel random intercept model (Model 10) reported in the Results section:

$$\begin{aligned} CO_{2ij} = \beta_0 + \beta COAL_{ij} + \beta SIZE_{ij} + \beta AGE_{ij} \\ + \beta CAPRATE_{ij} + \beta HEATRATE_{ij} \\ + \beta LAGCO_{2ij} + \beta EUMEMBER2004_j \\ + \beta EUMEMBER2007_j + \beta GDP_j \\ + \beta POPULATION_j + \beta EXPORTS_j \\ + \mu_{0j} + \varepsilon_{ij} \end{aligned}$$

where the dependent variable, CO_{2ij}, is plant-level CO_2 emissions, and the level-one predictors include coal as the primary fuel ($\beta COAL_{ij}$), plant size ($\beta SIZE_{ij}$), plant age (βAGE_{ij}), capacity utilization rate ($\beta CAPRATE_{ij}$), heat rate ($\beta HEATRATE_{ij}$), and lagged CO_2 emissions ($\beta LAGCO_{2ij}$). The level-two predictors include joined EU in 2004 ($\beta EUMEMBER2004_j$), joined EU in 2007 ($\beta EUMEMBER2007_j$), GDP per capita (βGDP_j), population size ($\beta POPULATION_j$), and exports as percent of GDP ($\beta EXPORTS_j$).

Given the small level-two sample size (i.e. 25 nations), in the reported model estimates we treat p-values of .10 or less as statistically significant. Following the suggestion of an anonymous reviewer and consistent with other multilevel studies of plant-level emissions [6], we report R^2 statistics for each model, which we estimated through the use of Stata's 'xtreg' group of commands for random effects models [48].

Results

The multilevel regression model estimates are reported in table 2. Model 1 consists of coal, plant size, plant age, capacity utilization rate, and heat rate. All five independent variables have positive and statistically significant effects on plant-level CO_2 emissions in 2009. These level-one predictors are included in every estimated model. Model 2 introduces the other level-one predictor, lagged CO_2 emissions. As expected, lagged CO_2 emissions has a positive effect on emissions in 2009, and the other five level-one predictors continue to exhibit positive effects on emissions. The effects of coal, plant age, and capacity utilization rate are reduced in magnitude with the inclusion of the lagged dependent variable, while the effect of heat rate slightly increases in magnitude. The remaining eight models, which include different combinations of level-two predictors, have the same patterned structure with the level-one predictors, where the odd-numbered models (Models 3, 5, 7, 9) include coal, plant size, plant age, capacity utilization rate, and heat rate, and the even-numbered models (Models 4, 6, 8, 10) also include lagged CO_2 emissions.

Models 3 and 4 introduce the measure for EU membership, while controlling for the level-one predictors. As a reminder, Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia were EU member nations in the year 2009. The estimated effect of EU membership on plant-level emissions is negative and statistically significant in both models, but smaller in magnitude in Model 4, which includes the lagged dependent variable. Overall, it appears that, on average, CO_2 emissions in 2009 were lower for fossil-fuel plants in EU member transition nations than for power plants in non-member transition nations.

GDP per capita, population size, and exports as percent of GDP are added to Models 5 and 6. The estimated effect of GDP per capita on plant-level CO_2 emissions is negative and statistically significant, while the estimated effects of population size and exports as percent of GDP are both positive and statistically significant in Model 5. However, with the inclusion of the lagged dependent variable in Model 6, the effects of GDP per capita and population size on plant-level emissions become nonsignificant. For these two models the effect of EU membership remains negative and statistically significant and smaller in magnitude when lagged CO_2 emissions is included as well.

Models 7 and 8 introduce the two more nuanced EU membership predictors: joined EU in 2004 (Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, and Slovenia) and joined EU in 2007 (Bulgaria and Romania). GDP per capita, population size, and exports as percent of GDP are included as well in Models 9 and 10. Across all four models, the estimated effect of joined EU in 2004 is negative and statistically significant and stronger in magnitude than the effect of joined EU in 2007, which, with the exception of Model 9, is also negative and statistically significant. Exports as a percent of GDP continues to have a positive effect on plant-level emissions, and the effect of population size is positive and statistically significant in Model 9, but becomes nonsignificant with the inclusion of lagged CO_2 emissions in Model 10. However, with the inclusion of the more nuanced EU membership measures, the estimated effect of GDP per capita is nonsignificant in both of these final models.

In an unreported sensitivity analysis we estimated multilevel models that also include country-level measures of urban population as a percent of total population, manufacturing as a percent of GDP, overall industrialization as a percent of GDP, and services as a percent of GDP. The effects of these additional level-two predictors on plant-level CO_2 emissions are all nonsignificant, and the estimated effects for the other predictors remain consistent with the findings reported in table 2. We also estimated sensitivity models that include a plant-level dummy-coded measure for natural gas as the primary fuel. In such models, which include both the dummy-coded measures for coal and for natural gas, liquid fossil-fuels as the plant-level primary fuel is the reference category. The estimated effect of coal remains positive and statistically significant, while the effect of natural gas is nonsignificant.

Following the suggestion of an anonymous reviewer, we estimated two additional series of multilevel models, each of which includes a country-level measure to account for climate-related conditions that could potentially influence electricity consumption and thus plant-level carbon emissions. The first series includes country-level heating degree days (HDD), a measure designed to reflect the demand for energy needed to heat a home or business to a human comfort level of 18 °C. The second series includes the midpoint latitude for each nation [7, 51], with the general assumption that since each nation in the analysis is north of the equator, higher values of (northern) latitude will be associated, in general, with colder climate conditions. We note that these two country-level measures are correlated at .886 for the 25 nations in the study. The estimated effect of both country-level climate measures on plant-level emissions are nonsignificant in all models, and the estimated effects for the other predictors remain entirely consistent with the results presented in table 2. Also at the advice of an anonymous reviewer, in additional sensitivity models we included a country-level measure of average electricity price [6], which yielded a nonsignificant effect while not substantively altering the estimated effects of the facility-level and country-level factors on plant-level emissions.

We have also estimated multilevel models for samples that systematically exclude the power plants within each of the twenty-five nations in the study. The results for all of the reduced samples are generally consistent with the reported findings for the full sample, suggesting that the analysis presented in table 2 is not overly influenced by nations with relatively large numbers of fossil-fuel power plants or those with small numbers of plants within their borders. There are two notable exceptions. First, the estimated effect of population size on plant-level CO_2 emissions becomes nonsignificant in all estimated models if the Russian Federation's 528 power plants are excluded. Second, the estimated effect of joining the EU in 2007 becomes nonsignificant or borderline statistically significant if either (1) the 27 power plants in Bulgaria or (2) the 52 power plants in Romania are excluded. This second exception is not surprising, since these are the only two transition nations that joined the EU in 2007.

Finally, we have also estimated models that include interactions for pairings of the level-one predictors and for pairings of the level-two predictors, as well as cross-level interactions between country-level and plant-level predictors. The estimated effects of all the interactions on plant-level CO_2 emissions are nonsignificant.

Discussion and conclusion

The 25 transition nations of Central and Eastern Europe and Eurasia provide a unique vista from which to examine the relationship between plant-level CO_2 emissions and both plant-level and national-level characteristics, as the development strategies taken by most countries in the region rapidly increased electricity consumption as they began transitioning away from centrally planned economies with limited connections to the world economy. Consistent with prior research, we found that facility-level measures such as plant size, plant age, capacity utilization, heat rate, and coal as the primary fuel source are all positively associated with plant-level emissions. Our findings further suggest that one development strategy in particular—export oriented development—might have been particularly consequential for CO_2 emissions: exports as a percent of GDP exhibits a positive association with plant-level emissions across all estimated models.

However, not all of these nations adopted the same political and economic strategies as they transitioned away from Soviet-era, centrally planned economies. For some, accession into the European Union introduced an extensive set of market and environmental reforms that shaped energy production and subsequent emissions. In terms of market reforms, the transition to a market economy upon accession into the EU led countries like Poland, Hungary, and the Czech Republic to privatize energy production and lift energy price subsidies, which incentivized energy providers and investors to pursue more efficient energy production [52]. As a consequence, energy intensities of the EU-member transition economies began to converge with other EU countries [52, 53].

In addition, accession into the EU introduced a host of environmental sustainability directives pertaining to energy efficiency, climate change mitigation, and other environmental concerns, such as the Accession Treaties of 2003, which consisted of greenhouse gas monitoring mechanisms associated with the Kyoto Protocol, and other directives that addressed greenhouse gas emissions from large facilities, including the Integrated Pollution Prevention and Control Directive (adopted in 1996 and codified in 2008), the Large Combustion Plant Directive (issued in 2001) and the National Emissions Ceiling Directive (originally agreed to in 2001). And although EU environmental directives have been unevenly implemented to some extent across Member States [54, 55], we found that transition nations that joined the EU had lower plant-level CO_2 emissions in 2009, *ceteris paribus*, than their non-EU counterparts in the region. We also found that the eight Member States that joined the EU in 2004 had, on average, lower plant-level emissions in 2009 than the two transition nations that joined the EU in the year 2007.

Our study is not without its limitations, such as those with CARMA's estimated data that we describe in the Methods section. We conclude by briefly highlighting two additional shortcomings. First, we are unable to ascertain which specific policies adopted in compliance with EU directives are directly associated with reduced plant-level emissions in any of the new Member States. Rather, EU accession is a proxy for a constellation of new policies, programs, and procedures that together are associated with reduced CO_2 emissions, despite the likely counter pressures of increased export-oriented development. Second, 2009 is the most recent year in which the plant-level emissions data are currently available. Therefore, we are unable to evaluate long-term effects of EU accession and other country-level and plant-level factors on plants' emissions, nor are we able to evaluate if and how the recent global economic recession might have influenced these particular socioenvironmental relationships.

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