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Will future climate change increase global energy use?

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University of Neuchâtel

Institute of Economic Research

IRENE Working paper 18-08

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Will future climate change increase global energy use?

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Abstract:

Currently fossil-fuel-based energy accounts for 82% of global energy use and is the source of two-thirds of anthropogenic greenhouse-gas emissions (GHG). Such emissions are a primary climate change driver ultimately altering temperature and in turn influences energy use. This paper presents a global analysis of the link between energy use and temperature, along with the contributing factors of income, urbanization and population. We use an econometric model to estimate this link based on a panel dataset arising from 147 countries during 1990-2014. We find that energy use per capita has a nonlinear, convex relationship with temperature—the use initially high at low temperatures, then declining to an inflection point, and subsequently rising at high temperatures. The temperature effects on energy use per capita are not globally uniform with differences across rich and poor countries. In particular, rich countries show a larger energy use response at high temperatures than poor countries do. Projections under unmitigated climate change indicate an increase in the global, annual total energy use of 41% by 2100, relative to a baseline of no climate change. The projected increases in global total energy use are substantially larger than prior estimates from studies focused on residential energy use and may further motivate aggressive GHG mitigation and climate change adaptation.

Key words: climate change, energy use

JEL: Q4, Q54

Currently fossil-fuel-based energy accounts for 82% of global energy use¹ and is the source of two-thirds of anthropogenic greenhouse-gas emissions (GHG)². Climate change, along with income and population growth and urbanization, is influencing energy use, and could further increase GHG emissions feeding back to yet more climate change. Quantifying this feedback has implications for contributing information on deliberations of the appropriate transition into low-emission energy systems and other forms of GHG mitigation efforts to limit climate change such as the Paris Agreement's 2 degrees Celsius target.

Many previous studies have examined the relationship between temperature and residential energy use, with a primary focus on electricity consumption³⁻⁶. These studies find a U-shaped relationship between temperature and residential energy use. They generally project a small influence of climate change on energy use by 2100 due to reductions in heating demand that offset increases in cooling demand. Yet few empirical studies have evaluated climate change's impacts on the total energy use that includes both residential and non-residential uses⁷⁻¹⁰. This paper will address this issue by examining how climate affects the total energy use and projecting climate-change induced alterations in future energy use.

Previous studies also show that as household income rises, the adoption and use of air-conditioning increases in response to temperature increases and hence drives up residential electricity consumption substantially^{11,12}. Nonetheless, it is unclear to what degree income and other non-climate factors such as urbanization affect the relationship between countries' climate and total energy use.

More importantly, we need a global and holistic view on future energy use. Most previous studies use limited geographic areas such as single states³ and single countries^{11,13,14} and thus do not reflect the overall global movements in energy use. In particular, without taking into account a catch-up of low-income countries in energy use with high-income countries, we could substantially underestimate the need of energy to sustain the future economy.

In light of the importance of the question, we use a statistical approach to establish an empirical relationship between total energy use and temperature. We do this using an econometric model based on a historical panel dataset that covers 147 countries from 1990 to 2014 (see the data section in the Supplemental materials).

Methods

The statistical model is a country-level, panel, fixed effects regression model. We use exogenous year-to-year and place-to-place variations in heating and cooling degree-days to

identify low and high temperature effects on energy use per capita, controlling for unobserved time-invariant factors to avoid omitted variable biases.^{15,16}

The model contains total energy use per capita (in the log form) as the dependent variable and the independent variables including: (1) annual heating and cooling degree-days, total amount of precipitation and its square to account for non-linear effects of temperature and precipitation; (2) GDP per capita measured in international dollars and urbanization measured in percent of population living in urban areas; (3) country-specific intercepts to account for constant differences between countries such as energy endowment, culture and topography; and (4) year-specific intercepts to account for common contemporaneous shocks (see the method section in the Supplemental materials).

Up to now, we assume that the relationship between energy use per capita, temperature and the other factors is generalizable for all countries. It is possible that rich and poor countries have differential response functions of energy use per capita to temperature changes. Thus, we examine this possibility by estimating heterogeneous energy-use response functions across rich and poor countries (see the section on rich and poor country responses in the Supplemental materials).

Findings

The resultant regression estimates show that heating and cooling degree-days both have a positive, statistically significant effect on energy use per capita (Table 1). This result indicates that total energy use per capita is nonlinear and convex in temperature (Figure 1) as found in residential studies^{3,5,6,17}. As heating degree-days drop, energy use per capita declines and this occurs up until a threshold (15-24 °C) due to reduced heating demand. Then, as cooling degree-days rise, energy use increases reflecting increased cooling demand.

We find that income (in the form of GDP per capita) and urbanization have a significant positive effect on energy use per capita (Table 1), consistent with the findings from previous studies^{6,11,12}. Namely as income grows, consumers increase their energy demand as reviewed in the IPCC AR4 Working Group III report¹⁸. Meanwhile, a rising share of population in urban areas increases total energy use per capita due to the greater energy-intensity of urban areas again as found elsewhere.^{19,20}

Note that we use annual heating and cooling degree-days, rather than annual average temperature, in our estimation to capture the non-linear temperature effect on total energy use per capita. The reason is that annual average temperature may mask within-year temperature

variations, although annual average temperature also shows a non-linear, convex effect on energy use per capita (see Figure S1 in the Supplementary Materials).

We also find that rich and poor countries have differential responses of energy use per capita to changes in cooling degree-days (Table 2). As shown in Figure 2, there is a substantial difference in energy-use responses to temperature changes across rich and poor countries at high temperatures. However, rich and poor countries' energy-use responses are not statistically different at low temperatures (the 90% confidence level), because there are few cold, poor countries in the sample (Table 2).

Our exploration shows that these results are robust to alternative samples and controlling variables: 1) excluding countries with few observations, 2) excluding oil producing countries, 3) excluding the United States and China, 4) adding continental fixed effects, and 5) replacing year fixed effects with time trends (Tables 1 and 2).

Projections under future climate change

We simulate total energy use at the national, regional and global levels under future climate change and changes in socioeconomic conditions with estimated baseline response functions (Tables 1 and 2). We use a high GHG emission scenario (Representative Concentration Pathway 8.5) and two socioeconomic scenarios (Shared Socioeconomic Pathways (SSP) 3 and 5²¹) that exhibit alternative future income, urbanization and population levels and are consistent with the high GHG emission scenario. This simulation approach assumes future energy use responds to temperature changes similarly to what we observe today³⁻⁵.

Projected future climate change impacts on global total energy use are substantially underestimated without taking into differential energy-use responses across rich and poor countries (Figure 3). With differential response functions, the global result shows a 41% increase in annual total energy use by 2100 relative to the no climate-change scenario, which is substantially larger than previous estimates based on residential electricity use³⁻⁶. By contrast, the global result shows a 17% increase in annual total energy use by 2100 using a uniform global response function.

We also find energy use per capita is higher under the greater income growth and urbanization scenario (SSP5), relative to the case with lower ones (SSP3) (Figure 4a). Accounted for differences in population growth, the global energy use by 2100 is expected to increase more than five folds under both SSP3 and SSP5 in combination with the high GHG emission scenario (Figure 4b).

The projections indicate that 82% of the countries will use more energy by 2100 relative to a scenario with no climate change under both SSP3 and SSP5 (Figure 5a). Differences in the projected impacts of climate change across countries reflect the alternative countries' baseline temperatures and development status. Aggregated to the regional level, warming reduces energy use from heating in areas with high heating degree-days, mainly European countries, while regions with high cooling degree-days such as Africa and Asia show substantial increases in energy use under the increased warming (Figure 5b). Low-income countries that are located in hot areas will be most vulnerable to future climate change due to increasing energy expenditure. Globally we must find ways making a transition into a either a lower emitting or less energy-intensive economy if we are not to be forcing yet more climate change.

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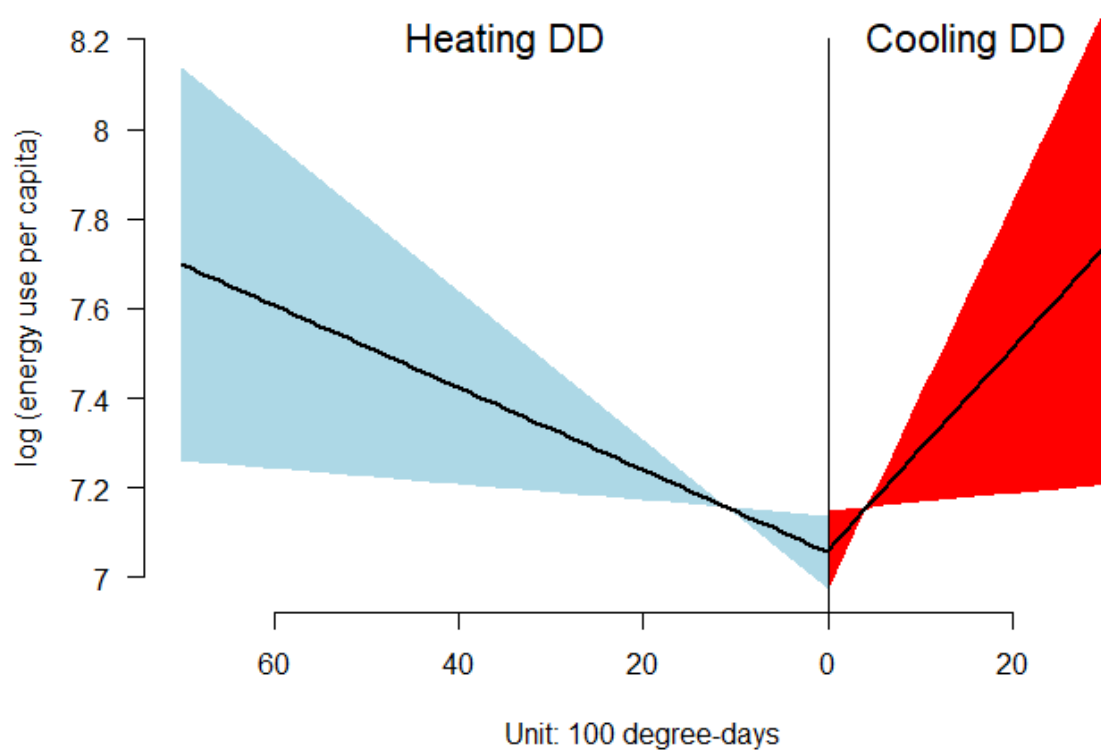


Figure 1. Effects of heating and cooling degree-days (DD) on energy use per capita.

Global non-linear relationship between temperature and logged energy use per capita (black line) during 1990-2014, with the 95% confidence level (blue for heating degree-days and red for cooling degree-days, clustered by country). Model includes gross domestic product (GDP) per capita, urbanization, country fixed effects, and precipitation (see the Supplementary Materials).

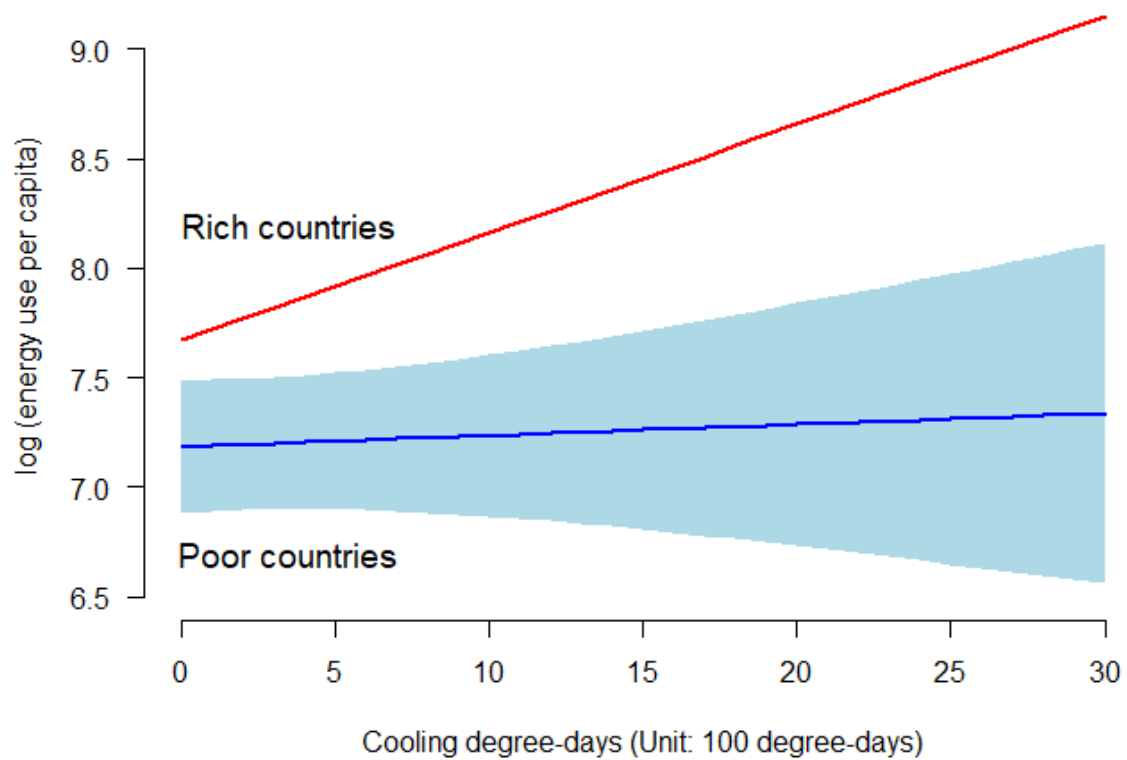


Figure 2. Effects of cooling degree-days on energy use per capita for rich and poor countries.

Comparing rich (above the global median GDP per capita in 2014, red) and poor (below the global median GDP per capita in 2014, blue) countries. Light-blue shaded region is the 95% confidence level for poor countries.

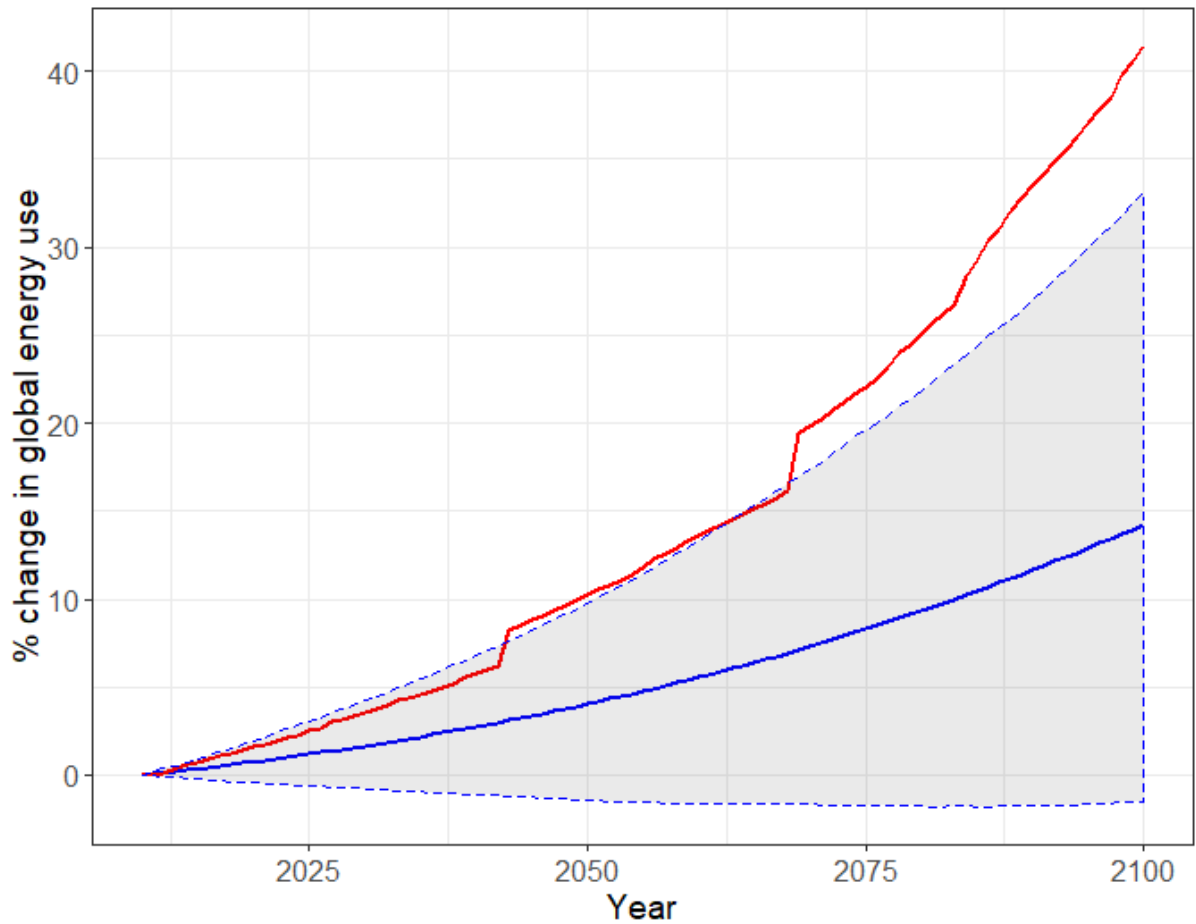


Figure 3. Projected effect of warming on global energy use.

Percent change in global total energy use over years, relative to projections using constant 1990-2014 averaged heating and cooling degree-days. The red line represents projections using estimates from a regression of energy use that allows differential responses between rich and poor countries. The blue line represents projections using estimates from a regression of energy use that pools rich and poor countries, and the shaded area represents the 95% confidence level from such a pooled model.

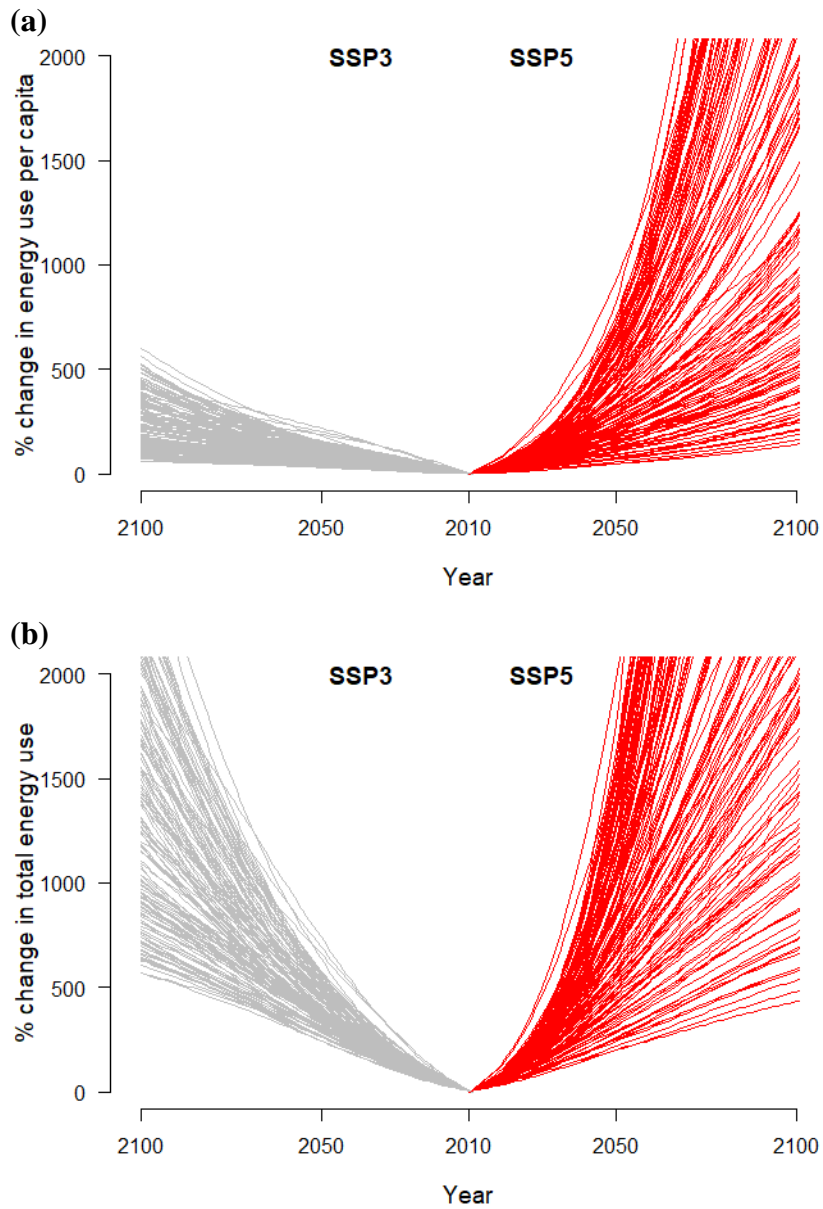


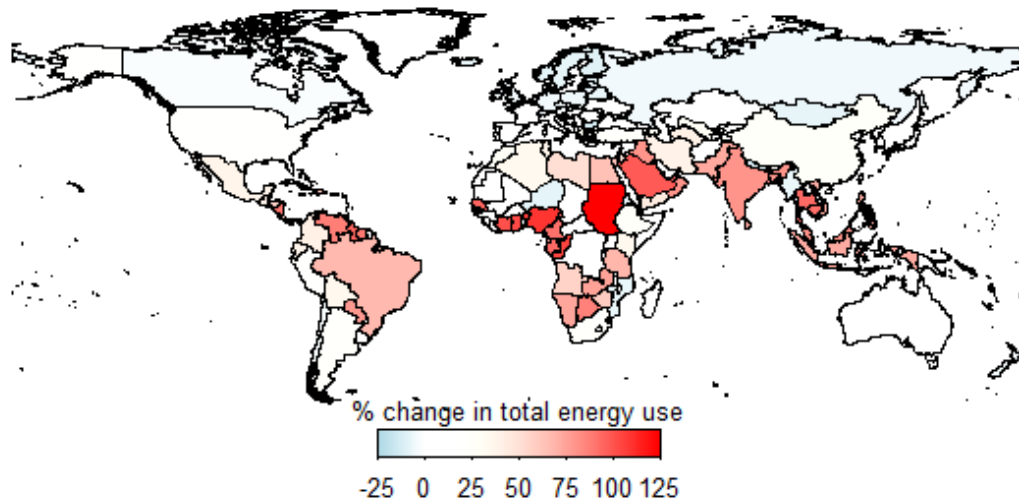
Figure 4. Projected future changes in country-level energy use per capita and total energy use.

(a) Change in energy use per capita, relative to the level in 2010.

(b) Change in total energy use, relative to the level in 2010.

Each line represents a specific country.

(a)



(b)

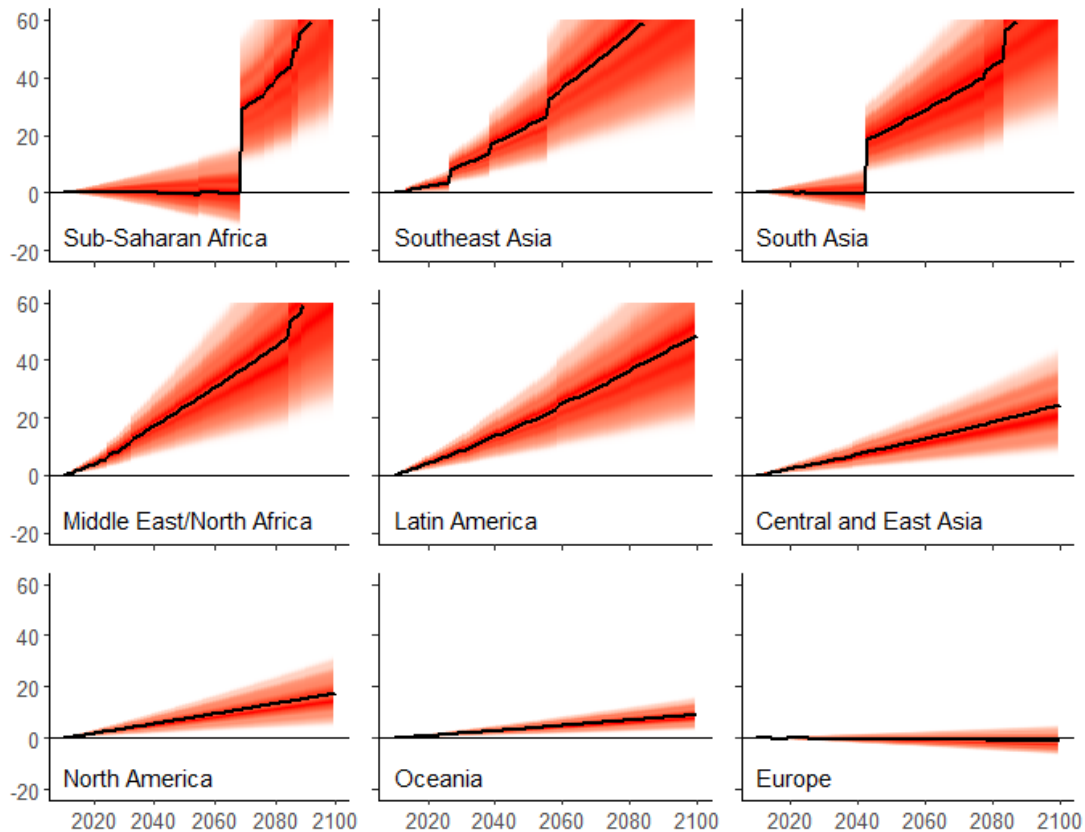


Figure 5. Projected effects of warming on national and regional energy uses.

(a) Country-level estimates of change in total energy use in 2100, relative to projections using constant 1990-2014 averaged heating and cooling degree-days and allowing for differential responses between rich and poor countries.

(b) Percent change in total energy use over years for nine regions, relative to projections using constant 1990-2014 averaged heating and cooling degree-days and allowing for differential responses between rich and poor countries. Black lines are projections using point estimates. Red shaded area is the 95% confidence level²². Kinks reflect a catch-up of low-income countries in energy use with high-income countries as their income per capita rises over time.

Table 1. Regression estimates for global sample, main estimates and robustness

	(1) Base	(2) >10yrs	(3) No oil	(4) No US/China	(5) Cont FE	(6) TimeTrend
Heating degree-days	0.0091** (0.0036)	0.0093** (0.0036)	0.0100*** (0.0035)	0.0093** (0.0037)	0.0091** (0.0036)	0.0095*** (0.0033)
Cooling degree-days	0.0234** (0.0114)	0.0248** (0.0117)	0.0296** (0.0116)	0.0230** (0.0114)	0.0234** (0.0114)	0.0212** (0.0104)
Precipitation	-0.0529 (0.0496)	-0.0436 (0.0508)	-0.0429 (0.0528)	-0.0552 (0.0497)	-0.0529 (0.0496)	-0.0571 (0.0489)
Precipitation square	0.0244** (0.0109)	0.0234** (0.0112)	0.0245* (0.0125)	0.0249** (0.0109)	0.0244** (0.0109)	0.0246** (0.0109)
Log (GDP)	-0.4678 (0.3252)	-0.5020 (0.3220)	-0.6180* (0.3376)	-0.4773 (0.3298)	-0.4678 (0.3252)	-0.4643 (0.3230)
Log (GDP) square	0.0498** (0.0195)	0.0513*** (0.0193)	0.0650*** (0.0198)	0.0503** (0.0197)	0.0498** (0.0195)	0.0499** (0.0193)
Urbanization	0.0233*** (0.0040)	0.0232*** (0.0041)	0.0205*** (0.0039)	0.0232*** (0.0042)	0.0233*** (0.0040)	0.0233*** (0.0040)
Constant	5.9148*** (1.4144)	6.1050*** (1.4024)	5.8724*** (1.4671)	5.9630*** (1.4525)	5.9148*** (1.4144)	23.1529*** (4.4692)
Observations	3242	3148	2815	3192	3242	3242
R squared	0.985	0.984	0.987	0.985	0.985	0.985

Notes: All models include country fixed effects with standard errors clustered at the country level. Heating and cooling degree-days are measured in 100 degree-days. Precipitation is measured in meters. Columns: (1) main specification with year fixed effects; (2) as in column 1 but dropping countries with fewer than 10 years of energy use data; (3) as in column 1 but dropping large oil exporting countries; (4) as in column 1 but dropping United States and China; (5) as in column 1 but adding continent fixed effects; (6) as in column 1 but replacing year fixed effects with a linear time trend.

Asterisks indicate statistical significance at the 1%(***), 5%(**) and 10%(*) levels.

Table 2. Temperature effects on energy use per capita in rich versus poor countries

	(1) Base	(2) poor-yr FE	(3) >10Yrs	(4) \$>\$10Yrs+ poor-yr FE	(5) Cont FE	(6) TimeTrend
Heating degree-days	0.0064** (0.0031)	0.0064* (0.0034)	0.0066** (0.0031)	0.0063* (0.0034)	0.0064** (0.0031)	0.0070** (0.0027)
Cooling degree-days	0.0489*** (0.0160)	0.0440*** (0.0160)	0.0484*** (0.0161)	0.0435*** (0.0160)	0.0489*** (0.0160)	0.0418*** (0.0146)
Heating degree-days * poor	0.0164 (0.0134)	0.0147 (0.0132)	0.0164 (0.0133)	0.0149 (0.0132)	0.0164 (0.0134)	0.0137 (0.0127)
Cooling degree-days * poor	-0.0523*** (0.0192)	-0.0471** (0.0210)	-0.0497** (0.0195)	-0.0441** (0.0215)	-0.0523*** (0.0192)	-0.0432** (0.0186)
Observations	3185	3185	3091	3091	3185	3185
R squared	0.986	0.986	0.985	0.985	0.986	0.986

Notes: All models include country fixed effects, logged GDP per capita and its square term, urbanization, precipitation and its square term, with standard errors clustered at the country level. Heating and cooling degree-days are measured in 100 degree-days. Columns: (1) main specification with year fixed effects as well as independent variables interacted with an indicator whether a country is poor; (2) as in column 1 but allowing year fixed effects to differ across rich and poor countries; (3) as in column 1 but restricting sample to countries with as least 10 observations; (4) as in column 1 but restricting sample to countries with as least 10 observations and allowing year fixed effects to differ across rich and poor countries; (5) as in column 1 but adding continent fixed effects; (6) as in column 1 but replacing year fixed effects with linear time trends that differ across rich and poor countries.

Asterisks indicate statistical significance at the 1%(***), 5%(**) and 10%(*) levels.

Supplementary Materials

1. Data and method

2. Robustness to model specifications and alternative samples

3. Rich and Poor country responses

4. Projections of climate change impact

1. Data and method

1.1 Data

Our observed economic data, including energy use, gross domestic product (GDP), urbanization, and population, come from the World Bank's World Development Indicators¹. Energy use data for most developing and developed countries are available for 1990-2014. The energy use measure is kg of oil equivalent. GDP is measured in 2011 dollars, accounted for purchasing parity power (PPP). Urbanization is measured as percent of total population living in urban areas.

The data source for weather, including monthly average temperature and total precipitation, is the Terrestrial Air Temperature and Precipitation dataset at the University of Delaware². Weather data are available for the years from 1900 to 2014. We aggregate this 0.5-degree gridded data to the country level, weighting by population density data in the year 2000 from the Gridded Population of the World³. Then, we compute monthly heating degree-days (HDD) and cooling degree-days (CDD) from monthly average temperature according to the following formula:

$$(1) \quad HDD = \begin{cases} 0 & \text{if } T > T_h \\ N(T - T_h) & \text{if } T \leq T_h \end{cases},$$
$$CDD = \begin{cases} N(T_c - T) & \text{if } T > T_c \\ 0 & \text{if } T \leq T_c \end{cases},$$

where N is the number of days in a month, T is monthly average temperature, T_h and T_c are the base temperatures for calculating heating and cooling degree-days. In this study, we use 15 °C as the threshold for cooling degree-days and 24 °C for heating degree-days, following practices used by the European Commission

(http://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm). Finally, we aggregate monthly heating and cooling degree-days and total precipitation to obtain annual measures.

Our final sample contains 3390 country-year observations from 1990 to 2014.

1.2 Empirical method

We use a fixed effects model to quantify the relationship between energy use per capita and heating and cooling degree-days. We estimate logged energy use per capita by:

$$(2) \quad \log(E_{it}) \\ = \beta_1 HDD_{it} + \beta_2 CDD_{it} + \beta_3 P_{it} + \beta_4 P_{it}^2 + \beta_5 \log(GDP_{it}) + \beta_6 [\log(GDP_{it})]^2 + \beta_7 Urban_{it} \\ + \alpha_i + \theta_t + \varepsilon_{it}$$

where i and t index countries and years. E_{it} is total energy use per capita. HDD_{it} and CDD_{it} are annual heating and cooling degree-days, respectively. P_{it} is annual total precipitation. GDP_{it} is countries' real GDP per capita adjusted for PPP. $Urban_{it}$ is countries' urbanization rate. ε_{it} is an idiosyncratic error term. α_i , θ_t , β_1 , β_2 , β_3 , β_4 , β_5 , β_6 , and β_7 are parameters to be estimated.

Equation (2) represents a response function of total energy use to temperature changes. β_1 and β_2 describe the non-linear response of energy use per capita to temperature change through heating and cooling degree-days.

The country-specific intercept term, α_i , captures country-level fixed effects, controlling for time-invariant factors that influence a country's energy use such as energy endowment, culture and topography. The year-specific intercept, θ_t , captures year fixed effects, controlling for technological advancement such as energy efficiency and contemporaneous global shocks such as global crude oil price changes. This fixed effects model controls for unobservable country time-invariant factors and hence avoids omitted-variable biases⁴.

Parameters β_5 and β_6 capture the GDP per capita or income effects on energy use with a quadratic term, allowing the nonlinear response. β_7 captures the urbanization effect on a country's energy use, controlling for the rural-urban difference in energy use.

In Equation (2), the effect of temperature on energy use per capita is identified through within- and between-country temperature variations through heating and cooling degree-days, allowing estimation over greater temperature ranges than would single country models. More

importantly, heating and cooling degree-days reveal within-year temperature variations that are averaged out in annual average temperature.

2. Robustness to model specifications and alternative samples

One of our two main results is that temperature has a non-linear and convex effect on energy use per capita. We test whether this main result is robust to alternative samples. Table 1 provides our baseline regression estimates (column 1) and shows how these estimates change when we (a) restrict the sample to countries with at least 10 years of energy use data (column 2); (b) drop oil-rich countries, those with at least 20% of GDP from oil production (column 3); and (c) drop large heterogeneous countries—the United States and China (column 4). We also test whether this main result is robust to alternative set of independent variables: (a) adding continent fixed effects (column 5); (b) replacing year fixed effects with a linear time trend (column 6). Across these model specifications and samples, basic signs and magnitudes of our main result remain unchanged.

Alternatively, we estimate the logged energy use per capita as a quadratic function of heating and cooling degree-days. However, we find that square terms of heating and cooling degree-days are statistically insignificant as shown in Table S1. Thus, we report our estimates derived from a linear form in heating and cooling degree-days in the manuscript.

In addition, we replace heating and cooling degree-days with annual average temperature and its square in the baseline model. As shown in Figure S1, energy use per capita has a U-shaped relationship with annual average temperature, which is consistent with our findings using heating and cooling degree-days, with a minimum reaching at 16 degree C. However, annual average temperature masks within-year temperature variations, so we prefer estimates of temperature effects using heating and cooling degree-days.

3. Rich and Poor country responses

The other main result in this study is that rich and poor countries have differential responses of energy use per capita to temperature changes. We obtain this result by estimating an extended version of Equation 2 that includes interaction terms:

$$\begin{aligned}
 (3) \quad & \log(E_{it}) \\
 &= \beta_1 HDD_{it} + \beta_2 CDD_{it} + \beta_3 P_{it} + \beta_4 P_{it}^2 + \beta_5 \log(GDP_{it}) + \beta_6 [\log(GDP_{it})]^2 + \beta_7 Urban_{it} \\
 &+ \lambda_1 HDD_{it} D_i + \lambda_2 CDD_{it} D_i + \lambda_3 P_{it} D_i + \lambda_4 P_{it}^2 D_i
 \end{aligned}$$

$$+ \lambda_5 \log(GDP_{it}) D_i + \lambda_6 [\log(GDP_{it})]^2 D_i + \lambda_7 Urban_{it} D_i$$

$$+ \alpha_i + \theta_t + \varepsilon_{it}$$

where D_i is an indicator variable of whether a country is poor or not. $D_i = 1$ if a country's PPP-adjusted GDP per capita is below the global median in 2014 (the last year in our sample); otherwise, $D_i = 0$. In this specification, β_1 and β_2 reflect the non-linear temperature responses of energy use per capita for rich countries, while $\beta_1 + \lambda_1$ and $\beta_2 + \lambda_2$ reflects temperature effects for poor countries.

Table 2 provides the consequent regression results. Column 1 shows that β_2 and λ_2 are significantly different from zero. This implies that rich and poor countries have differential responses of energy use per capita to changes in cooling degree-days. As shown in Figure 2, there is a wide gap of energy use responses to temperature changes between rich and poor countries at high temperatures. By contrast, λ_1 is not statistically significant at the 90% confidence level, because there are few cold, poor countries in the sample.

We also test robustness of the results of rich and poor countries under altered data samples and model specifications. We test: (a) allowing differential year-fixed effects for rich and poor countries (column 2); (b) restricting the sample to countries with at least 10 energy use observations (column 3); (c) allowing differential year-fixed effects for rich and poor countries plus restricting the sample to countries with at least 10 observations (column 4); (d) adding continent fixed effects (column 5); (e) replacing year-fixed effects with linear time trends that differ across rich and poor countries. In all cases, rich countries have a larger response in energy use to changes in cooling degree-days than poor countries do.

4. Projections of climate change impact

We use our estimated response functions to simulate projected future changes in energy use per capita and total energy use under different climate and socioeconomic scenarios, relative to a world with temperatures fixed at their 1990-2014 averages.

The country-specific heating and cooling degree-days are the changes that are averaged across 21 global climate models in CMIP5 (the ensemble mean) covering 2081-2100⁵. We do this under a high emission scenario, Representative Concentration Pathway (RCP) 8.5.

We also need estimates of future GDP per capita, population and urbanization. These items are extracted from the Shared Socioeconomic Pathways (SSPs) scenarios⁶. Two of the SSPs

(SSP3 and SSP5) are consistent with the high emission scenario RCP 8.5 and used for simulation. SSP3 assumes relative low income and urbanization rate but high population growth, while SSP5 assumes high income and urbanization but low population growth.

For comparative purpose, we use two statistical models to project the future energy use per capita and total energy use at the national, regional and global levels: (a) a pool model (Equation 2) assuming rich and poor countries with the same response function of energy use per capita to heating and cooling degree-days; and (b) the rich-poor model (Equation 3) assuming rich and poor countries with differential response functions. We graph the results in Figures 3-5, and in Figure 4 we group countries into nine regions as in Burke, Hsiang and Meng⁷. To quantify uncertainty, we bootstrap the historical response function 1000 times with replacement to account for autocorrelation. We use the resulting distribution of estimates to characterize uncertainty for projections (Figure 3).

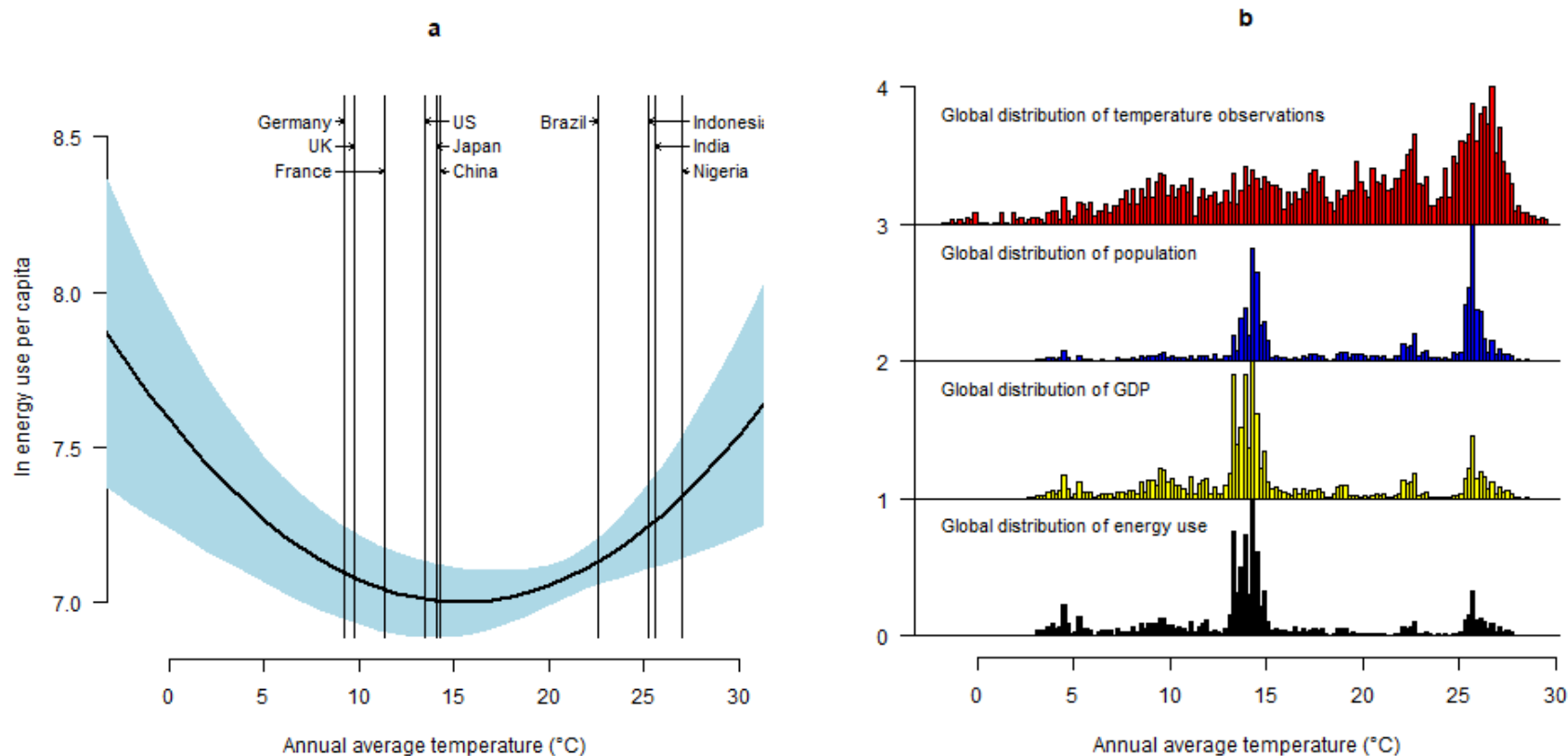


Figure S1. Effect of annual average temperature on energy use per capita

(a) Global non-linear relationship between annual average temperature and logged energy use per capita (thick black line) during 1990-2014 with 90% confidence interval (blue, clustered by country). Model includes gross domestic product (GDP) per capita, urbanization, country fixed effects, and precipitation (see the method section in the Supplementary Materials). Vertical lines indicate average temperature for selected countries.

(b) Histograms of global distribution of temperatures (red), population (blue), GDP (yellow) and energy use (black).

Table S1: Regression estimates for global sample, main estimates and robustness

	(1) Base	(2) >10yrs	(3) No oil	(4) No US/China	(5) ContYr FE	(9) Trend
Heating degree-days (HDD)	0.0099 (0.0104)	0.0105 (0.0104)	0.0113 (0.0105)	0.0104 (0.0106)	0.0099 (0.0104)	0.0120 (0.0100)
Cooling degree-days (CDD)	0.0306 (0.0207)	0.0327 (0.0210)	0.0415** (0.0163)	0.0304 (0.0209)	0.0306 (0.0207)	0.0266 (0.0194)
HDD square	-0.0000 (0.0002)	-0.0000 (0.0002)	-0.0000 (0.0002)	-0.0000 (0.0002)	-0.0000 (0.0002)	-0.0000 (0.0002)
CDD square	-0.0004 (0.0009)	-0.0004 (0.0009)	-0.0008 (0.0007)	-0.0004 (0.0009)	-0.0004 (0.0009)	-0.0003 (0.0008)
Precipitation	-0.0390 (0.0484)	-0.0290 (0.0495)	-0.0260 (0.0514)	-0.0412 (0.0484)	-0.0390 (0.0484)	-0.0457 (0.0477)
Precipitation sq.	0.0218** (0.0106)	0.0207* (0.0109)	0.0211* (0.0124)	0.0222** (0.0107)	0.0218** (0.0106)	0.0224** (0.0107)
ln(GDP)	-0.4590 (0.3230)	-0.4931 (0.3195)	-0.5897* (0.3372)	-0.4682 (0.3276)	-0.4590 (0.3230)	-0.4548 (0.3212)
ln(GDP) sq.	0.0492** (0.0194)	0.0506*** (0.0192)	0.0632*** (0.0198)	0.0496** (0.0195)	0.0492** (0.0194)	0.0493** (0.0191)
Urbanization	0.0233*** (0.0040)	0.0232*** (0.0041)	0.0206*** (0.0039)	0.0232*** (0.0042)	0.0233*** (0.0040)	0.0233*** (0.0040)
Constant	5.8553*** (1.4054)	6.0439*** (1.3924)	5.7845*** (1.4468)	5.9027*** (1.4431)	5.8553*** (1.4054)	23.2912*** (4.5286)
Observations	3242	3148	2815	3192	3242	3242
R squared	0.985	0.984	0.987	0.985	0.985	0.985

Notes: All models include country fixed effects with standard errors clustered at the country level. Heating and cooling degree-days are measured in 100 degree-days. Precipitation is measured in meters. Columns: (1) main specification with year fixed effects; (2) as in column 1 but dropping countries with fewer than 10 years of energy use data; (3) as in column 1 but dropping large oil exporting countries; (4) as in column 1 but dropping United States and China; (5) as in column 1 but adding continent fixed effects; (6) as in column 1 but replacing year fixed effects with a linear time trend.

Asterisks indicate statistical significance at the 1%(***), 5%(**) and 10%(*) levels.

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