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Climate change impacts on energy demand

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SUMMARY This paper estimates the impact of changes in future exposure to hot and cold days on the demand for electricity, natural gas, and fuel oil in four different sectors (residential, industry, commercial and public services, and agriculture) at the global scale. We use an econometric model to infer the short-run and long-run sensitivity of final energy use to historical variations in exposure to hot, cold, dry and humid days. The estimated responses provide insights into the potential impacts of climate change on the final use of energy and into the adaptation responses along the intensive and extensive margin. This paper improves over prior global studies by proposing a framework for evaluating climate change impacts that can characterize the spatial variability within countries at the global scale. We illustrate the implications on future energy demand by combining the behaviors inferred from the past with the future climatic shifts of the Representative Concentration Pathways (RCPs) as predicted by the CMCC Global Circulation Model (GCM) and with the future socioeconomic trends for population and income growth of the Shared Socioeconomic Pathway (SSPs).

Keywords: Panel data, climate change, adaptation, energy.

JEL: N5, O13, Q1, Q54

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1. INTRODUCTION

Energy demand is directly linked to changes in weather and climate conditions. While being one of the main sources of greenhouse gas emissions, it is also a fundamental strategy for human systems to adapt to climate change and weather shocks. With higher mean temperature the energy use for heating could decline whereas the energy use for cooling could increase. It is thus not clear whether energy use will eventually go up or down. In the residential sector, significant changes can be observed especially in shoulder seasons, such as spring (De Cian et al. 2013). Other fuels might be more sensitive to changes in exposure to low temperature levels, as in many countries the heating system uses more natural gas or fuel oil, while electricity heaters might be used as temporary solutions when the main heating system is switched off. There are outliers and some countries, such as Norway, where commercial and residential buildings mostly use electricity for heating.

Most climate impact assessments on energy demand have focused on the residential sector, whereas less research has been conducted to study the response of energy demand in other sectors (Auffhammer and Mansur 2014, Schaeffer et al. 2012). More recent studies, however, mostly using US data, have started to show that energy use in other sectors of the economy also responds to weather variations. Specific industrial activites, such as food processing and storage, water heating and cooling, can be particularly sensitive to climate change (Schaeffer et al. 2012, Howell and Rogner 2014) and more recent studies did find a signficant response of the industrial and commercial sector to weather shocks (Considine 2000). The use of energy in the commercial and public service sector, such as water supply, collection, and treatment, transportation, public administration, education, health, tourism, entertainment and recreation, financial sector, has been studied for some regions in the United States (Ruth and Lin 2006). In the agriculture sector energy-intensive activities include water lifting, pumping, and desalinization (Bazilian et al. 2011) and a growing number of studies has started to investigate the impacts of climate change on energy use in irrigation in the United States (Wilbanks et al. 2012). The demand for cooling livestock can also be expected to increase in a warmer climate. With regards to the meteorological drivers, the focus has been on temperature, in terms of either seasonal averages (De Cian et al. 2013), heating and cooling degree days (see among others, Isaac and van Vuuren 2009, Ruth and Lin 2006), or daily temperature bins (Deschenes and Greenstone 2011). Compared to temperature, precipitation, humidity, and solar radiation have received little investigation (Barreca 2012).

The common approach that has been used in the panel econometric literature is to infer the future impacts of climate change and the adaptation potential from the estimated short-run responses. This approach can underestimate the potential of adaptation or overestimate the impacts of climate change (Auffhammer and Mansur 2014) because short-term elasticities identified using inter-annual weather variation only capture adaptation responses on the intensive margin, that is the change in energy use for a given stock of equipment and appliances. Neglecting changes in the quantity and characteristics of the energy-intensive capital stock understates the possible changes in electricity consumption (Sailor and Pavlova 2003). On macro scale, the dichotomy between intensive and extensive margin can be addressed by specifying an error correction model, which allows differentiating the short- and long-run responses to weather shocks (Masish and Masish 1996, De Cian et al. 2013), which is the approach followed in this paper.

We use an econometric model to estimate the long-run sensitivity of energy demand to variations in historical exposure to hot, cold, dry and humid days in four sectors, residential, industry, commercial and public services, and agriculture. We use the estimated elasticities to provide insights into the potential impacts of climate change on energy use and into the adaptation responses by final sectors along the intensive and extensive margin. Although the long-run response comes closer to describe changes along the extensive margin, yet our approach does not make it possible to quantify explicitly the additional shift in energy demand potentially induced by changes in the quantity and characteristics of energy-using investments. Here we explore two possible ways for approximating for changes on the extensive margin. This paper improves over prior global studies by proposing a framework for evaluating future impacts of climate on energy demand at the global scale capable of characterizing the spatial variability within boundaries of countries. We illustrate the methodology for one combination of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs).

2. EMPIRICAL ANALYSIS

2.1 EMPIRICAL MODEL

We are interested in estimating a relationship between impact endpoints and a vector of meteorological variables. Our impact endpoint indicators are the final energy demand of electricity, fuel oil, and natural gas in the four sectors agriculture, residential, industry, commercial and public services. Our meteorological indicators include bins of daily temperature and, in the specification of the model for electricity demand, of specific humidity. Although relative humidity might be a preferable indicator of heat stress because it takes into account the evaporative cooling that occurs through perspiration of the skin, we selected the specification with specific humidity because this variables is less correlated to temperature.

The count of days of exposure to temperature and humidity ranges in country i in year t is computed as the weighted sum of days of exposure to k temperature range in the grid cells belonging to country i:

$$T^k_{i,t} = \sum_{c \in i} T^k_{c,i,t} * \frac{POP_{c,i,2000}}{POP_{i,2000}} = \sum_{c \in i} T^k_{c,i,t} * \omega_{c,i,2000}$$

Using temperature and humidity bins is perhaps less common than using cooling and heating degree days. The idea of the degree days approach is that there is a range of temperature (17-20°C) of comfort (building balance point) at which energy is not used neither for heating nor for cooling. Deviations from this balance point increase demand for heating and cooling. However, the balance point differs between types of buildings and between regions, as it tends to be lower for cooling and higher for heating in northern countries, while the reverse is true in southern countries. An alternative approach uses the days of exposure to various temperature ranges (Deschenes & Greenstone, 2011). By estimating a different coefficient for each temperature and humidity bins it is possible to identify the shape of the response functions from the data, without imposing a prori functional forms. However, this method is data intensive and identifying a large number of bins require sufficient degrees of freedom. We do not have sufficient degrees of freedom in the dataset used for this study, which is a global panel of countries. Therefore, here we focus on changes in the extreme temperature and humidity bins.

Since the demand for energy is a derived demand for energy services and energy use is related to the stock of energy-utilizing appliances, a weather shock can induce two forms of adjustments. The first change along the intensive margin is the short-run change in variable energy input for a given stock of energy-using capital. The second is a change on the extensive margin, namely the long-run additional energy use that follows adjustments in the energy-using stock or its characteristics (such as the purchase of air conditioners, humidifiers, insulation, energy-efficiency). Moreover, Gross Domestic Product (GDP) is a key driver of energy use and various studies have shown these two variables share a long-run, cointegration relationship. To account for these issue we therefore model the relationship between per capita energy use, real per capita GDP and the meteorological variables as an Error Correction Model. As shown in Eq. (1), the dependent variable, per capita energy demand in the four different sectors, is modeled as a function of the deviation from the long-run equilibrium and of the short-run changes in the other explanatory variables:

$$\begin{aligned}\Delta lny_{it} = \alpha_i + \eta \Delta X_{it} + \sum_{k=1}^{K} \beta_1^k \Delta T_{it}^k + \sum_{j=1}^{J} \beta_2^j \Delta SH_{it}^j \\ + \gamma \left(lny_{it-1} - \sum_{k=1}^{K} \theta_1^k T_{it-1}^k - \sum_{j=1}^{J} \theta_2^j SH_{it-1}^j - \lambda X_{it-1} \right) + \epsilon_{it}\end{aligned}$$

where α_i is the country fixed effect, T_{it}^k and SH_{it}^j are the count of each year days with average daily temperature and humidity in each of k or j bins, and X is a set of other control variables. Here, y_{it} indicates the sectoral per capita energy demand in country i and year t. The meteorological variables T_{it}^k and H_{it}^j are annual counts of days with average temperature in interval k and specific humidity in interval j. The control variable $X_{i,t}$ is the real per capita gross domestic product. A country-specific intercept, α_i, captures the influence on energy demand of unobserved heterogeneous time-invariant factors and ϵ_{it} is a random disturbance term. At each point in time the change in per capita energy use depends on the contemporaneous change in real per capita GDP, temperature and humidity (short-run effect), as well on the feedback of the deviation from the long-run relationship. The error-correction speed of adjustment parameter, λ, measures countries' average rate of adjustment toward the long-run equilibrium. The β coefficients capture the short-run response to inter-annual shocks, while the θs capture the feedback of the disequilibrium. The long-run response is the cumulative effect during the adjustment period until the system returns to the long-run equilibrium and is computed using the long-term elasticities, $\widetilde{\theta}_1^k = \frac{\theta_1^k}{-\gamma}$ and $\widetilde{\theta}_2^j = \frac{\theta_2^j}{-\gamma}$. We estimate the demand for each sector-fuel combination independently.

2.2 DATA

We use a balanced panel of 29-48 countries (depending on the fuel-sector combination) over the period 1978-2010. We match the global country-level annual data on energy demand from the International Energy Agency (IEA) database with high-resolution meteorological data. Time series for the meteorological variables are constructed by combining the spatially gridded daily data from the Global Land Data Assimilation System (GLDAS) global dataset (Rodell et al., 2004) with geospatially referenced data on population[1]. Gridded population data are used to weight the grid cells of the GLDAS database (1 degree x 1 degree) by the population intensity of each cell. More precisely, we weight the values of the climate variables in each cell with the share of population in a given cell, normalized with respect to the total population of a country. It is important to mention that population data refer to the year 2005 and therefore the same weight is assumed throughout the time period considered. GDP per capita is computed using data on real Purchasing Parity Power (PPP) converted GDP and population from the Penn World Tables version 7 (Heston et al. 2013). Annual country-level data on final energy use are from the Energy Balance of the International Energy Agency, which covers the period 1978-2011. We consider the final consumption of electricity, natural gas (consisting mainly of methane), and fuel oil (liquid petroleum products burned in a furnace or boiler for the generation of heat or used in an engine for the generation of power). As final users, we consider the sectors residential, agriculture, commercial/public services and industry. Table 1 and 2 summarize the descriptive statistics for the world, tropical, and temperate regions. The distinction between temperate and tropical-subtropical regions is based on the climate zones as classified by Koeppen-Geiger climate zones. Industry and residential are the primary users of electricity. Fuel oil is mostly used in industry, electricity and natural gas in industry and residential. The commercial sector uses mostly electricity and to a lower extent natural gas in temperate regions. In tropical countries, the use of electricity in agriculture is higher in percentage terms (16% as opposed to the 2% in temperate regions), though absolute levels are comparable to those in temperate countries.

[1] Center for International Earth Science Information Network - CIESIN - Columbia University, International Food Policy Research Institute - IFPRI, The World Bank, and Centro Internacional de Agricultura Tropical - CIAT. 2011. Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://sedac.ciesin.columbia.edu/data/set/grump-v1-population-count.

Temperate	Obs	Mean	Std. Dev.	Min	Max
<7.5°C	1311	106.22	69.56	0.00	283.24
7.5-10°C	1311	32.72	11.88	1.58	82.81
10-12.5°C	1311	36.67	11.88	7.12	77.54
25-27.5°C	1311	15.42	16.28	0.00	84.00
27.5-30°C	1311	12.15	17.25	0.00	94.00
>30°C	1311	10.39	22.35	0.00	153.26
<4 g/Kg	1311	60.66	53.69	0.00	238.38
14-16 g/Kg	1311	10.05	13.85	0.00	76.00
16-18 g/Kg	1311	4.46	8.54	0.00	56.00
>18 g/kg	1311	3.83	11.82	0.00	71.46
Population ('000)	1311	62107.32	189128.40	223.59	1337799.00
Real GDP per capita (2005USD)	1311	18746.21	11823.07	558.18	51791.63
TFC per capita (Ktoe)	1311	0.46	0.47	0.02	4.39
TFC (Ktoe)	1311	18677.37	45864.48	50.74	329017.50
Electricity	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	1126	393.66	1096.78	0.95	10103.54
COMMPUB (Ktoe)	1240	4712.76	13864.40	1.72	114923.10
RESIDENT (Ktoe)	1307	5366.23	14756.55	12.90	124330.80
TOTIND (Ktoe)	1311	7895.00	18605.81	18.06	214149.00
Natural gas	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	1650	133.52	626.61	0.00	9497.29
COMMPUB (Ktoe)	1650	2621.29	9624.51	0.00	74893.42
RESIDENT (Ktoe)	1650	5928.67	17833.01	0.00	122053.10
TOTIND (Ktoe)	1650	6752.48	20568.38	0.00	152059.00
Fuel oil	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	1311	36.01	95.54	0.00	1505.81
COMMPUB (Ktoe)	1311	285.18	1191.92	0.00	22158.58
RESIDENT (Ktoe)	1311	102.10	323.61	0.00	3487.15
TOTIND (Ktoe)	1311	2180.94	4241.66	0.00	35522.10

Table 1

Descriptive statistics - Temperate countries

Tropical	Obs	Mean	Std. Dev.	Min	Max
<7.5°C	1252	2.29	8.92	0.00	89.57
7.5-10°C	1252	2.12	5.35	0.00	29.00
10-12.5°C	1252	4.73	10.07	0.00	53.46
25-27.5°C	1252	90.00	55.03	10.00	279.26
27.5-30°C	1252	69.31	49.51	0.99	207.48
>30°C	1252	53.47	61.87	0.00	228.46
<4 g/Kg	1252	8.05	17.29	0.00	126.52
14-16 g/Kg	1252	43.66	29.32	0.00	172.22
16-18 g/Kg	1252	59.51	44.06	0.00	250.07
>18 g/kg	1252	114.48	84.76	0.00	342.04
Population ('000)	1252	59295.00	149980.00	713.83	1173108.00
Real GDP per capita (2005USD)	1252	5496.30	7955.42	275.70	65415.68
TFC per capita (Ktoe)	1252	0.08	0.15	0.00	1.31
TFC (Ktoe)	1252	2909.24	6395.03	5.93	61117.96
Electricity	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	615	447.43	1429.40	0.17	11098.39
COMMPUB (Ktoe)	1171	557.49	1109.86	0.26	9175.94
RESIDENT (Ktoe)	1241	824.97	1585.35	2.67	13174.60
TOTIND (Ktoe)	1226	1286.36	3013.71	0.69	27643.07
Natural gas	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	1980	2.27	17.75	0.00	357.40
COMMPUB (Ktoe)	1980	43.71	306.71	0.00	5011.17
RESIDENT (Ktoe)	1980	289.41	2187.10	0.00	35011.25
TOTIND (Ktoe)	1980	1040.85	2776.72	0.00	25418.18
Fuel oil	Obs	Mean	Std. Dev.	Min	Max
AGRICULT (Ktoe)	1252	34.39	217.62	0.00	2631.80
COMMPUB (Ktoe)	1252	40.28	174.57	0.00	2078.75
RESIDENT (Ktoe)	1252	0.62	7.10	0.00	209.88
TOTIND (Ktoe)	1252	1040.17	1925.37	0.00	13225.96

Table 2

Descriptive statistics - Tropical countries

Region	Sector	Energy type	Heating (Response to cold days) Central [90% Conf.Int.]	Cooling (Response to hot days) Central [90% Conf.Int.]
Temperate	Agr	Ely	ns	0.021 [0.009,0.033]
		FuelOil	0.046 [0.006,0.086]	ns [0,0]
	Comm	Ely	-0.006 [-0.012,0]	0.019 [-0.001,0.038]
		Gas	0.009 [0,0.019]	ns
	Ind	Ely	ns	ns
		FuelOil	0.059 [0.008,0.11]	ns
	Res	Ely	0.011 [0.004,0.019]	0.013 [0.005,0.021]
		FuelOil	0.099 [0.003,0.196]	ns
		Gas	0.016 [0.003,0.028]	ns
Tropical	Agr	Ely	ns	0.021 [0.009,0.033]
		FuelOil	0.046 [0.006,0.086]	ns
	Comm	Ely	ns	ns
		Gas	0.009 [0,0.019]	ns
	Ind	Ely	-0.023 [-0.033,-0.013]	0.004 [0,0.007]
		FuelOil	ns	ns
	Res	Ely	ns	0.006 [0.002,0.01]
		FuelOil	0.099 [0.003,0.196]	ns
		Gas	ns	ns

Table 3
Long-run estimated elasticities

2.3 EMPIRICAL RESULTS

Table 3 shows the the estimated long-run semi-elasticities of logarithmic per capita energy demand, describing how energy final consumption in different sectors respond to changes in exposure to hot and cold days, while the estimated effect of humidity and other covariates is reported in Table 5. We find that energy use responds to the inter-annual variation in a set of different meteorological variables. The response of energy demand varies across sectors, fuels, and regions. Electricity handles virtually the entire cooling load, whereas the heating load is distributed among a wider range of fuels (electricity, natural gas and fuel oil). Our results show that the cooling effect, as revealed by an increase in electricity demand, is larger in temperate regions for the residential and commercial sectors. The heating effect mostly shows up as changes in fuel oil and natural gas. Concerning industry, we find a significant response of electricity for cooling in tropical countries and of fuel oil for heating in temperate countries. Low and high specific humidity has a significant impact on electricity demand in agriculture, whereas low humidity has a significant impact on on electricity use in the commercial sector and residential in tropical countries.

Our results also suggest that the long-run response to a change in the frequency of weather patterns is greater that the short-run effect. Moreover, the response of electricity, which is sensitive to both cold and hot days, is not symmetric. A change in the frequency of days with mean temperature above 27.5°C is larger than the response to a change in frequency of cold days. The error correction coefficient (Table 5-7) is significant and negatively signed in all fuel-sector combinations, indicating that presence of longer term adjustments following a weather shock. Across all fuel-sector combinations, tropical countries have larger speed of adjustment coefficients. Especially low humidity levels are found the be positively correlated with electricity use. In the agriculture sector the sign is reversed, as higher humidity levels are a good indicator of precipitations and can thus be associated with less requirements for irrigation, a major source of electricity use in agriculture. Energy, and in some places electricity (Shah et al. 2009) is a widely used source of power in agriculture, and earlier studies have shown that the price elasticity of electricity demand in agriculture can exceed that of other sectors. Maddigan et al. (1982) report price elasticities greater than -1 for various regions in the US, while most studies tend to estimate elasticities less than 1 (see for example De Cian et al. 2013, Table 7). Residential and commercial electricity demand shows a higher elasticity to real per capita GDP than industry and agriculture, while commercial demand for gas is the more sensitive than that of residential. The long-term elasticity of fuel oil is negative, indicating a tendency to shift away from this fuel with economic growth.

3. FUTURE CHANGES IN ENERGY DEMAND DUE TO CLIMATE CHANGE AND SOCIO-ECONOMIC GROWTH

3.1 CLIMATE CHANGE IMPACTS

We illustrate how to use the empirical results discussed in the previous section to assess future climate change impacts. We combine the estimated long-run responses with the Representative Concentration Pathways (RCPs, van Vuuren et al. 2011) 4.5 as predicted by the CMCC Global Circulation Model (GCM)[2]. Here we do not address the issue of climate projection uncertainty, which should certainly be considered when generating future impact scenarios. The purpose of this section is to illustrate the methodology that can be used to formulate vulnerability assessments. We focus on the RCP 4.5 as an example of a medium warming scenario leading to an average temperature increase above pre-industrial levels of 1.9 and 2.7°C in 2050 and 2100, respectively. We focus on temperature, as this variable is the main meterological driver of changes in energy response. We define current and future distribution of daily temperature, weighting the frequencies in each cell with the normalized share of population, as we did for the historical data. Future climate (henceforth 2050) is defined as the decadal mean between 2046 and 2055, current climate as the average conditions between 2006 and 2015 (henceforth present). We use the predicted per capita energy demand by multiplying the long-term semi-elasticities to the difference between future and current frequency of hot and cold days in each grid cell c of country i:

$$\frac{q^F_{c\in i}}{q^C_{c\in i}} = \frac{exp[\sum_{k=1}^{K} \widetilde{\theta}_1^k T^k_{c,i,F} * \omega_{c,i,F}]}{exp[\sum_{k=1}^{K} \widetilde{\theta}_1^k T^k_{c,i,C} * \omega_{c,i,C}]}$$

Socioeconomic growth dynamics of GDP and population will scale up and down the future impact of climate change:

[2] http://cmcc.it/models/cmcc-cm

$$\frac{q^F_{c\in i}}{q^C_{c\in i}} = exp(\widetilde{\lambda} ln \frac{RGDP_PC_{i,F}}{RGDP_PC_{i,C}}) exp \sum_{k=1}^{K} \widetilde{\theta}^k_1 (T^k_{c,i,F} * \omega_{c,i,F} - T^k_{c,i,C} * \omega_{c,i,C})$$

This equation highlights the interaction among the factors that determine the future impacts of climate change:

- the estimated response function to meteorological variables
- the change in future exposure relative to present
- the change in spatial distribution of population, as population weights interact with the changes in exposure
- socio-economic growth

Figure 1 visualizes the spatial distribution of change in future exposure to hot and cold days. Hot days will become more frequent in the tropics, whereas the frequency of cold days will decrease especially in temperate regions. Large countries, such as the United States, China, Australia, and Brazil are characterized by a heterogeneous patterns, with the tendency toward warming more concentrated in specific regions. In Southern Europe hot days will increase but cold days will go down. Whether total final energy and electricity use in these countries will increase or decrease is an empirical question, as more electricity will be used in the summer for cooling, but less electricity, gas, and oil will be used in winter for heating.

By combining the changes in exposure with the sensitivity we can generate the maps of future change in energy demand. Figure 2 shows the spatial distribution of the percentage change in per capita energy demand across countries in the residential sector. As downscaled projections of GDP and population are not yet available, maps show the pure climate change impact without including the socioeconomic component. As we do not have the downscaled projections of future population we assume that $\omega_{c,i,F} = \omega_{c,i,C}$.

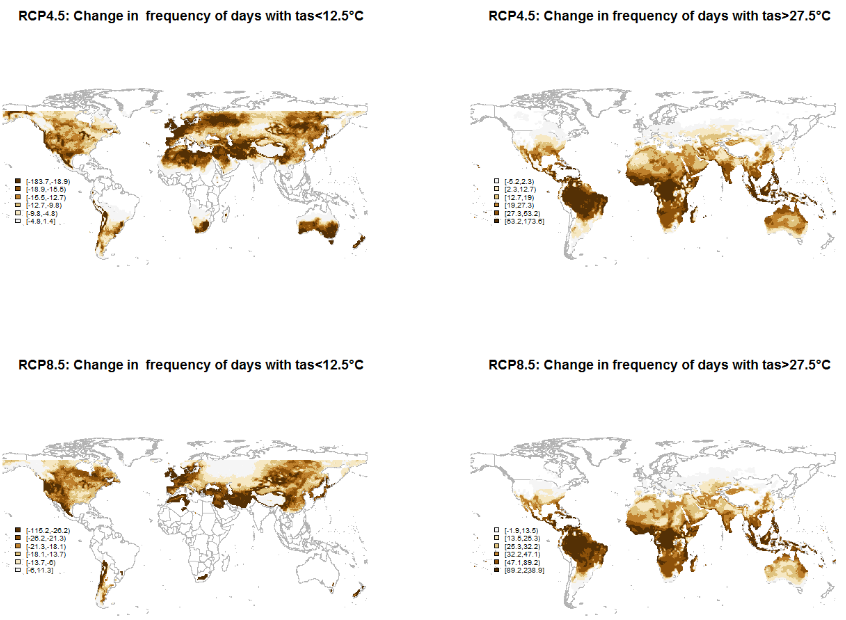

Figure 1:
Future exposure to hot and cold days. RCP4.5 and RCP8.5, CMCC-CM model.

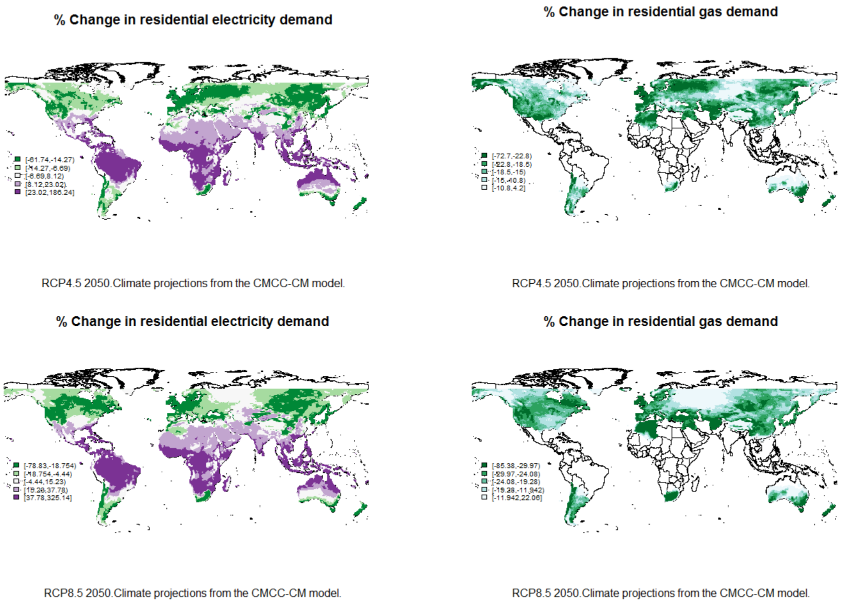

Figure 2:
Climate change impacts on residential per capita energy demand(%) in 2050, RCP 4.5 and RCP8.5

3.2 FUTURE ENERGY DEMAND DUE TO SOCIO-ECONOMIC GROWTH AND CLIMATE CHANGE

Since in our model we have also estimated the elasticity to real per capita GDP, we can assess how future socio-economic scenarios will interact with climate change to determine the final vulnerability. Since we lack statistics of energy demand at the grid cell level, and since the projections for GDP and population are also available at the country level, we assess the role of socio-economic drivers at the national level. As a first step we have aggregated the difference in counts of hot and cold days to the national level and computed country-average impacts. By using the elasticity to real per capita GDP, we project future baseline average per capita energy use, without climate change:

$$q_i^{F,BAU} = exp\widetilde{\lambda}ln\frac{RGDP_PC_{i,F}}{RGDP_PC_{i,C}}q_i^{C,BAU}$$

The impact of climate change relative to the future baseline is computed as follows:

$$q_i^{F,CC} = q_i^{F,BAU}exp\sum_{k=1}^{K}\widetilde{\theta}_1^k\omega_{c,i,C}(T_{c,i,F}^k * -T_{c,i,C}^k)$$

Using future population we can compute future national energy demand with and without climate change:

$$\begin{aligned} Q_i^{F,CC} &= q_i^{F,CC} POP_i^{F,BAU} \\ Q_i^{F,BAU} &= q_i^{F,BAU} POP_i^{F,BAU} \end{aligned}$$

Future projections of per capita GDP and population are from the Shared Socio-Economic Pathways (Kriegler et al 2012 and IIASA, 2013). For the illustrative purpose of the paper we focus on the SSP5 scenario[3], characterized by fast growth in per capita income. Note that, under this baseline, meeting a forcing level of RCP 4.5 W/m2 would require dedicated mitigation policies. Figure 3 show the distribution of percentage changes in per capita energy demand across countries in 2050, using central estimates and confidence intervals at the 90% level. Boxes span the interquartile range in estimated responses. Outliers are suppressed. Electricity is the only form of energy being sensitive to high temperature extremes across the four sectors of the economy. Fuel oil and natural gas are more sensitive to changes in exposure to cold days.

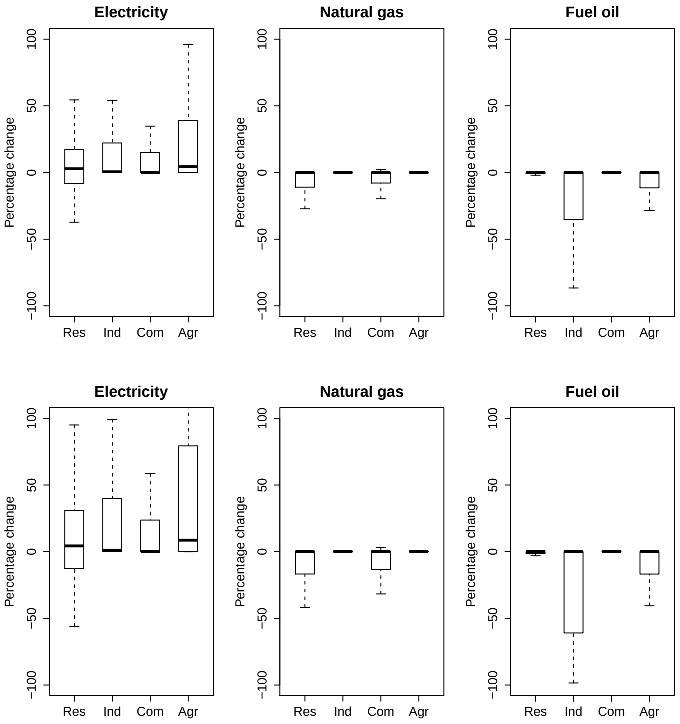

Figure 3:
Climate change impacts on per capita energy use (%) in 2050, RCP 4.5 and RCP8.5. Boxplot shows the distribution across countries using central estimates and the 90% confidence intervals.

The bar chart in Figure 4 decomposes the future change in final energy by fuel and the future change in final electricity by sector due to climate change. It highlights the significant absolute

[3] International Institute for Applied Systems Analysis (IIASA) SSP Database (Version 9 downloaded on November 3 2013) https://secure.iiasa.ac.at/web-apps/ene/SspDb/ (2013).

increase in large countries, such as the United States, and emerging economies such as India, China, Indonesia, and Brazil, and the heterogeneity in driving sectors, with commercial being the main cause in electricity increase in temperate regions, and residential and industrial in tropical countries. Some African and Central American countries would need more electricity to cope with the future changes in temperature. Though the absolute figures for these places would be small, the relative change to the baseline represents huge percentage changes. For example, a fourth-fold increase could occur in the agriculture sector of El Salvador, Ghana, Nicaragua, Panama, and Senegal. These changes represent potential change in energy demand, or potential adaptation, assuming countries will actually have the capacity to adapt. They also highlight a possible additional benefit of enhancing energy access, namely avoiding the future impacts of climate change.

Table 4 compares the climate-induced change in energy with the baseline change due to socio-economic growth. With the exceptio of fuel oil, which has a negative elasticity to GDP, in most cases the baseline increase in energy demand dominates the effect due to climate change. In tropical emerging economies (for example, Mexico and Indonesia), climate change could go up to 20% to the increase in electricity demand induced by growth.

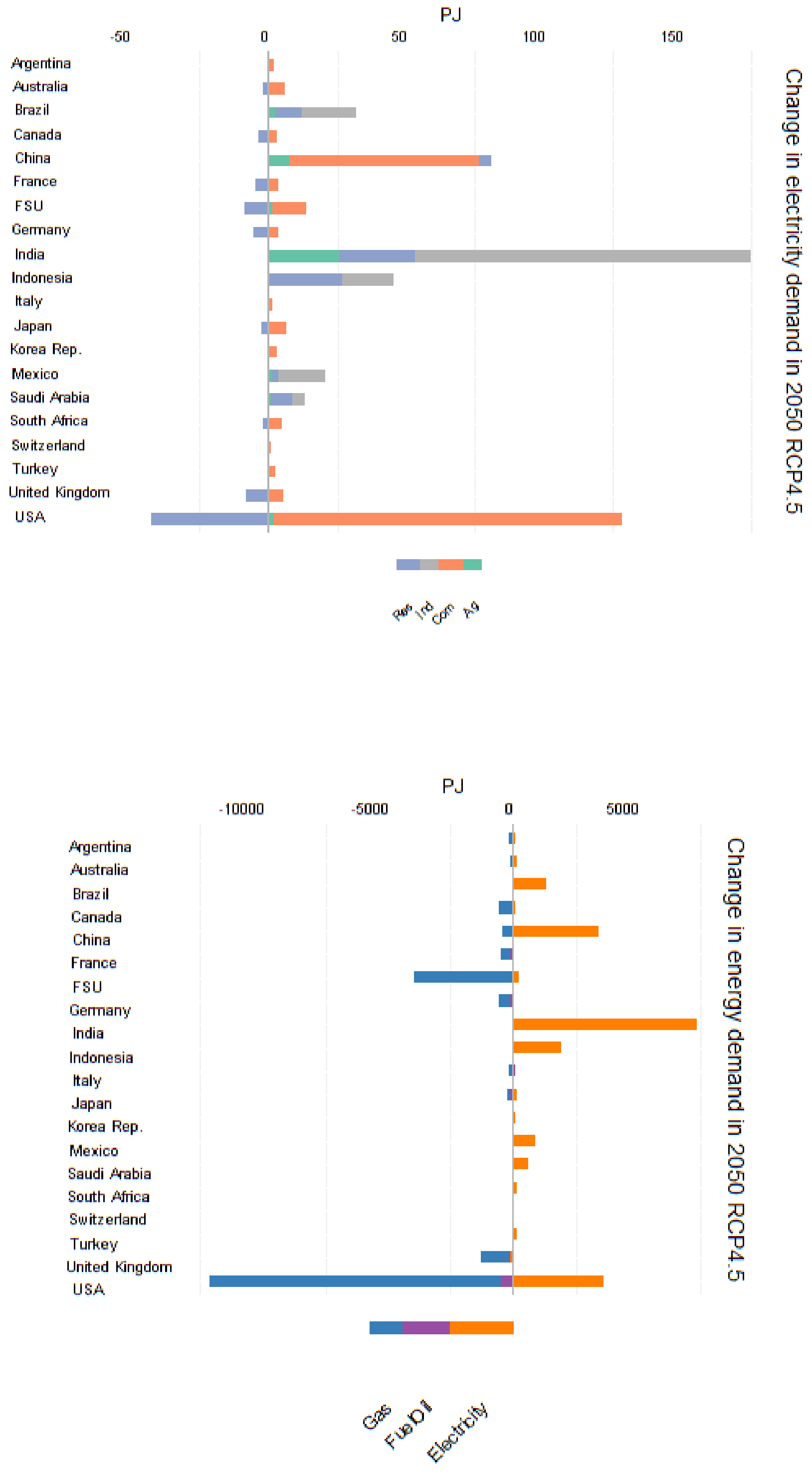

Figure 4:
Climate change impacts on energy demand (PJ) in RCP4.5.

BAU Change in energy demand			
country	Electricity	Gas	Fuel oil
Argentina	780	1139	-27
Australia	1909	559	-5
Brazil	8717	54	-97
Canada	3990	3654	-38
China	18157	3319	-505
France	1911	1505	-111
FSU	6482	17801	-266
Germany	1696	1369	-171
India	35049	3	-76
Indonesia	8110	58	-36
Italy	826	1075	-261
Japan	2458	859	-501
Korea Rep.	1423	603	-185
Mexico	3471	52	-48
Saudi Arabia	4143	0	82
South Africa	2200	0	-1
Switzerland	302	95	-11
Turkey	857	594	-107
USA	24791	28325	-212
United Kingdom	1982	2619	-111
Climate-induced change in energy demand			
	Electricity	Gas	Fuel oil
Argentina	34	-203	-3
Australia	131	-111	-22
Brazil	1307	-1	0
Canada	-48	-486	-75
China	3357	-485	-16
France	-73	-388	-97
FSU	189	-3979	-19
Germany	-105	-461	-68
India	7295	0	-3
Indonesia	1889	0	0
Italy	13	-176	-60
Japan	129	-146	-151
Korea Rep.	65	-85	-26
Mexico	841	-2	0
Saudi Arabia	541	0	0
South Africa	80	0	0
Switzerland	-6	-22	-10
Turkey	72	-96	-14
USA	3555	-11701	-530
United Kingdom	-138	-1057	-116

Table 4

Baseline (SSP5) and climate-induced change in energy demand in 2050 (PJ)

3.3 FURTHER CONSIDERATIONS ON THE EXTENSIVE MARGIN

Our empirical strategy differentiates the short-run and long-run response in energy demand. Although the long-run response is perhaps closer to describe changes along the extensive margin, yet our approach does not make it possible to quantify explicitly the additional shift in energy demand potentially induced by changes in the quantity and characteristics of energy-using investments. Historical data on investments or capital stocks with sufficient granularity would make it possible to statistically control for their effects, but this information is not available at the global scale. To the best of our knowledge the closest data available to proxy for the stock of energy using capital is the imports of heating and cooling equipment (SITC2 741) from the ICTS data. As shown in Table 8, Model (5) and (6), we do find a significant impact in tropical regions where 1% increase in imports increases residential electricity use by 0.05% As an alternative approach we use real per capita income as a proxy for the availability of energy-using capital stock, assuming that increases with income. To test whether the marginal effect of temperature exposure on energy demand varies with the stock, we multiply days of exposure by income to stratify its marginal effect by per capita income. Table 8, Model (1) and (2), shows that indeed the marginal effect varies between .88% (low income, 5% percentile) and 1.5% (high income, 95% percentile) in temperature regions and between .4% and .5% in tropical regions, with the difference relative to the mean marginal effect signifying the extensive margin.

4. CONCLUSION

We use a panel regression model to estimate the parameters characterizing a reduced-form relationship between sectoral energy demand at country level, a set of meteorological indicators, and a number of other covariates controlling for time-invariant country-specific heterogeneity (country effect), unspecified exogenous influences affecting all countries (time effects), and other confounding factors in particular real per capita GDP.

We find that energy use responds to the inter-annual variation in a set of different meteorological indicators. The response of energy demand varies across sectors, fuels, and climate. Electricity handles virtually the entire cooling load, whereas the heating load is distributed among a wider range of fuels (natural gas and fuel oil). Our results show that the cooling effect, as revealed by an increase in electricity demand, is larger in temperate regions for the residential and commercial sectors. The heating effect mostly shows up as changes in fuel oil and natural gas, with a generally larger and more significant marginal effect in tropical regions. Concerning industry, we find a significant response of electricity for cooling in tropical countries and of fuel oil for heating in temperate countries.

The illustrative analysis of the future potential vulnerability of energy demand in 2050 shows how empirically-estimated response functions could be combined with future climate and socio-economic projections to compute future change in energy demand due to economic growth as well as to climate change, which is the type of input needed by integrated assessment models. Generating empirically-based estimates of climate change impacts on energy demand at global scale would ultimately provide important inputs to global economic models used to analyze mitigation scenarios and future transformation towards low carbon economies. So far the literature on mitigation reviewed by the Working Group III of the IPCC in the 5th Assessment omits climate change impacts and adaptation. Accounting for the interactions between mitigation, impacts, and adaptation is a major gap in the transformation pathways literature and it is relevant for mitigation analysis and transition dynamics because impacts and adaptation could influence the effectiveness of mitigation options and adaptation responses to climate change could themselves alter emissions from human activities.

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A. REGRESSION RESULTS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
D.log(rgdppc)	0.2859***	0.2097**	0.5085***	0.4295***	0.7041***	0.7430***	0.3263
	(7.8092e-02)	(8.6332e-02)	(6.0278e-02)	(1.1247e-01)	(1.0205e-01)	(1.0869e-01)	(2.5682e-01)
D.DH<4g/kg	0.0005**	0.0026***	-0.0001	-0.0042***	0.0001	0.0013**	0.0010***
	(1.8949e-04)	(6.1629e-04)	(5.0983e-04)	(9.6751e-04)	(1.0480e-04)	(5.3912e-04)	(2.8069e-04)
D.DH>14g/kg	-0.0001	0.0005	0.0002	-0.0011	0.0001	0.0009	-0.0011
	(3.1614e-04)	(3.5088e-04)	(6.5704e-04)	(8.5693e-04)	(3.8253e-04)	(6.0113e-04)	(1.1969e-03)
D.DT<12.5°C	0.0009***	0.0001	-0.0004	-0.0001	0.0001	-0.0001	-0.0005
	(2.0096e-04)	(3.5691e-04)	(2.9415e-04)	(1.2099e-03)	(1.8629e-04)	(6.1209e-04)	(5.8566e-04)
D.DT>27.5°C	0.0009**	0.0006***	0.0013*	0.0007	0.0001	-0.0001	0.0033***
	(3.4295e-04)	(1.1898e-04)	(6.7927e-04)	(4.0667e-04)	(4.7009e-04)	(1.5920e-04)	(6.6977e-04)
L.lelypc	-0.0636***	-0.0783***	-0.0765***	-0.0987***	-0.0373	-0.0780***	-0.1214***
	(1.3849e-02)	(1.1499e-02)	(2.7284e-02)	(1.3618e-02)	(3.4127e-02)	(2.3197e-02)	(3.0738e-02)
L.log(rgdppc)	0.0610**	0.0982***	0.1004**	0.1643***	0.0175	0.1023**	0.0690
	(2.2488e-02)	(1.9087e-02)	(4.7961e-02)	(3.4053e-02)	(3.1050e-02)	(4.1829e-02)	(4.0805e-02)
L.DH<4g/kg	0.0000	0.0018**	-0.0004	-0.0021***	-0.0000	0.0002	0.0012**
	(2.1805e-04)	(6.4616e-04)	(4.9582e-04)	(5.2610e-04)	(1.4670e-04)	(1.0230e-03)	(5.2768e-04)
L.DH>14g/kg	-0.0003	0.0004	-0.0006	-0.0003	0.0001	0.0009	-0.0020*
	(2.1874e-04)	(3.1342e-04)	(7.3292e-04)	(9.1762e-04)	(3.9952e-04)	(8.5742e-04)	(1.1778e-03)
L.DT<12.5°C	0.0007**	-0.0002	-0.0004	0.0016	0.0003	-0.0018***	-0.0002
	(2.7577e-04)	(5.2636e-04)	(2.9759e-04)	(2.1841e-03)	(2.4474e-04)	(3.5745e-04)	(6.4773e-04)
L.DT>27.5°C	0.0008*	0.0005**	0.0014	0.0003	-0.0002	0.0003*	0.0026**
	(4.0717e-04)	(1.7701e-04)	(9.4052e-04)	(4.4961e-04)	(5.3184e-04)	(1.6242e-04)	(1.2046e-03)
Constant	-0.8699***	-1.2420***	-1.0536**	-1.7460***	-0.2855	-1.3686***	-1.2827**
	(2.7872e-01)	(2.1172e-01)	(4.8881e-01)	(4.4888e-01)	(3.8967e-01)	(4.1167e-01)	(5.7233e-01)
Region	Temp.	Trop.	Temp.	Trop.	Temp.	Trop.	All
Sector	Res.	Res.	Comm.	Comm.	Ind.	Ind.	Agr.
Observations	960	576	896	544	960	576	928
R-squared	0.126	0.177	0.094	0.086	0.181	0.156	0.097
Number of id2	30	18	28	17	30	18	29

Table 5

Regression results: Electricity.Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$

	(1)	(2)	(3)
D.log(rgdppc)	0.7295**	-0.1243	-1.3509
	(3.4525e-01)	(2.0979e-01)	(1.0138e+00)
D.DT<7.5°C	0.0031***	0.0048***	-0.0532
	(1.0175e-03)	(7.9307e-04)	(1.6044e-01)
D.(7.5C-10°C)	0.0037**	0.0028**	0.0070
	(1.4675e-03)	(1.0189e-03)	(3.5702e-02)
D.(10C-12.5°C)		0.0030***	-0.0088
		(5.2804e-04)	(5.4163e-03)
D.(12.5C-15°C)		0.0024*	
		(1.2328e-03)	
D.(15C-17.5°C)		-0.0013**	
		(5.2972e-04)	
L.lngaspc	-0.3297***	-0.1381***	-0.2439**
	(7.5189e-02)	(1.9666e-02)	(6.7592e-02)
L.log(rgdppc)	0.5281***	0.1517**	-0.0468
	(1.6169e-01)	(5.3908e-02)	(2.7510e-01)
L.DT<7.5°C	0.0026*	0.0021*	0.1047
	(1.4728e-03)	(1.1230e-03)	(1.3260e-01)
L.(7.5C-10°C)	0.0035*	0.0027*	0.0737
	(1.8183e-03)	(1.5222e-03)	(7.4061e-02)
L.(10C-12.5°C)		-0.0003	-0.0238
		(8.4876e-04)	(1.4310e-02)
L.(12.5C-15°C)		0.0024	
		(1.8068e-03)	
L.(15C-17.5°C)		-0.0015**	
		(6.9057e-04)	
Constant	-6.7276***	-2.1588***	-1.0740
	(1.8694e+00)	(7.2832e-01)	(1.9878e+00)
Region	ALL	Temperate	Tropical
Sector	Commercial	Residential	Residential
Observations	552	552	168
R-squared	0.233	0.329	0.189
Number of id2	23	23	7

Table 6

Regression results: Natural gas.Robust standard errors in parentheses.*** p<0.01, ** p<0.05, * p<0.1

	(1)	(2)	(3)	(4)
D.log(rgdppc)	0.7719***	-0.1271	0.9535	-0.3727
	(1.8955e-01)	(4.7807e-01)	(5.4536e-01)	(7.5888e-01)
D.DT$<$7.5°C	0.0021	0.0405	0.0043	0.0076**
	(1.3246e-03)	(4.6819e-02)	(4.4752e-03)	(2.3848e-03)
D.(10C-12.5°C)	0.0013	0.0153		
	(1.7803e-03)	(1.9918e-02)		
L.lfoilpc	-0.0709**	-0.2812***	-0.1433**	-0.0633**
	(3.2236e-02)	(9.1887e-02)	(5.5244e-02)	(2.4646e-02)
L.log(rgdppc)	-0.0936*	-0.1735*	-0.0589	-0.2093*
	(5.4031e-02)	(8.6125e-02)	(6.7081e-02)	(9.6522e-02)
L.DT$<$7.5°C	0.0042**	0.0754	0.0066*	0.0063
	(1.5737e-03)	(8.6954e-02)	(3.3152e-03)	(3.6669e-03)
L.(7.5C-10°C)	0.0046*	-0.0037		
	(2.6456e-03)	(4.4115e-02)		
Constant	-0.0047	0.3430	-1.1998	0.7285
	(5.5427e-01)	(7.5531e-01)	(7.1974e-01)	(1.0737e+00)
Region	Temperate	Tropical	ALL	ALL
Sector	Industry	Industry	Agriculture	Residential
Observations	928	512	384	240
R-squared	0.044	0.130	0.071	0.061
Number of id2	29	16	12	8

Table 7

Regression results: Heating oil.Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$

	(1)	(2)	(3)	(4)	(5)	(6)
D.log(rgdppc)	0.2699***	0.1847**	0.2859***	0.2093***	0.1925**	0.2847***
	(6.2867e-02)	(7.3261e-02)	(6.3131e-02)	(6.9443e-02)	(8.4999e-02)	(9.0404e-02)
D.DH<4g/kgxlog(rgdppc)	0.0000***	0.0003***				
	(1.5839e-05)	(9.7653e-05)				
D.DH>14g/kgxlog(rgdppc)	0.0000	0.0001				
	(2.7076e-05)	(4.6876e-05)				
D.DT<12.5°Cxlog(rgdppc)	0.0001***	0.0000				
	(1.8086e-05)	(8.0559e-05)				
D.DT>27.5°Cxlog(rgdppc)	0.0001***	0.0001***				
	(3.1204e-05)	(1.8411e-05)				
L.lelypc	-0.0633***	-0.0785***	-0.0636***	-0.0783***	-0.0864***	-0.0711***
	(1.7235e-02)	(9.8883e-03)	(1.7201e-02)	(9.8427e-03)	(1.4024e-02)	(1.2596e-02)
L.log(rgdppc)	0.0455**	0.0740***	0.0610***	0.0976***	0.1195***	0.0641**
	(1.9782e-02)	(1.8788e-02)	(2.1100e-02)	(1.7746e-02)	(2.3698e-02)	(2.3488e-02)
L.DH<4g/kgxlog(rgdppc)	0.0000	0.0002**				
	(2.2438e-05)	(9.7427e-05)				
L.DH>14g/kgxlog(rgdppc)	-0.0000	0.0001				
	(2.8161e-05)	(4.6542e-05)				
L.DT<12.5°Cxlog(rgdppc)	0.0001**	-0.0000				
	(2.5808e-05)	(8.7514e-05)				
L.DT>27.5°Cxlog(rgdppc)	0.0001**	0.0000*				
	(4.4259e-05)	(2.5438e-05)				
D.DH<4g/kg			0.0005***	0.0026***	0.0024**	0.0005**
			(1.6827e-04)	(7.8078e-04)	(1.0394e-03)	(2.0679e-04)
D.DH>14g/kg			-0.0001	0.0004	0.0006	-0.0002
			(2.8386e-04)	(4.1121e-04)	(4.8294e-04)	(3.7340e-04)
D.DT<12.5°C			0.0009***	0.0001	0.0002	0.0009***
			(1.7928e-04)	(6.5699e-04)	(4.0602e-04)	(2.0366e-04)
D.DT>27.5°C			0.0009***	0.0008***	0.0006***	0.0009**
			(3.0923e-04)	(2.4061e-04)	(1.5520e-04)	(3.4753e-04)
L.DH<4g/kg			0.0000	0.0018**	0.0018**	0.0000
			(2.3727e-04)	(7.7035e-04)	(7.1707e-04)	(2.2912e-04)
L.DH>14g/kg			-0.0003	0.0004	0.0006	-0.0004*
			(3.1738e-04)	(3.7316e-04)	(3.9483e-04)	(2.3569e-04)
L.DT<12.5°C			0.0007***	-0.0002	-0.0001	0.0007**
			(2.5049e-04)	(7.1792e-04)	(5.8725e-04)	(2.9061e-04)
L.DT>27.5°C			0.0008*	0.0005*	0.0003	0.0008*
			(4.2643e-04)	(2.7961e-04)	(2.1980e-04)	(4.1435e-04)
D.log(AC/GDP)					0.0038**	-0.0006
					(1.4474e-03)	(2.1603e-03)
L.log(AC/GDP)					0.0048*	0.0009
					(2.6205e-03)	(2.9311e-03)
Constant	-0.7056***	-1.0740***	-0.8699***	-1.2393***	-1.5136***	-0.9081***
	(2.4058e-01)	(1.8500e-01)	(2.6254e-01)	(2.2532e-01)	(3.0915e-01)	(2.9650e-01)
Region	Temperate	Tropical	Temperate	Tropical	Temperate	Tropical
Sector	Residential	Residential	Residential	Residential	Residential	Residential
Observations	960	576	960	576	509	925
R-squared	0.124	0.176	0.126	0.177	0.135	0.176
Number of id2	30	18	30	18	30	18

Table 8

Regression results: Further analysis on the extensive margin.*** $p<0.01$, ** $p<0.05$, * $p<0.1$

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