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Global Energy Demand in a Warming Climate

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SUMMARY This paper combines an econometric analysis of the response of energy demand to temperature and humidity exposure with future scenarios of climate change and socioeconomic development to characterize climate impacts on energy demand at different spatial scales. Globally, future climate change is expected to have a moderate impact on energy demand, in the order of 6-11%, depending on the degree of warming, because of compensating effects across regions, fuels, and sectors. Climate-induced changes in energy demand are disproportionally larger in tropical regions. South America, Asia, and Africa, increase energy demand across all sectors and climate scenarios, while Europe, North America and Oceania exhibit mixed responses, but with consistent reductions in the residential sector. Even so, only Europe and Oceania in the moderate warming scenario experience aggregate reductions in energy use, as commercial electricity use increases significantly. We find that climate change has a regressive impact on energy demand, with the incidence of increased energy demand overwhelmingly falling on low- and middle-income countries, raising the question whether climate change could exacerbate energy poverty.

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

JEL: N5, O13, Q1, Q54

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1 Introduction

How climate change will impact the consumption of energy is one of the most important topics in energy economics. The demand for energy is directly affected by changes in weather and climatic conditions. In addition to being the major source of greenhouse gas (GHG) emissions, energy use makes space conditioning possible, and, in turn, facilitates adaptation to high and low temperatures. Compared with the historical record, climate warming increases the frequency of high temperature extremes—and with it the energy necessary to satisfy additional demand for cooling—while simultaneously decreasing the frequency of low temperature extremes—and the energy associated with a smaller demand for heating. The central question is whether, and if so by what margin, the former effect outweighs the latter, or vice versa. Over the coming century energy energy demand will be driven by the interactions of changing socio-economic and climatic conditions. Countries' final energy consumption will depend on their economies' overall size and sectoral composition, the way in which these characteristics jointly impact on the mix of fuels, and ultimately the manner in which these sectoral demands respond to future meteorological exposures.

A large and growing literature attempts to project the future demand for energy and associated GHG emissions, principally for the purpose of analyzing the economic and environmental consequences of climate change mitigation policies. Much of this research is at the global scale, employing sophisticated numerical simulation models that divide the world into large regional economies encompassing substantial sectoral and technological detail (e.g. Bruckner et al, 2014; Clarke et al, 2014; Calvin et al, 2013). Yet, application of this analytical machinery to quantify the impacts of climate change on energy demand is still limited (Ciscar and Dowling, 2014). The key missing elements are (i) the heterogeneous responsiveness of the demand for different fuels to meteorology in their constituent regions and sectors, and (ii) the manner in which these responses interact with geographically and temporally changing fields of temperature. Characterizing these elements is the focus of this paper.

Regarding (i), energy demand has been extensively studied over several decades. However, empirical assessments at broad geographic scales are comparatively rare (see De Cian, Lanzi and Roson (2013) for a recent exception). The geographic coverage of regional studies is patchy and tends to overrepresent industrialized countries. The literature's coverage of combinations of different sectors and fuels is also limited, focusing on electricity and, less commonly, natural gas, especially in the residential sector, with comparatively less attention paid to other areas of the economy (Auffhammer and Mansur, 2014; Schaeffer, 2012).

This omission is potentially important given the recent accumulation of engineering and economic evidence of non-residential sectors' differential responses to weather variations—albeit mostly from the U.S. and Europe (e.g., Schaeffer, 2012; Howell and Rogner, 2014; Considine, 2000; Ruth and Lin, 2006; Bazilian et al, 2012; Wilbanks et al, 2012).

Turning to (ii), the precise manner in which empirical studies articulate the response of energy demand to meteorology has a direct bearing on the ways in which their results are able to be used in conjunction with climate projections in order to characterize climate change impacts. Energy demand tends to be recorded on an annual (e.g., Deschenes and Greenstone, 2013) or monthly basis (e.g., Aroonruengsawat and Auffhammer, 2011; Auffhammer and Aroonruengsawat, 2011), with higher temporal frequency data being comparatively rare, except perhaps in electric power (e.g., Scapin et al, 2015). Temperature is the meteorological driver that has been most widely considered, while others that are relevant to the question of climate change (such as precipitation and humidity) have received less attention (Barreca, 2012). Commonly-used approaches estimate elasticities of energy demand with respect to temperatures that are either averaged on an annual (Bigano et al, 2006) or seasonal basis (e.g., De Cian, Lanzi and Roson, 2013), accumulated heating and cooling degree days (e.g., Isaac and Van Vuuren, 2009; Ruth and Lin, 2006; Eskeland and Mideksa, 2010), and, more recently, temporal exposure to different intervals of temperature (e.g., Aroonruengsawat and Auffhammer, 2011; Auffhammer and Aroonruengsawat, 2011; Deschenes and Greenstone, 2013). The last approach, which we adopt here, is particularly attractive because of its ability to capture potential nonlinearity in the responses of demand to temperature extremes.

A critical issue in combining such estimates with future climate data to construct impact projections is consistently aggregating current and future meteorological data across spatial and temporal scales. The earth system models (ESMs) that are the principal tool for projecting future states of the climate simulate climatic variables on time steps of hours to months at grid scales of hundreds of kilometers. The need to average ESM outputs over space and/or time is inevitable, but doing so has the unpleasant effect of shrinking the tails of the distribution of meteorological drivers, which understates the large impacts that are likely to arise when nonlinear demand responses are convolved with exposure to weather extremes. This is a particular problem where energy consumption data are coarse (e.g., country-year observations) and the observational units have a large latitudinal extent that encompasses different climatic regimes across which impacts on energy demand may switch signs. Consequently, to effectively capture the impacts of future extremes it is necessary to pursue empirical modeling in a way that anticipates the challenges that attend the projection of future impacts. Key desiderata include assembling high spatial and temporal resolution datasets of historical meteorological observations and future climate simulations, processing the weather observations in such a way that they are able to be matched to the energy data with a minimum of aggregation for estimation purposes, and applying the identical data transformations to ESM outputs.

In this paper we develop a flexible methodology to characterize geographic variations in climate change impacts on energy demand across the globe. Our first step is to econometrically disentangle the short- and long-run responses of per-capita energy consumption to variations in exposure to hot and cold, dry and humid days. The resulting long-run semi-elasticities capture the nonlinear effect of the climate on energy use indicative of adaptation responses by final consumers along the intensive as well as the extensive margins. Second, we combine these estimates with ESM temperature projections and consistent scenarios of population and Gross Domestic Product (GDP) growth to elucidate the potential climate change impacts on final energy consumption at the sectoral, regional, and global levels. Our temperature projections are simulations of two representative concentration pathways (RCPs— Van Vuuren, 2012) indicative of a high-warming no-policy scenario and moderate-warming mitigation poicy scenario. These are augmented with a shared socioeconomic pathway (SSP— Kriegler et al, 2012; Van Vuuren, 2014) scenario of conventional economic development, slow population growth, international convergence, and rapid increases in final energy consumption. A comprehensive assessment of the implications of different climate and socio-economic trends on future energy demand is left to future work.

The rest of the paper is organized as follows. Section 2 provides the background and develops the simple theoretical framework that is used to motivate the empirical model of energy demand response to weather and that constitutes the foundation of the paper. Section 3 describes the results and uses the estimated elasticities to per capita income and the semi-elasticities to temperature exposure to calculate future baseline and climate-induced energy demand. Section 4 presents a number of robustness tests and compare our results to the existing literature. Section 5 concludes the paper by summarizing the main findings.

2 Methods

2.1 Empirical energy demand modeling

We model the global final demand for three energy commodities (electricity, fuel oil and natural gas) in four economic sectors (residential, commercial, industrial, agriculture), characterizing its response to tempera-

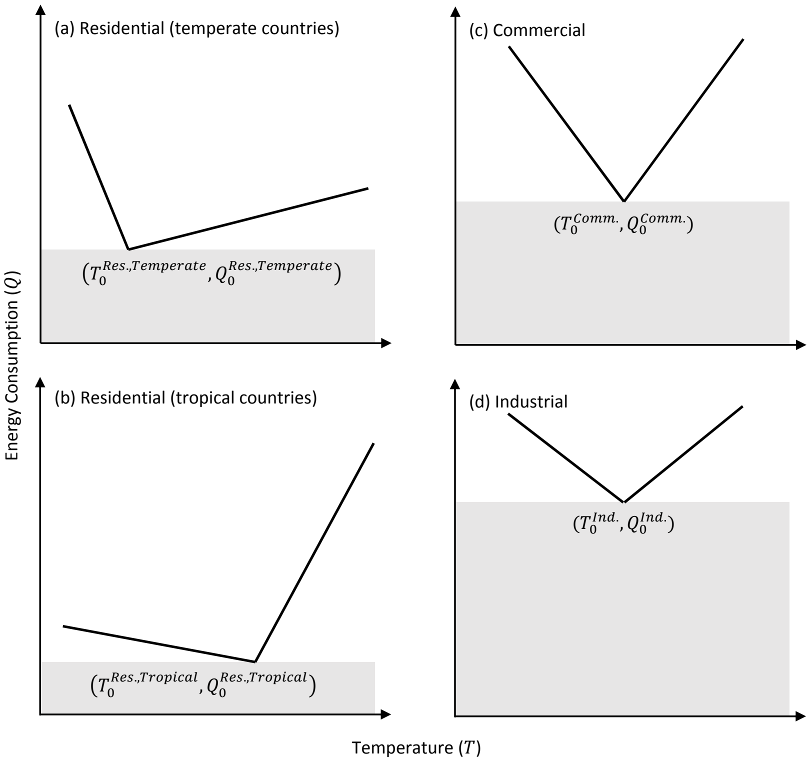

Figure 1: Temperature dependence of energy demand: stylized facts

ture and humidity exposures. As shown schematically in Fig. 1, the response of energy demand (Q) to temperature (T) differs by region and economic sector. Copious engineering and economic evidence suggests that energy response functions exhibit generalized V-shape, with a nadir at the so-called "balance point" (T_0, Q_0) and the slope of each segment capturing the marginal effect on demand of additional exposure to heat or cold (see variously Engle et al, 1986; Aroonruengsawat and Auffhammer, 2011; Auffhammer and Aroonruengsawat, 2011; Deschenes and Greenstone, 2013). These attributes vary with different regions' climate and the extent of different sectors' weather exposure. The height of the gray area (Q_0) indicates non-weather responsive energy consumption, which is highest (lowest) in the parts of the economy that are least (most) exposed to weather—the industrial and residential sectors, respectively. The decrease in average year-round temperatures with latitude suggests that residential balance point temperatures in the tropics exceed those in temperate regions ($T_0^{\text{Res, Tropical}} > T_0^{\text{Res, Temperate}}$). Moreover, the demand functions are likely to be asymmetric, with tropical regions' energy consumption for cooling varying elastically with high temperatures while that for heating varies relatively inelastically with low temperatures, and this pattern being reversed in temperate regions. Given such heterogeneity, our challenge is to develop an empirical model that is parsimonious yet capable of identifying differences in asymmetric demand responses across regions, sectors and fuels from limited data.

The customary empirical framework for estimating the short-run response of energy demand to weather is static cross section-time series regressions. Elasticities estimated by these models are likely to underestimate the potential change in energy demand as form of adaptation to changes in climate because they capture the adaptation responses along the intensive margin, namely, changes in energy consumption that are conditional on the stock of energy-using durable goods. By contrast, over the long time horizon on which the climatic changes occur, the key additional influence on energy consumption will come from adjustments in the quantity and energy efficiency characteristics of the capital stock—i.e., movements along the extensive margin (Auffhammer and Mansur, 2014). A particular concern is that increasing summer temperatures will amplify electricity demand by accelerating the diffusion of air conditioning throughout the developing world beyond its baseline rate determined by the growth of income. Studies that have captured the impact of changes on the extensive margin typically rely on estimates of the stocks of energy-using durables (Sailor and Pavlova, 2003; McNeil and Letschert, 2008; Mansur et al, 2008). However, at the global scale of this analysis such data are not available. Our workaround to address the dichotomy between intensive and extensive margins is to employ an error correction model that distinguishes the short-run effects of weather shocks from the long-run responses to climate (Masish and Masish, 1996; De Cian, Lanzi and Roson, 2013).

Our theoretical framework for bringing together these ideas is deliberately simple. We consider an intertemporally optimizing agent whose objective is to achieve a target equilibrium level of thermal performance, π^*. Here "performance" is an inclusive concept that is meant to encompass a range of settings: the physiologically-determined level of indoor comfort (conditional on space conditioning) in residential and commercial sectors (Eskeland and Mideksa, 2010), the output of temperature-sensitive production processes (conditional on insulation and operation of thermal regulation equipment) in industrial sectors, or crop yields (conditional on irrigation in response to evapotranspiration) in agriculture. Given information available at time t, the agent selects a sequence of future performance levels, π, that minimize the expectation of discounted performance loss $\mathscr{L}$, specified as a quadratic function of divergence from the target level and inter-period variability:

$$\mathbb{E}_t\mathscr{L} = \mathbb{E}_t \sum_{\tau=0}^{\infty} \rho^{\tau} \left[\varpi_1(\pi_{t+\tau} - \pi^*_{t+\tau})^2 + (\pi_{t+\tau} - \pi_{t+\tau-1})^2 + \varpi_2(\pi^*_{t+\tau} - \pi^*_{t+\tau-1})(\pi_{t+\tau} - \pi_{t+\tau-1})\right] \quad (1)$$

where $\varpi_1, \varpi_2 > 0$ are weights. Nickell (1985) shows that with static expectations and a fixed target, when $\varpi_2 = 0$ the solution to (1) reduces to the simple partial adjustment model

$$\pi_t - \pi_{t-1} = \Omega(\pi_{t-1} - \pi^*_{t-1}) \tag{2}$$

in which the change in performance in a subsequent period is a fraction $\Omega \in (0, 1)$ of the divergence between the target and realized levels of performance in the current period.

Performance depends fundamentally on weather, which we specify as the agent's exposure to vectors of intervals of temperature and humidity, $\boldsymbol{\mathcal{E}}^T$ and $\boldsymbol{\mathcal{E}}^H$. As alluded to in the examples above, weather impacts are modulated by the agent's choices of space conditioning equipment, other energy-using capital, irrigation infrastructure, building characteristics, etc.—which we indicate using the vector $\mathbf{X}$. Crucially, the agent's consumption of energy, Q, determines the intensity of utilization of these durable goods, and in turn the agent's ability to shield herself from performance-degrading ambient meteorological conditions. It is simplest to express performance as the linear function:

$$\pi_t = \zeta + \boldsymbol{\mathcal{E}}^T_t \boldsymbol{\psi}^T + \boldsymbol{\mathcal{E}}^H_t \boldsymbol{\psi}^H + \mathbf{X}_t \boldsymbol{\xi} + \chi q_t + \nu_t \tag{3}$$

in which q is the logarithm of energy consumption, ν is a random disturbance term, and ζ, $\boldsymbol{\psi}^T$, $\boldsymbol{\psi}^H$, $\boldsymbol{\xi}$ and χ are parameters. Then, substituting (3) into (2) enables us to solve for the error-correcting form of the agent's demand for energy:

$$\Delta q_t = \alpha + \left[\Delta \boldsymbol{\mathcal{E}}^T_t \boldsymbol{\beta}^T + \Delta \boldsymbol{\mathcal{E}}^H_t \boldsymbol{\beta}^H + \Delta \mathbf{X}_t \boldsymbol{\eta}\right] + \theta \left\{ q_{i,t-1} - \boldsymbol{\mathcal{E}}^T_{t-1} \boldsymbol{\gamma}^T - \boldsymbol{\mathcal{E}}^H_{t-1} \boldsymbol{\gamma}^H - \mathbf{X}_{t-1} \boldsymbol{\lambda} \right\} + u_t \tag{4}$$

where Δ indicates first differences.

Eq. (4) is what we take to the data. We specify the dependent variable as the logarithm of fuel (f) × sector (s) × country (i) × year (t) demand for final energy per person. The covariates of interest are the exposure over each calendar year (measured in days) to J intervals of average daily temperature and K intervals of average daily specific humidity.[1] These country-specific variables are derived from global gridded meteorological reanalysis data in two steps. First, for the j^{th} temperature interval with support

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[1] Relative humidity is a better indicator of the demand for cooling to counteract heat stress because it accounts for the attenuation of evaporative cooling through perspiration. Notwithstanding this, we use specific humidity because it is less correlated with temperature.

$\langle \underline{T}_j, \overline{T}_j \rangle$, and the k^{th} humidity interval with support $\langle \underline{H}_k, \overline{H}_k \rangle$, year t exposure at the c^{th} grid cell is the accumulated count of days whose average temperature and humidity (T_c and H_c) fall into the appropriate ranges:

$$\varepsilon^T_{j,c,t} = \mathcal{C}\left[T_c \in \langle \underline{T}_j, \overline{T}_j \rangle\right] \quad \text{and} \quad \varepsilon^H_{k,c,t} = \mathcal{C}\left[H_c \in \langle \underline{H}_k, \overline{H}_k \rangle\right] \tag{5}$$

were $\mathcal{C}$ is the count operator. Country i exposures are computed as the population-weighted sum of exposures over the county's constituent grid cells $c \in i$:

$$\mathcal{E}^T_{j,i,t} = \sum_{c \in i} w_{c,i,t} \varepsilon^T_{j,c,t} \quad \text{and} \quad \mathcal{E}^H_{k,i,t} = \sum_{c \in i} w_{c,i,t} \varepsilon^H_{k,c,t} \tag{6}$$

where the weights, $w_{c,i,t} = n_{c,t}/N_{i,t}$, are the ratio of the grid cell to national population. Suppressing fuel and sector subscripts, we then estimate the cross section-time series error-correction model:

$$\begin{aligned} \Delta q_{i,t} = \alpha_i &+ \left[\sum_{j=1}^{J} \beta^T_j \Delta \mathcal{E}^T_{j,i,t} + \sum_{k=1}^{K} \beta^H_k \Delta \mathcal{E}^H_{k,i,t} + \Delta \mathbf{X}_{i,t} \boldsymbol{\eta} \right] \\ &+ \theta \left\{ q_{i,t-1} - \sum_{j=1}^{J} \gamma^T_j \mathcal{E}^T_{j,i,t-1} - \sum_{k=1}^{K} \gamma^H_k \mathcal{E}^H_{k,i,t-1} - \mathbf{X}_{i,t-1} \boldsymbol{\lambda} \right\} + u_{i,t} \end{aligned} \tag{7}$$

where α is a fixed effect that captures the influence of unobserved time-invariant country-specific factors on the average growth rate of energy demand, and u is a random disturbance term.

Eq. (7) partitions the influence of the covariates into short- and long-run effects, captured by the terms in square and curly braces, respectively. The former are identified from the contemporaneous co-variation between interannual differences of energy use and of the regressors. The latter are identified from the co-variation between interannual differences of lagged energy use and of previous year covariates. The error-correction speed of adjustment parameter, θ, measures countries' common rate of adjustment toward the long-run equilibrium. The parameter vectors $\boldsymbol{\beta}^T$ and $\boldsymbol{\beta}^H$ identify the disequilibrium demand response to meteorology in the short run, while $\boldsymbol{\gamma}^T$ and $\boldsymbol{\gamma}^H$ capture the feedback of the divergence between observed demand and the long-term equilibrium. The long-run demand response can be computed as the cumulative disequilibirum demand response throughout the adjustment period, which is given by $-\gamma/\theta$. The individual coefficient estimates are semi-elasticities that indicate the percentage by which demand shifts relative to its conditional mean level due to additional time spent in a given interval, which are the distinct marginal effects of each exposure range (e.g., the average annual impact of an additional day with 10-15 °C versus 25-30 °C temperatures). Collectively, the elements of $\boldsymbol{\gamma}^v$ flexibly capture variable v's long-run effect of as a piecewise linear spline, whose shape is determined by the covariation between observed demand and meteorology within each interval, as well as the distribution of observations across intervals over the historical period of the sample. The advantage of this formulation is its ability to capture potential nonlinearity in the demand responses to weather (cf Fig. 1) and more precisely resolve the effects of extreme heat and humidity relative to alternative specifications such as seasonally averaged temperatures or degree-days.

2.2 Data

Our dataset is a balanced panel of 29-48 countries, depending on the fuel-sector combination, over the period 1978-2010, stratified by climatic regime into tropical or temperate groups according to the Koeppen-Geiger classification. Our dependent variable is weather-sensitive final energy consumption from the International Energy Agency (IEA) World Energy Statistics and Balances (Table 1). Of the 108 exajoules (EJ) of such energy consumed in 2010,[2] tropical countries accounted for less than one-fifth, with household and commercial demand skewed toward temperate regions (by factors of five and ten, respectively). The interfuel distribution is dominated by electricity (55%) with natural gas a close second (48%), a pattern which is shared by both tropical and temperature regions. The intersectoral distribution is more even, but global concentrations in industry (45%) and to a lesser extent households (32%) reflect temperate countries' energy systems. In the tropics industrial demand is more than double residential. In agriculture electricity is overwhelmingly dominant. Topical commercial demand is almost entirely satisfied by electricity, while in temperate regions it supplies two-thirds of demand, with the other third supplied by natural gas. Industrial demand for electricity demand is slightly less than that for gas in the tropics, but more than twice as large in temperate countries. Residential electricity and gas are similar in temperate countries, whereas in tropical areas electricity satisfies 65% of final energy demand.

Our meteorological covariates are derived from gridded 3-hourly fields of surface temperature and specific humidity from the Global Land Data Assimilation System (GLDAS) dataset (Rodell et al, 2004). Following eq. (5) we first temporally aggregate the raw meteorological data to construct daily averages in each grid cell before binning them into the different intervals over the course of each year. We then spatially ag-

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[2] Global total final energy consumption in 2010 was 376 EJ. Our total is lower because we omit energy use in transportation and not all countries report demand for all fuel × sector combinations.

	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*
	Tropical				Temperate				World			
Agriculture	0.8	0.0	0.1	*0.9*	0.8	0.2	0.0	*1.1*	1.6	0.3	0.2	*2.0*
Commercial	2.4	0.3	0.1	*2.8*	12.5	7.2	0.3	*20.0*	14.9	7.5	0.3	*22.7*
Industrial	4.5	5.7	1.8	*11.9*	21.6	13.7	1.5	*36.8*	26.1	19.4	3.3	*48.7*
Residential	3.5	1.9	0.0	*5.5*	14.0	15.7	0.0	*29.7*	17.6	17.6	0.0	*35.2*
Total	*11.2*	*8.0*	*2.0*	*21.1*	*49.0*	*36.8*	*1.8*	*87.6*	*60.2*	*44.7*	*3.8*	*108.7*

Table 1: Global weather-sensitive final energy consumption in 2010 (EJ)

gregate the resulting counts of daily exposure to the country level using geospatially referenced population for the year 2000 from the Global Rural-Urban Mapping Project (GRUMPv1). As dynamic population maps were not available, we assume identical weights for all years in our sample, $\overline{w}_{c,i,\text{Current}}$. Our base statistical control is PPP GDP per capita from the Penn World Table (Heston et al, 2013). Descriptive statistics are summarized in the appendix (Table A1).

2.3 Projecting the impacts of climate change

The second phase of our analysis combines econometrically estimated long-run elasticities with scenarios of climate change and global socio-economic development to characterize future impacts on energy demand, circa 2050. Projected changes in meteorology due to climate warming are taken from simulations of the CMCC-CM earth system model (Scoccimarro et al, 2011). We consider ESM runs under two representative concentration pathways (RCPs, Van Vuuren, 2012) that are illustrative of medium and high warming scenarios: RCP 4.5 and RCP 8.5, with radiative forcing of 4.5 W/m^{-2} and 8.5 W/m^{-2}, respectively, by century's end. ESM projections of climate are subject to considerable uncertainty, with models reproducing historical weather observations at different spatial scales with varying degrees of reliability. Observed and modeled surface temperatures tend to be in closest agreement, but despite agreement in the latitudinal-longitudinal distribution of moisture, large uncertainties remain in the vertical structure of water vapor (Flato et al, 2013). For this reason we restrict our attention to temperature as the main climatic driver of changes in sectors' demand for different fuels. Additionally, individual ESM reconstructions of historical climate exhibit biases that tend to increase with spatial and temporal resolution, which threatens the validity of direct comparison between ESM simulations of future climate and observations of the current climate. To minimize the potential for bias we employ the "delta" method of comparing ESM simulations of the current and future climate, applying (5) to CMCC-CM gridded model output to construct annualized PDFs of temperature exposures over the base and projection periods 2006-2015 and 2046-2055, denoted as $\widetilde{\varepsilon}^{T}_{j,c,\text{Current}}$ and $\widetilde{\varepsilon}^{T}_{j,c,\text{Future}}$, respectively.

The results, summarized in Fig. 2, indicate that the majority of grid cells will experience increased frequency of hot days (mean temperature $> 27.5°\text{C}$) and decreased frequency of cold days (mean temperature $< 0°\text{C}$). The geographic incidence of these changes in uneven. Hot days become much more common in the tropics, whereas cold days decrease, especially in temperate regions. Particularly in large countries such as the U.S., China, Australia, and Brazil heat increases and cold declines are localized in different sub-national zones. In Southern Europe hot days become more frequent but cold days will be more rare. The empirical question is the sign and magnitude of the country-specific final energy demand consequences, as more electricity will be used for summer cooling, but less electricity, gas, and oil will be used for winter heating.

Our basic measure of climate change impact is the change in per capita energy demand[3]at the grid-cell level, c, which we calculate by combining the fitted long-run climatic estimates in (7) with our synthetic historical and future exposure series:

$$\phi^{\text{Climate}}_{c,f,s} = \exp\left\{ \sum_{j=1}^{J} \widehat{\gamma}^{T}_{j,f,s} \left(\widetilde{\varepsilon}^{T}_{j,c,\text{Future}} - \widetilde{\varepsilon}^{T}_{j,c,\text{Current}} \right) \right\} \tag{8}$$

The index ϕ^{Climate} can be interpreted as the ratio of per-capita fuel × sector energy consumption in a future climate relative to a base level of consumption under the current climate. In the empirical literature, these sorts of impact metrics are customarily used to quantify the effects that climatic shifts would have on *today's* economy. For example, using current energy consumption as the base, the net impact on contemporary country-level final energy demand, i, is found by aggregating across grid cells, fuels and sectors:

$$\Phi_{i,\text{Current}} = \frac{\sum_f \sum_s \left\{ \sum_{c \in i} \overline{w}_{c,i,\text{Current}} \phi^{\text{Climate}}_{c,f,s} \right\} \widetilde{Q}_{i,f,s,\text{Current}}}{\sum_f \sum_s \widetilde{Q}_{i,f,s,\text{Current}}} \tag{9}$$

where $\widetilde{Q}_{i,f,s,\text{Current}}$ indicates average 2006-2015 consumption.

But this approach has an important shortcoming. The future global energy system is likely to differ substantially from the present, especially given the population increase and economic expansion anticipated in the developing world. The broader implication is that assessments should account for the character of

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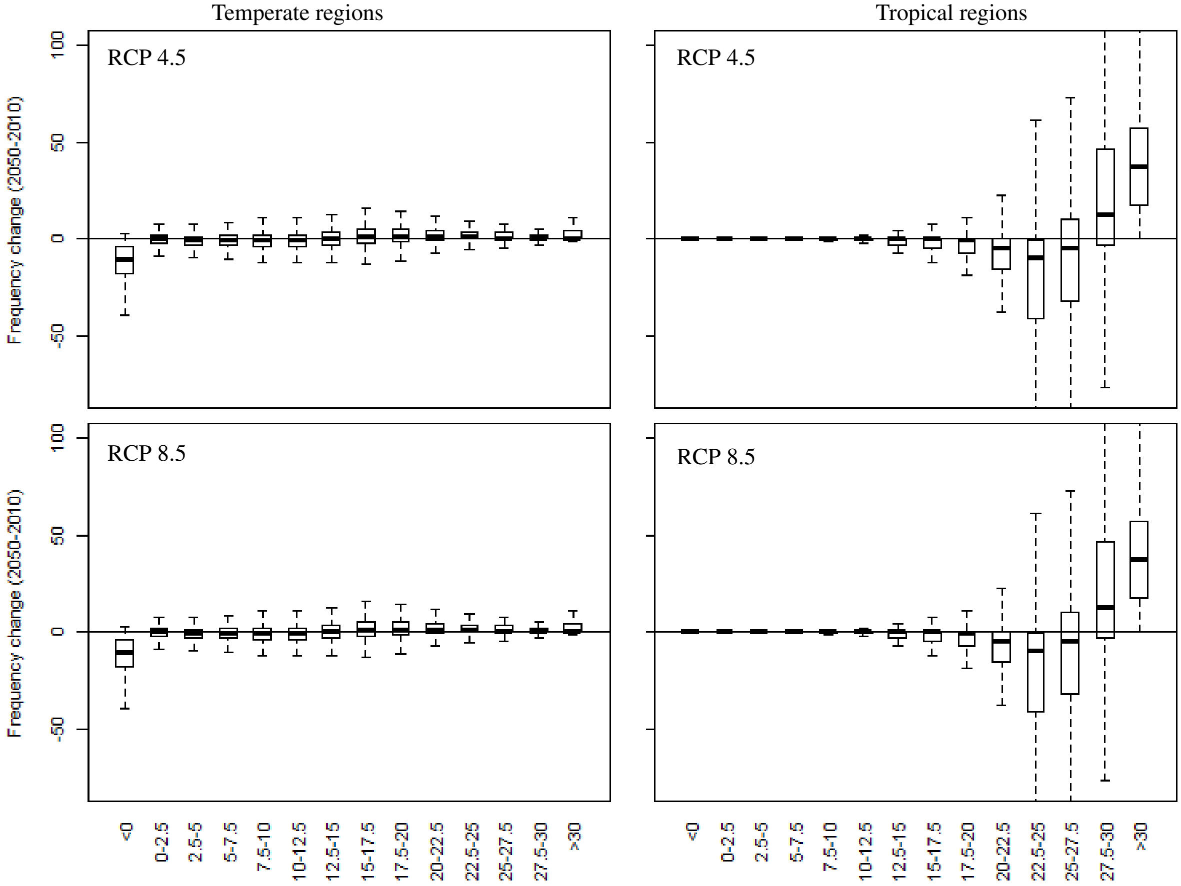
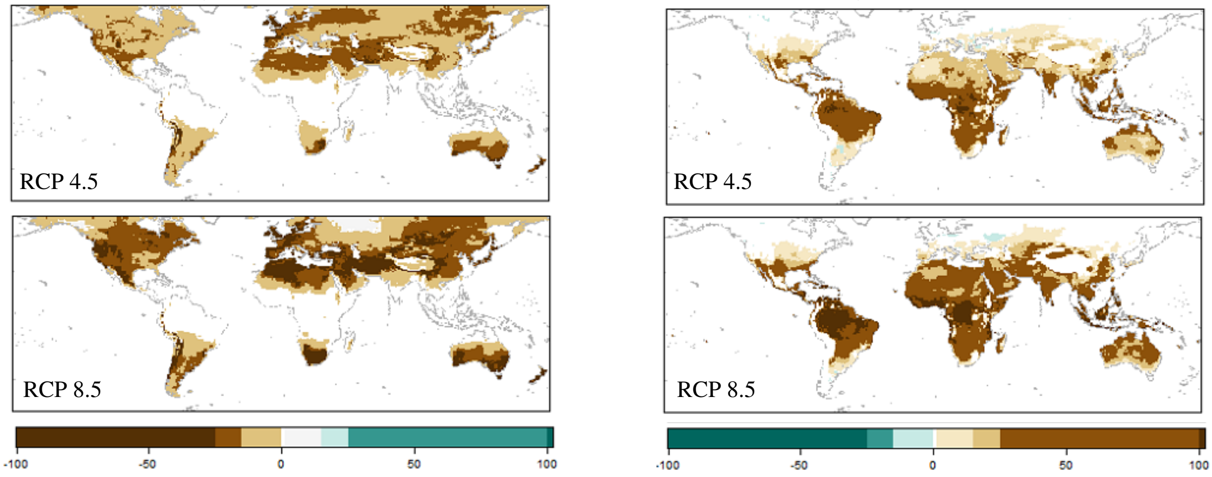
[3] Energy demand statistics are available at the country level. In the present study we assume that sub-national per capita energy demand is uniformly distributed and equal to the national average.

A. Absolute change in the distribution of daily temperatures (outliers suppressed).


Temperate regions

Tropical regions

B. % change in and future exposure to hot (left) and cold (right) days, RCP 4.5 (top) and RCP 8.5 (bottom)


Days with $\overline{T} < 12.5$°C

Days with $\overline{T} > 27.5$°C

Figure 2: CMCC-CM simulated changes in and future temperature exposure for different warming scenarios, circa 2050.

vulnerable human systems in the future periods when climatic changes generate impacts (Kriegler et al, 2012). In the present setting it is the *future* fuel × sector levels of per-capita demand to which fine spatial scale climatic shocks (8) apply. To consistently aggregate those changes across grid cells, fuels and sectors, it is therefore necessary to project the evolution of the corresponding demands in a "business as usual" (BaU) scenario of future population increase and economic expansion without climate change. We take advantage of the shared socioeconomic pathway (SSP) scenarios formulated to complement the RCPs (O'Neill et al, 2014). Our BaU scenario assumes growth rates of regional population and per-capita GDP to 2050 from SSP5,[4] yielding year-2050 gridded and national population distributions, $n_{c,\text{Future}}$ and $N_{i,\text{Future}}$ (Jones et al, 2015), as well as the logarithms of countries' average per-capita GDP in 2010 and 2050, $\widetilde{y}_{i,\text{Current}}$ and $\widetilde{y}_{i,\text{Future}}$. By combining these assumptions with long-run income elasticities estimates in eq. (7), we allow economic growth to scale the country-level per capita demands for energy:

$$\phi_{i,f,s}^{\text{Economy}} = \exp\left\{\widehat{\lambda}_{f,s}^{y}\left(\widetilde{y}_{i,\text{Future}} - \widetilde{y}_{i,\text{Current}}\right)\right\} \tag{10}$$

where $\widehat{\lambda}_{f,s}^{y}$ is the estimated long-run fuel × sector income elasticity of demand. In a "business as usual" (BaU) future in which there is no climate change, future energy consumption at the country level is:

$$Q_{i,f,s,\text{BaU}} = \phi_{i,f,s}^{\text{Economy}} \widetilde{Q}_{i,f,s,\text{Current}} \tag{11}$$

The analogue of eq. (9) accounting for future expansion in energy demand is then:

$$\Phi_{i,\text{Future}} = \frac{\sum_f \sum_s \left\{\sum_{c\in i} \overline{w}_{c,i,\text{Future}} \phi_{c,f,s}^{\text{Climate}}\right\} \widetilde{Q}_{i,f,s,\text{BaU}}}{\sum_f \sum_s \widetilde{Q}_{i,f,s,\text{BaU}}} \tag{12}$$

where the weights indicate future population exposure, $\overline{w}_{c,i,\text{Future}} = n_{c,\text{Future}}/N_{i,\text{Future}}$. The corresponding distribution of demand changes at the grid cell-level is given by the fuel, sector, and fuel × sector margins

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[4] SSP5 evisages a future with conventional economic development, slow population growth, rapid growth in aggregate productivity and international convergence of GDP, and rapid increases in final energy consumption. See the International Institute for Applied Systems Analysis (IIASA) SSP Database https://secure.iiasa.ac.at/web-apps/ene/SspDb/.

		Heating response to days with $\overline{T} < 12.5$°C		Cooling response to days with $\overline{T} > 27.5$°C		Log real GDP per capita elasticity	
		Temperate regions					
Agriculture	Electricity	–		0.021	[0.009,0.033]	0.57	[0.19,0.95]
	Fuel Oil	0.046	[0.006,0.086]	–		–	
Commercial	Electricity	-0.006	[-0.012,0]	0.019	[-0.001,0.038]	1.31	[0.9,1.72]
	Natural Gas	0.009	[0,0.019]	–		1.6	[1.12,2.08]
Industrial	Electricity	–		–		–	
	Fuel Oil	0.059	[0.008,0.11]	–		-1.32	[-2.3,-0.34]
Residential	Electricity	0.011	[0.004,0.019]	0.013	[0.005,0.021]	0.96	[0.61,1.31]
	Fuel Oil	0.099	[0.003,0.196]	–		-3.31	[-6.44,-0.18]
	Natural Gas	0.016	[0.003,0.028]	–		1.07	[0.53,1.61]
		Tropical regions					
Agriculture	Electricity	–		0.021	[0.009,0.033]	0.57	[0.19,0.95]
	Fuel Oil	0.046	[0.006,0.086]	–		–	
Commercial	Electricity	–		–		1.66	[1.26,2.07]
	Natural Gas	0.009	[0,0.019]	–		1.6	[1.12,2.08]
Industrial	Electricity	-0.023	[-0.033,-0.013]	0.004	[0,0.007]	1.31	[0.84,1.78]
	Fuel Oil	–		–		-0.62	[-1.21,-0.02]
Residential	Electricity	–		0.006	[0.002,0.01]	1.25	[1.02,1.49]
	Fuel Oil	0.099	[0.003,0.196]	–		-3.31	[-6.44,-0.18]
	Natural Gas	–		–		–	

Table 2: Long-run estimated semi-elasticities of energy demand to temperature bins. 90% confidence intervals shown in square brackets.

of (12):

$$\varphi^{\text{Fuel}}_{c,f,\text{BaU}} = \frac{\sum_s \delta_{i,c}\phi^{\text{Climate}}_{c,f,s}\widetilde{Q}_{i,f,s,\text{BaU}}}{\sum_s \delta_{i,c}\widetilde{Q}_{i,f,s,\text{BaU}}} \tag{13a}$$

$$\varphi^{\text{Sector}}_{c,s,\text{BaU}} = \frac{\sum_f \delta_{i,c}\phi^{\text{Climate}}_{c,f,s}\widetilde{Q}_{i,f,s,\text{BaU}}}{\sum_f \delta_{i,c}\widetilde{Q}_{i,f,s,\text{BaU}}} \tag{13b}$$

$$\varphi^{\text{Total}}_{c,\text{BaU}} = \frac{\sum_f \sum_s \delta_{i,c}\phi^{\text{Climate}}_{c,f,s}\widetilde{Q}_{i,f,s,\text{BaU}}}{\sum_f \sum_s \delta_{i,c}\widetilde{Q}_{i,f,s,\text{BaU}}} \tag{13c}$$

where the indicator variable, $\delta_{c,i} = 1 \cdot (\overline{w}_{c,i,\text{Future}} > 0)$, takes a value of unity if cell c lies within country i's administrative boundary, and zero otherwise.

3 Results

3.1 Empirical Results: Energy Demand Response to Weather Variation

Our main empirical findings are shown in Table 2, which summarizes the estimated long-run semi-elasticities of per capita energy final energy consumption to daily temperature exposure. Due to the small size of our sample, identification of the response to each of the 14 intervals illustrated in Fig. 2 was not possible. We therefore aggregated adjacent bins to focus on exposures to hot and cold days—$\overline{T} < 12.5$°C and $\overline{T} > 27.5$°C respectively, which we associate with consumption of energy for cooling and heating, respectively[5].

Temperature semi-elasticities are generally small in magnitude and vary across sectors, fuels and regions. Cooling energy demand in response to greater exposure to hot days is entirely satisfied by electricity, whereas the corresponding heating response is distributed among all fuels in temperate regions, and concentrated in fuel oil in the tropics. Residential and commercial cooling energy elasticities are generally small in magnitude, the more so in tropical regions. Heating energy demands in residential and industry are concentrated in fuel oil, whose elasticities are uniformly larger compared to electricity, and natural gas. In industry, electricity satisfies tropical heating and cooling energy demand, while fuel oil satisfies temperate heating energy demand.

As foreshadowed by Fig. 1, the demand responses of each fuel to heat and cold exposures are asymmetric. For most fuel × sector combinations either the heating or the cooling response is significant, and most of these effects are positive. The exceptions are residential electricity use in temperate regions, where heat and cold exposures both increase consumption, commercial electricity use in temperate regions and industrial electricity use in the tropics, which is increased (reduced) by exposure to heat (cold).

Also shown in the table are our long-run income elasticities, which are positive for gas and electricity, but negative for fuel oil, indicating a tendency to shift away from this fuel with economic growth. Energy consumption is generally income elastic outside of the agriculture sector, with the exception of industrial fuel oil in the tropics and residential electricity in temperate countries. Residential and commercial electricity demand are generally more responsive to real per capita GDP than industry and agriculture, while commercial demand for natural gas is more responsive than in the residential sector.

Estimated effects of humidity and other covariates are reported in Tables A2-A4. Exposure to high and low extremes of specific humidity both significantly affect agricultural electricity consumption, while low humidity influences commercial and residential electricity demand in the tropics. High humidity increases electricity use in the residential and industrial sector, but in agriculture the reverse is true, as high humidity is correlated with precipitation and concomitant reductions in movement of water for irrigation, which in some regions can be a major source of electricity use in agriculture (see, e.g., Maddigan at al , 1982; Shah

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[5] Changes in temperature also affects final energy demand for other usages, such as cooking and heating water. Within each sector, the energy data used in this paper do not distinguish demand by purpose. Cooling and heating are the major usages to be sensitive to weather variations.

	Tropical				Temperate				World			
	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*
					2050 Energy Consumption (EJ)							
Agriculture	3.1	0.0	0.2	*3.3*	2.4	0.3	0.0	*2.8*	5.5	0.3	0.2	*6.0*
Commercial	56.7	4.1	0.1	*60.9*	62.4	50.6	0.3	*113.4*	119.1	54.7	0.4	*174.3*
Industrial	73.9	8.4	1.0	*83.4*	49.5	18.1	0.5	*68.0*	123.4	26.5	1.5	*151.4*
Residential	47.4	2.3	0.0	*49.7*	54.0	66.1	0.0	*120.1*	101.3	68.4	0.0	*169.8*
Total	*181.1*	*14.9*	*1.3*	197.3	*168.3*	*135.1*	*0.8*	304.2	*349.3*	*150.0*	*2.1*	501.5
					Energy Consumption Growth Factor (2010 = 1.0)							
Agriculture	4.0	1.2	1.2	*3.5*	2.9	1.3	1.4	*2.5*	3.4	1.3	1.2	*3.0*
Commercial	23.8	13.4	1.3	*22.0*	5.0	7.0	1.3	*5.7*	8.0	7.3	1.3	*7.7*
Industrial	16.6	1.5	0.6	*7.0*	2.3	1.3	0.3	*1.8*	4.7	1.4	0.5	*3.1*
Residential	13.3	1.2	0.0	*9.1*	3.8	4.2	0.1	*4.0*	5.8	3.9	0.1	*4.8*
Total	*16.2*	*1.9*	*0.6*	9.3	*3.4*	*3.7*	*0.5*	3.5	*5.8*	*3.4*	*0.6*	4.6

Table 3: Global weather-sensitive final energy consumption circa 2050 and change relative to 2010

et al, 2008).

Long-run demand responses to temperature exceed their short-run counterparts. The error correcting speed of adjustment coefficient is negative and significant in all fuel × sector combinations, indicating that sectors adjust their energy consumption to contemporaneous weather shocks at rates of 6-8% per year in the case of electricity, 14-32% in the case of gas, and 6-28% in the case of fuel oil. Tropical countries tend to adjust more quickly, behavior which is consistent with their stocks of energy-using capital that are smaller.

3.2 The 2050 Baseline: Energy Consumption and Climate Change Exposure

Our first step is to use the foregoing empirical results in conjunction with SSP5 projections of per capita GDP growth to the year 2050 to calculate future BaU energy consumption according to eqs. (10) and (11). The results, summarized in Table 3, indicate that without climate change total weather-sensitive energy demand can be expected to reach 502 EJ, an almost five-fold increase over 2010. This total is within the general range of integrated assessment model (IAM) simulation results, which project global total final energy demand between 733 and 869 EJ in 2050.[6] Table 3 highlights the heterogenous change in energy demand across regions, sectors and fuels, reflecting the different relationship with socioeconomic growth. Compared to the current energy system, the 2050 fuel mix is more skewed toward electricity (68%) with

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[6] According to the IIASA-SSP database, for the SSP5 reference scenario liquid fuels account for 360-405 EJ of 2050 final energy, leaving 230-250 EJ to electricity and 102-154 EJ to gaseous fuel. Our projections for natural gas are at the high end of this range, and for electricity are some 40% higher. Symmetrically, transportation uses 264-299 EJ, implicitly leaving 469-570 EJ to be consumed by the residential, commercial and industry sectors.

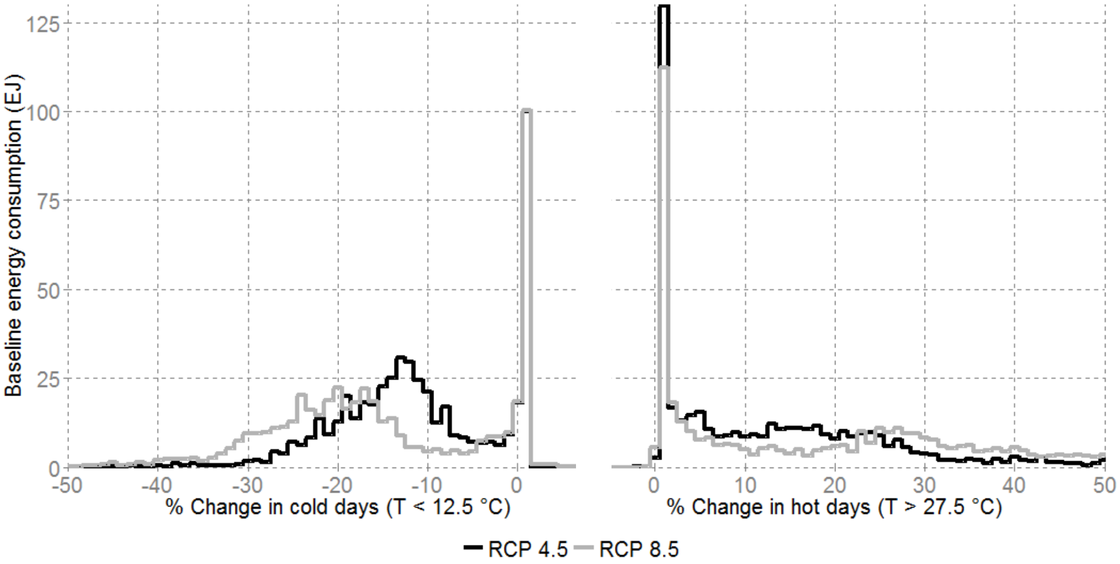

Figure 3: Exposure of business as usual energy demand to temperature changes

the sectoral distribution of energy use dominated by commercial and residential consumption. We see a ninefold increase in final energy consumed by emerging economies in the tropics, and a quadrupling of energy demand in more advanced nations at high latitudes, which together portend a shift in developing countries share of global energy use from the current 20% to 60% by mid-century.

Fig. 3 summarizes how the regional patterns of projected future energy consumption intersect with the climatic changes highlighted in Fig. 2.B. In 2050 nearly half of energy consumption is unaffected by climate change. Where there is an effect, energy use has the largest spatial overlap with zones exposed to either moderate declines in the frequency of cold days or slight increases in the frequency of hot days. Absolute increases in hot days are concentrated in Southeast Asia, Latin America and Sub-Saharan Africa, where per capita and total final energy use are small but the frequency of hot days under the current climate is already high. As a consequence, the distribution of energy consumption exposure to growth in high temperatures exhibits a long upper tail, with small quantities of energy use exposed to a wide range of percentage increases in heat (25% to more than 400%). These patterns are accentuated when warming is more vigorous, which results in increased exposure of energy consumption in areas with larger proportional reductions (increases) in cold (hot) days.

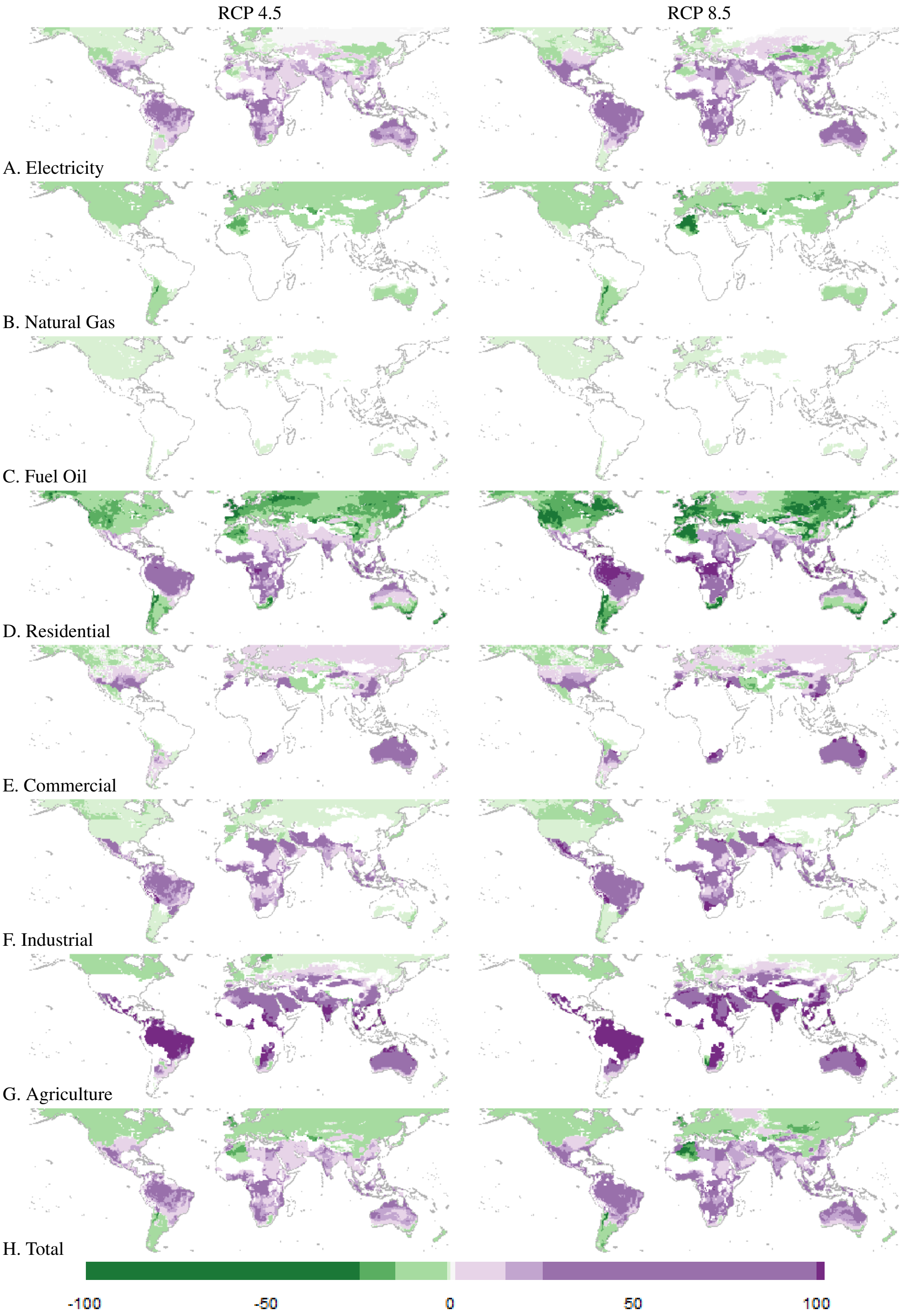

Figure 4: CMCC-CM simulated impacts on final energy demand for different warming scenarios (RCP4.5 and RCP8.5) circa 2050

3.3 Climate Change Impacts on Future Energy Consumption

The stratification of our econometric estimates means that a key determinant of the direction of climate change impact is distance from the equator, with the implication that tropical (temperate) responses disproportionately drive demand changes in developing (advanced) countries (cf Fig. 2). Fig. 4 presents the future potential change in the demand for energy at the grid-cell level for our three fuels (panels A-C), four sectors (panels D-G), and in total (panel H). Projected changes in energy demand are calculated using eqs. (13a)-(13c). They take into account the character of the future energy system, as aggregate changes by sector and fuel are based on the projected fuel and sectoral mix described in Table 3.

The decreased frequency of cold days in Fig. 2 interacts with the fuel × sector responses described in Table 2 to lower the demand for oil and gas where low temperatures are experienced. Electricity demand increases unequivocally in the tropics, as the industrial, residential, and agriculture sectors demand more energy to cope with more frequent warm days. Potential impacts in temperate regions are mixed, but positive changes tend to prevail in the regions where commercial and residential activities are concentrated. Overall, future potential impacts on total final consumption depends on the prevailing energy source used across sectors, as well as on the projected expansion of their size. Positive changes in energy demand are concentrated in developing and industrializing economies located in tropical areas such as Sub-Saharan Africa, Central America, and South- and South-East Asia. In contrast to RCP 8.5, moderate warming reduces the magnitude of potential impacts, but regional patterns of × sectoral × fuel changes are similar in both warming scenarios.

Fig. 5 illustrates how these grid cell-level shocks are distributed across countries at different income levels defined as the approximate terciles of the SSP5 country per-capita GDP projections.[7] Under both warming scenarios more than 70% of the world's projected 7.9 billion people experience changes in weather-sensitive energy consumption in excess of $\pm 5\%$, with the majority of those affected seeing increases. At the global level these impacts are regressive. The incidence of increased energy consumption rests overwhelmingly on populations in low- and middle-income countries (around 75% and 85%, respectively), while populations of high-income countries are split evenly between energy consumption increases and declines. Where warming scenarios diverge is in the upper tail of the impact distribution. Declines of more than 25% are virtually non-existent in either scenario. With moderate warming, 15% of the world's population expe-

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[7] Low income: <\$9,750, Middle income: \$9750 - \$29,000, High income: > \$29,000.

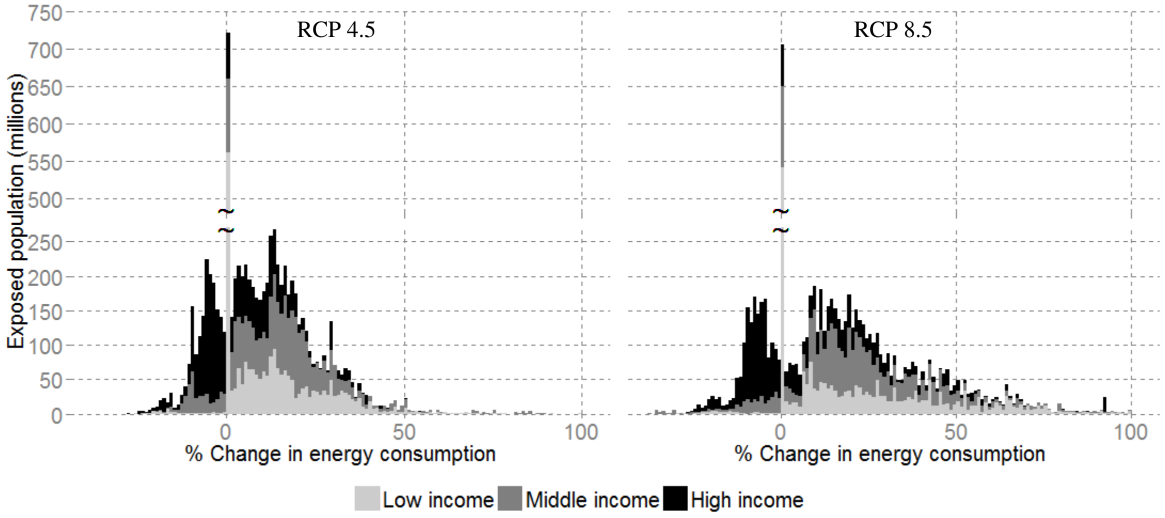

Figure 5: Incidence of Climate Change Impacts on Energy Demand

riences a $> 25\%$ increase in demand, a fraction which doubles with vigorous warming. Moreover, in both cases around 40% of individuals experiencing such large increases live in poor countries.

Fig. 6 illustrates how these changes aggregate to the country level, focusing on the 20 largest economies which are responsible for about 80% of global energy use. Impacts on agricultural energy consumption are large in percentage changes, though small in absolute magnitude because the use of energy in the agriculture sector is relatively small. With the exception of a few developed countries, impacts generally increase with warming. Commercial energy consumption also exhibits widespread increases that tend to be concentrated in developed countries outside of Europe. These changes, which are generally more modest in size compared to the other sectors, are exceeded by the magnitude of impacts in developing countries, though a number of energy-intensive developing economies see small declines. Industrial and residential energy use decline in advanced nations, but exhibits a mix of increases and decreases in the developing world. In developed countries residential energy consumption declines exceed those in industry. In developing countries the responses of the two sectors are similar in magnitude, and generally larger than in the developed world.

These patterns of response are amplified by stronger radiative forcing. The impacts on aggregate energy consumption that arise from the superposition of these changes are mostly negative in advanced countries, and mostly positive in developing nations. Aggregating changes in demand to the regional level, South America, Asia and Africa see ubiquitous increases, while Europe, North America and Oceania exhibit mixed responses but with consistent reductions in the residential sector. Even so, only Europe and Oceania in the

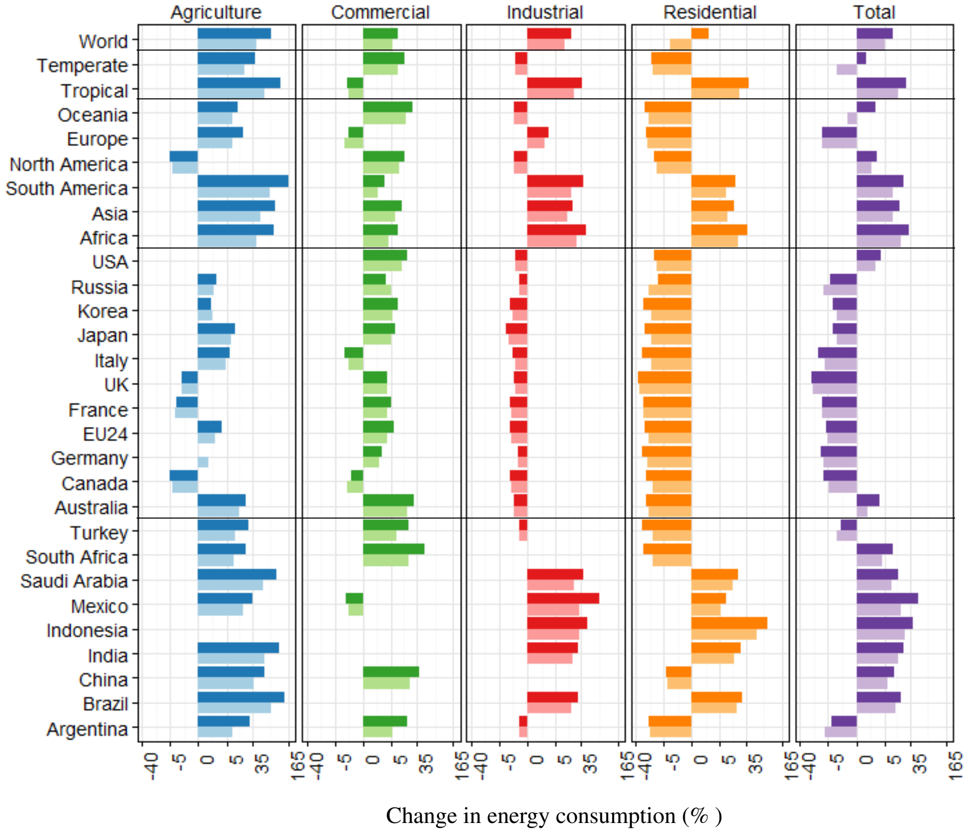

Figure 6: Sectoral and aggregate energy demand responses of G20 nations and world regions to different warming scenarios (RCP 4.5—light colors, RCP 8.5—dark colors) circa 2050.

moderate warming scenario experiences aggregate reductions in energy use. The global consequences are that countries in the tropics collectively experience modest increase in demand under both mild and vigorous warming, while temperate countries collectively see demand slightly decreasing with mild warming, but slightly increasing with vigorous warming. Under both warming scenarios there is a modest increase in global energy consumption, by 6% and 11%, respectively.

Lastly, Table 4 breaks down the intersectoral and interfuel distribution of projected consumption changes in physical units (EJ). Panel A revisits eq. (9), summarizing the shifts in energy consumption brought by the impacts of climate change on today's energy system. By constrast, panel B summarizes the combined effects of changing socio-economic and climatic conditions that have been the focus of this section. Accounting for the growth in size and shift in sectoral composition of the global energy economy increases impacts' size by an order or magnitude. Tropical countries account for most of the increase in energy consumption above BaU levels, which is concentrated in the industrial and residential sectors. In temperate areas, the large increase in commercial energy consumption is substantially offset by declines in residential and industrial consumption. Overall, changes in climate can be expected to increase global demand for energy by 55 EJ, a shift which is of secondary importance compared with the effect of economic expansion.

3.4 Sensitivity Analysis

The results thus far are point projections constructed at the means of our estimated responses to temperature and income. Given the small size of our estimation sample and the consequent imprecision in our long-run estimates, it is important to assess how sensitive our impact projections are to uncertainty in these responses. To this end, we evaluate the sensitivity of the impact projections that underlie Table 4 at the confidence bounds of our parameter estimates. For simplicity and tractability we assume independence among fuel × sector combinations, and between the responses to temperature and to GDP, setting all estimates to their lower, and then upper, bounds.

Table 5 shows our sensitivity results at the global level.[8] We first examine the range of hypothetical impact that an uncertain response to a given change in the climate circa 2050 would have on today's energy system (Panel A). The near-zero effects in Table 4.A reflect the potential for small increases or declines, to the tune of -1.2% to 2.2% (2.5% to 3.8%) of current world energy consumption in the RCP 4.5 (RCP 8.5) scenario. Turning to the consequences for the 2050 energy system, Panel B summarizes the effect of uncer-

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[8] Underlying fuel × region detail is reported in the appendix, see Table A9.

	RCP 4.5				RCP 8.5			
	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*
	A. Current energy system							
	Tropical							
Agriculture	0.53	0.00	0.00	*0.53*	1.01	0.00	0.00	*1.01*
Commercial	0.00	-0.04	0.00	*-0.04*	0.00	-0.05	0.00	*-0.05*
Industrial	1.25	0.00	0.00	*1.25*	2.15	0.00	0.00	*2.15*
Residential	0.76	0.00	0.00	*0.76*	1.29	0.00	0.00	*1.29*
Total	*2.55*	*-0.04*	*0.00*	2.50	*4.45*	*-0.05*	*0.00*	4.39
	Temperate							
Agriculture	0.18	0.00	-0.01	*0.17*	0.32	0.00	-0.02	*0.31*
Commercial	2.82	-0.78	0.00	*2.04*	4.22	-1.04	0.00	*3.18*
Industrial	0.00	0.00	-0.76	*-0.76*	0.00	0.00	-0.97	*-0.97*
Residential	-1.14	-3.04	-0.02	*-4.21*	-1.41	-3.71	-0.03	*-5.16*
Total	*1.85*	*-3.82*	*-0.79*	-2.76	*3.13*	*-4.75*	*-1.02*	-2.64
	World							
Agriculture	0.71	0.00	-0.01	*0.70*	1.33	0.00	-0.02	*1.32*
Commercial	2.82	-0.82	0.00	*2.00*	4.22	-1.09	0.00	*3.13*
Industrial	1.25	0.00	-0.76	*0.49*	2.15	0.00	-0.97	*1.17*
Residential	-0.38	-3.04	-0.02	*-3.45*	-0.12	-3.71	-0.03	*-3.86*
Total	*4.40*	*-3.86*	*-0.80*	-0.26	*7.58*	*-4.80*	*-1.02*	1.75
	B. Energy system circa 2050							
	Tropical							
Agriculture	2.14	0.00	0.00	*2.14*	4.03	0.00	-0.01	*4.03*
Commercial	0.00	-0.41	0.00	*-0.41*	0.00	-0.54	0.00	*-0.54*
Industrial	19.04	0.00	0.00	*19.04*	30.62	0.00	0.00	*30.62*
Residential	12.11	0.00	0.00	*12.11*	20.42	0.00	0.00	*20.42*
Total	*33.30*	*-0.41*	*0.00*	32.88	*55.08*	*-0.54*	*-0.01*	54.54
	Temperate							
Agriculture	0.62	0.00	-0.02	*0.61*	1.12	0.00	-0.02	*1.10*
Commercial	16.43	-5.83	0.00	*10.60*	25.82	-7.58	0.00	*18.24*
Industrial	0.00	0.00	-0.24	*-0.24*	0.00	0.00	-0.30	*-0.30*
Residential	-2.84	-12.75	0.00	*-15.60*	-3.20	-15.26	0.00	*-18.46*
Total	*14.21*	*-18.58*	*-0.26*	-4.63	*23.74*	*-22.84*	*-0.32*	0.58
	World							
Agriculture	2.76	0.00	-0.02	*2.74*	5.16	0.00	-0.03	*5.13*
Commercial	16.43	-6.24	0.00	*10.19*	25.82	-8.12	0.00	*17.70*
Industrial	19.04	0.00	-0.24	*18.80*	30.62	0.00	-0.30	*30.32*
Residential	9.27	-12.75	0.00	*-3.48*	17.22	-15.26	0.00	*1.96*
Total	*47.51*	*-18.99*	*-0.26*	28.26	*78.82*	*-23.38*	*-0.33*	55.12

Table 4: Sectoral and aggregate energy demand responses (EJ) for world regions for different warming scenarios circa 2050.

	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	A. Current energy system: sensitivity to temperature elasticities		B. 2050 energy system: sensitivity to GDP elasticity	
Agriculture	[0.26, 1.33]	[0.44, 2.97]	[1.23, 6.24]	[2.31, 11.60]
Commercial	[1.81, 2.49]	[3.38, 3.51]	[6.29,17.90]	[10.46, 32.67]
Industrial	[0.48, 0.90]	[1.44, 1.67]	[7.20,52.21]	[11.89, 82.69]
Residential	[-4.97,-1.21]	[-5.06,-1.50]	[-8.47,-1.39]	[0.69, 1.88]
Total	*[-1.35, 2.44]*	*[2.73, 4.12]*	*[13.33,67.88]*	*[26.54,127.65]*
	C. 2050 energy system: sensitivity to temperature elasticities		D. 2050 energy system: sensitivity to GDP and temperature elasticities	
Agriculture	[1.00, 5.20]	[1.69,11.36]	[0.44, 11.78]	[0.76, 25.31]
Commercial	[10.96,12.00]	[17.03,24.33]	[7.65, 21.16]	[10.80, 49.62]
Industrial	[13.14,26.28]	[21.02,44.51]	[5.44, 76.61]	[9.12,129.02]
Residential	[-1.82,-0.46]	[-1.20,14.79]	[-6.14, -0.98]	[-0.58, 19.51]
Total	*[24.32,41.98]*	*[38.54,94.99]*	*[12.55,103.41]*	*[20.10,223.46]*

Table 5: Sensitivity Analysis: Sectoral and aggregate energy demand responses (EJ) for world regions under different warming scenarios circa 2050.

tainty in income-driven growth of energy under the mean responses to temperature. Similar to our findings of the importance of increased exposure due to economic growth, these impacts are positive and larger in both absolute and percentage terms: 5.0-5.9% and 9.9-11.0% of baseline final energy use (respectively) under RCP 4.5 and 8.5. Symmetrically, Panel C shows the effect of uncertainty in the temperature response at our mean income elasticities. In relative terms the amplitude of the impact is amplifed relative to the effect of income uncertainty, ranging between a 4.8-8.4% and 7.7% and 18.9% increase in baseline demand under moderate and vigorous warming, respectively. Panel D emphasizes that when the effects of GDP and temperature response uncertainties are combined, the range of potential changes in demand is unequivocally positive but very wide. Uncertainty in responses is not additive, and generates increases of 4.7-8.9% under moderate warming, and 7.5-19.3% under rapid warming.

Our results highlight the long upper tail of impacts that arises purely from uncertainties in energy consumption's responses to income and meteorology. Even so, the upper bounds in Table 5.D may well understate the true uncertainty because our projections of temperature change rely on a single scenario of economic growth, and projections of future temperature change from a single ESM. Incorporating additional GDP forecasts and multiple spatial fields of temperature change projected by additional ESMs will almost surely broaden the envelope of uncertainty, but we leave such investigations to future research.

4 Discussion

4.1 Robustness Checks

Empirically-based projections of climate change impact are only as good as their underlying econometric models of the response of impact endpoints to meteorological variation. We assess the quality of our response estimates by making three comparisons: with first-difference and static models, taking a more nuanced look at the extensive margin, and including energy prices.

The fairly large values found for the error-correcting speed of adjustment raise the question of what difference our dynamic modeling approach makes to the elasticities used to project changes in energy consumption. To test this, we estimate analogues of eq. (7) in the form of the static and first-difference regressions shown below:

$$q_{i,t} = {}^{*}\alpha_i + {}^{*}\omega_t + \sum_{j=1}^{J} {}^{*}\gamma_j^T \mathcal{E}_{j,i,t}^T + \sum_{k=1}^{K} {}^{*}\gamma_k^H \mathcal{E}_{k,i,t}^H + {}^{*}\lambda y_{i,t} + {}^{*}u_{i,t} \tag{14}$$

$$\Delta q_{i,t} = {}^{**}\alpha_i + \sum_{j=1}^{J} {}^{**}\gamma_j^T \Delta\mathcal{E}_{j,i,t}^T + \sum_{k=1}^{K} {}^{**}\gamma_k^H \Delta\mathcal{E}_{k,i,t}^H + {}^{**}\lambda \Delta y_{i,t} + {}^{**}u_{i,t} \tag{15}$$

The results, reported in the appendix (Tables A6 and A5), share many attributes of our estimates in Table 2. Most fuel × sector combinations are characterized by an asymmetric response, with exposure to hot days increasing electricity consumption with a larger impact in the residential sector in temperate regions and the commercial sector in the tropics. Energy residential consumption from natural gas responds to exposure to cold days in temperate regions, whereas residential fuel oil is affected by an increase in cold days in both temperate and tropical countries. However several differences are apparent. The first difference estimates (${}^{**}\gamma^T$) substantially understate our long-run results, and are comparable in magnitude to our short-run semi-elasticities (cf Tables A2, A3, and A4). The static estimates (${}^{**}\gamma^T$) in some cases overstate and in others understate our long-run responses. Notably, income elasticities of fuel oil demand are positive, but those for the remaining fuels are generally similar in sign and magnitude to Table 2.

We now turn to the effect of extensive margin adjustments arising from changes in the quantity and/or quality of stocks of energy-using durables. Historical data on capital stocks with sufficient spatial granularity are not available at the global scale. As both investment and capital stocks are strongly correlated with per capita income, we use real per capita GDP as a proxy. An important question raised by our approach is the possibility that our capital stock proxies, z, affect the *marginal* effect of temperature and humidity, through, for example, interactions with weather exposure. To test this, we estimate the following model with interaction terms:

$$\begin{aligned}\Delta q_{i,t} = \alpha_i + \left[\sum_{j=1}^{J} \beta_j^T \Delta(\mathcal{E}_{j,i,t}^T z_{i,t}) + \sum_{k=1}^{K} \beta_k^H \Delta(\mathcal{E}_{k,i,t}^H z_{i,t}) + \eta \Delta x_{i,t}\right] \\ + \theta \left\{ q_{i,t-1} - \sum_{j=1}^{J} \gamma_j^T (\mathcal{E}_{j,i,t-1}^T z_{i,t-1}) - \sum_{k=1}^{K} \gamma_k^H (\mathcal{E}_{k,i,t-1}^H z_{i,t-1}) - \lambda x_{i,t-1} \right\} + u_{i,t} \qquad (16)\end{aligned}$$

We explore interactions with four proxies for weather-exposed capital stocks: the log of per capita GDP, the log of aggregate country capital stocks from Berlemann and Wesselhoft (2014), and accumulated real imports of heating and cooling equipment and machinery and transport equipment, taken from International Trade Statistics by Commodity.[9] We focus on residential electricity consumption, the fuel × sector combination with the largest number of observations.

Long-run semi-elasticities are reported in Table 6 whereas full regression results are given in Table A7. The marginal effect of temperature and humidity depends on the capital stock quantitiy, and therefore the marginal effect in each country is computed by multiplying the elasticities in Table 6 with 2010 value of the capital stock proxies. The boxplots in Figure 7 summarize the distribution in marginal effects of temperature across countries for the alternative proxies of capital stock used. The heterogeneity in the marginal responses is small and centered around the estimates from the main model specification described in Section 2.

Finally, our preferred specifications omit energy prices as controls due to lack of data, particularly for countries in the tropics. Even in temperate countries, the main data source, the International Energy Agency's Energy Prices and Taxes series,[10] suffers from gaps as well, so much so that limiting ourselves to countries with energy price data dramatically reduces our already small sample size. As prices are endogenously determined we include their one-period lag as covariates. With these caveats, Table A8 summarizes the results of tests of the robustness of our residential electricity semi-elasticities to the inclusion of household energy prices. Own-price elasticities are negative and significant, but do not appreciably change the estimated temperature semi-elasticites.

Interestingly, the largest impact of including energy prices is to reduce the speed of adjustment toward

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[9] SITC Rev 2 Commodity 741 and 7, respectively, http://comtrade.un.org/

[10] http://www.iea.org/

	Real GDP per capita		Aggregate capital stock		Heating/cooling equip.		Machinery/transport equip.	
	Temperate countries							
Log real GDP per capita	0.7193	[.2772-1.1614]	.8373	[.4066-1.2679]	.7483	[.2379-1.2587]	.7855	[.2302-1.3408]
$\overline{T} < 12.5$°C	.0010	[.0001-.002]	.0003	[.0001-.0006]		–	.0003	[.0000-.0006]
$\overline{T} > 27.5$°C	.0014	[.0006-.0022]	.0004	[.0000-.0008]	.0006	[.0002-.0009]	.0006	[.0001-.001]
	Tropical countries							
Log real GDP per capita	.9437	[.5854-1.302]	1.1744	[.7324-1.6163]	.9898	[.7172-1.2624]	1.016	[.6534-1.3785]
$\overline{T} < 12.5$°C		–	-.0006	[-.0011 - -.0001]		–	.0002	[.0001-.0004]
$\overline{T} > 27.5$°C	.0005	[.000-.0011]	.0002	[.0000-.0005]		–	.0002	[.0000-.0004]

Table 6: Long-run estimated semi-elasticities (90% confidence intervals) of energy demand to temperature bins with interaction terms. Robustness to different proxy variables for capital stock.

long-run equilibrium. The upshot is a 13% increase in the long-run effect of exposure to > 27.5°C days on energy consumption, a result which is consistent with adaptation. Price-driven energy demand adjustments are passive general equilibrium adaptations (Sue Wing and Fisher-Vanden, 2013), which our estimates suggest may have masked about 13% of the long-run impact of heat in temperature countries over the period of our sample, that our residential electricity impacts in temperate countries should be a interpreted as a lower bound. However, precisely because of the data issues discussed above, what this result implies less clear for other fuels or tropical countries where the bulk of the growth in energy demand is projected to occur. If we are to speculate, however, the fact that developing countries' energy markets have covered a smaller fraction of total final consumption, been more distorted, and slower to develop suggests that if expansions in demand are accompanied by substantial increases in the depth and scope of markets, then price-based adaptations can potentially lower the long-run impacts we project in Section 3.3.

4.2 Comparison with Previous Studies

Our results are generally consistent with the findings of previous regional and global studies. Regarding the relative contribution of climatic and socioeconomic drivers, our analysis shows that climate change can be expected to increase global demand for energy, but its impact is of secondary importance relative to the prevailing role of economic growth. Whereas economic expansion increases energy demand in tropical regions up to a factor of 9.3, a change in climate contributes with a factor of 1.3 (e.g., relative to the future baseline). Similar conclusions are pointed out by one of the few global studies, (Isaac and Van Vuuren, 2009), in the specific context of residential energy demand for heating and cooling, where future residential energy use will be driven by the growing demand for cooling services associated with the economic expansion of trop-

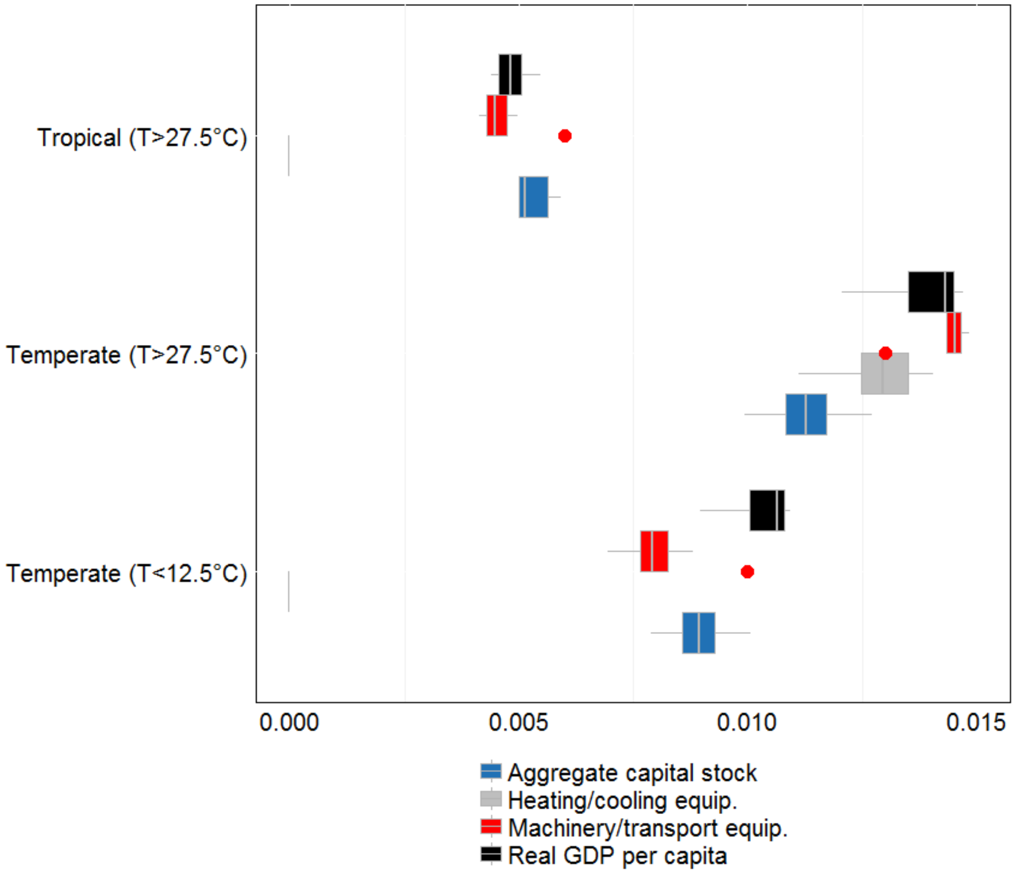

Figure 7: Sensitivity of marginal effect of temperature estimates to different capital proxies.

ical countries. The global demand for air conditioning could expand by a factor 20 in 2050, even assuming a constant climate.

Similarly to (Isaac and Van Vuuren, 2009), global aggregate changes in energy consumptions are small because of the compensating direction of changes across regions, fuels, and sectors. Yet, climate-induced changes in energy demand are disproportionally larger in tropical regions, where the overall percentage increase in total final energy consumption (26%) is greater than the one estimated for temperate countries (0.19%). Climate impacts lead to a geographic and seasonal re-distribution of energy consumption towards tropical regions and towards summer months, as most of the increase will be due to higher electricity use for cooling.

The analysis of the heterogenous response across sectors adds broader empirical evidence on sectoral heterogeneity that was previously confined to specific countries or regions, such as the Maryland State (Ruth and Lin, 2006) or Massachusetts (Amato et al, 2005). Consider for example our results for temperate regions. The small total aggregate increase in energy consumption is the result of two compensating effects across sectors, a 15% reduction in the residential sector and a 16% increase in the commercial sector. Previous regional and global studies focusing on residential energy use miss this heterogeneity and tend to find a prevailing negative impact on energy demand in temperate (De Cian, Lanzi and Roson, 2013) or Nordic countries (Pilli-Sihvola et al, 2010; Mima and Criqui, 2015). The sectoral dimension of our work points at commercial and industrial activities in temperate and tropical regions, respectively, as two sectors where changes in socioeconomic and climatic conditions could signficantly expand the use of electricity, leading to a net increase in energy demand in temperate regions, such as the United States, and globally.

5 Conclusion

This paper develops a flexible methodology to characterize geographic variations, sectoral and fuel heterogeneity in climate change impacts on global energy demand, while taking into account how vulnerable human and energy systems will change in future periods when climate changes generate impacts.

We use cross section-time series regressions to estimate short-run and long-run elasticities of energy demand with respect to different temperature and humidity intervals, controlling for other confounding factors. Long-run elasticities are subsequently combined with scenarios of climate change and socio-economic development to project the future baseline energy consumptions as well as the additional changes induced by climate change circa 2050. We map the spatial distribution of future percentage change in energy demand for the three fuels (electricity, natural gas, fuel oil), four sectors (residential, agriculture, industry, commercial), and in total. Future percentage and absolute changes (EJ) in energy demand due to socio-economic development and changes in climatic conditions are calculated globally, for different world regions, and at the country-level.

As foreshadowed by the engineering and economic literature, our estimated response of energy demand to exposure to heat and cold is asymmetric. It varies grographically, across sectors, and fuels. Electricity mostly satisfies cooling needs in the residential sector, agriculture, industry for the tropics, and in commercial activities in temperate regions. Energy consumption is income-elastic outside the agriculture sector, and with the exception of residential electricity in temperate regions and industrial fuel oil in the tropics.

Maps of grid-cell level shocks show that the majority of gridd-cells in the tropics will experience higher energy demand, driven by the increase in electricity in industry, residential, and agriculture sectors. In temperate regions the impact of climate shocks varies across sectors and fuel. Moreover, significant within-countries variation can be observed in large temperate countries, such as the United States, China, Australia.

Global energy consumption will increase by 6% and 11% under moderate (RCP4.5) and more significant (RCP8.5) warming, respectively, driven by tropical regions (16% and 26%, respectively). South America, Asia, and Africa will see unequivocal increases in final energy demand, whereas the response will be mixed in Europe, North America, and Oceania. When aggregated to the country level, total final energy go up in almost all emerging G20 economies located in the tropics, whereas temperate G20 countries experience a reduction, with the exception of the United States and Australia due to the expansion of their commercial sector.

Varying energy demand is an important form of adaptation that allows achieving desired levels of thermal performance. The estimates presented in the paper should be interpreted as potential changes, or potential adaptation, because barriers to energy access or to expanding energy use have not been considered. Our incidence analysis indeed suggests that globally climate change impacts are regressive, and more energy is expected to be overwhelmingly needed in low- and middle income countries, raising the question whether climate change will further exacerbate poverty. Moroever, energy use is an enabling condition for adaptation across various sectors. Accounting for the implications of energy consumption on emissions, and more generally for the interactions between mitigation, impacts, and adaptation in an Integrated Assessment Modeling framework remains an area calling for more research where the methodology developed in this paper could contribute to.

Our analysis is not without caveats. Energy demand data are available at the country-level. To calculate future projected energy demands at grid-cell level we assume a uniform distribution of per capita energy demand, which is set equal to the national average reported by energy statistics. We attempt to include in our assessment the energy demand that could be come from changes in energy-using durable goods, but the extensive margin is only indirectly modelled (by using long-term elasticities) or imperfectly quantified (by real per capita GDP or or other capital stock proxies). Finally, we have used global statistics on energy demand by sector and we cannot explicitely associate the estimated changes in energy consumption to specific end-use services, although it is reasonable to assume that, for example, the increase in electricity demand in response to greater exposure to heat can be associated with higher demand for cooling.

The objective of this paper is to establish a methodology, focusing on two key missing elements in the impact literature, namely the heterogeneity in demand response across sectors, fuels, and regions, and the way in which those responses interact with geographically and temporally varying temperature data. As a consequence of this, future climate impacts are illustrated using one specific ESM and socioeconomic scenario. Incorporating additional GDP scenarios and temperature projections from additional ESMs is left for future research.

6 References

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Appendix

	Tropical countries					Temperate countries				
	Obs	Mean	Std. Dev.	Min	Max	Obs	Mean	Std. Dev.	Min	Max
$\overline{T} < 7.5°C$	1252	2.29	8.92	0	89.57	1311	106.22	69.56	0	283.24
$\overline{T}$ 7.5-10°C	1252	2.12	5.35	0	29	1311	32.72	11.88	1.58	82.81
$\overline{T}$ 10-12.5°C	1252	4.73	10.07	0	53.46	1311	36.67	11.88	7.12	77.54
$\overline{T}$ 25-27.5°C	1252	90	55.03	10	279.26	1311	15.42	16.28	0	84
$\overline{T}$ 27.5-30°C	1252	69.31	49.51	0.99	207.48	1311	12.15	17.25	0	94
$\overline{T} > 30°C$	1252	53.47	61.87	0	228.46	1311	10.39	22.35	0	153.26
$\overline{H} < 4$ g/Kg	1252	8.05	17.29	0	126.52	1311	60.66	53.69	0	238.38
$\overline{H}$ 14-16 g/Kg	1252	43.66	29.32	0	172.22	1311	10.05	13.85	0	76
$\overline{H}$ 16-18 g/Kg	1252	59.51	44.06	0	250.07	1311	4.46	8.54	0	56
$\overline{H} > 18$ g/kg	1252	114.48	84.76	0	342.04	1311	3.83	11.82	0	71.46
Population ('000)	1252	59295	149980	713.83	1173108	1311	62107.32	189128.4	223.59	1337799
Real GDP per capita (2005 $)	1252	5496.3	7955.42	275.7	65415.68	1311	18746.21	11823.07	558.18	51791.63
Total final energy (ktoe)	1252	2909.24	6395.03	5.93	61117.96	1311	18677.37	45864.48	50.74	329017.5
Electricity (ktoe)										
Agriculture	615	447.43	1429.4	0.17	11098.39	1126	393.66	1096.78	0.95	10103.54
Commercial	1171	557.49	1109.86	0.26	9175.94	1240	4712.76	13864.4	1.72	114923.1
Residential	1241	824.97	1585.35	2.67	13174.6	1307	5366.23	14756.55	12.9	124330.8
Industry	1226	1286.36	3013.71	0.69	27643.07	1311	7895	18605.81	18.06	214149
Natural gas (ktoe)										
Agriculture	1980	2.27	17.75	0	357.4	1650	133.52	626.61	0	9497.29
Commercial	1980	43.71	306.71	0	5011.17	1650	2621.29	9624.51	0	74893.42
Residential	1980	289.41	2187.1	0	35011.25	1650	5928.67	17833.01	0	122053.1
Industry	1980	1040.85	2776.72	0	25418.18	1650	6752.48	20568.38	0	152059
Fuel oil (ktoe)										
Agriculture	1252	34.39	217.62	0	2631.8	1311	36.01	95.54	0	1505.81
Commercial	1252	40.28	174.57	0	2078.75	1311	285.18	1191.92	0	22158.58
Residential	1252	0.62	7.1	0	209.88	1311	102.1	323.61	0	3487.15
Industry	1252	1040.17	1925.37	0	13225.96	1311	2180.94	4241.66	0	35522.1

Table A1: Descriptive statistics of the dataset

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Short run (first differenced) terms							
Log real GDP	0.2859**	0.2097**	0.5085**	0.4295**	0.7041**	0.7430**	0.3263
per capita	(7.8092e-02)	(8.6332e-02)	(6.0278e-02)	(1.1247e-01)	(1.0205e-01)	(1.0869e-01)	(2.5682e-01)
$\overline{H} < 4$ g/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)
$\overline{H} > 14$ g/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)
$\overline{T} < 12.5°$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)
$\overline{T} > 27.5°$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)
Long run (lagged) terms							
Log electricity use	-0.0636**	-0.0783**	-0.0765**	-0.0987**	-0.0373	-0.0780**	-0.1214**
per capita	(1.3849e-02)	(1.1499e-02)	(2.7284e-02)	(1.3618e-02)	(3.4127e-02)	(2.3197e-02)	(3.0738e-02)
Log real GDP	0.0610**	0.0982**	0.1004**	0.1643**	0.0175	0.1023**	0.0690
per capita	(2.2488e-02)	(1.9087e-02)	(4.7961e-02)	(3.4053e-02)	(3.1050e-02)	(4.1829e-02)	(4.0805e-02)
$\overline{H} < 4$ g/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)
$\overline{H} > 14$ g/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)
$\overline{T} < 12.5°$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)
$\overline{T} > 27.5°$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	Temperate	Tropical	Temperate	Tropical	Temperate	Tropical	World
Sector	Residential	Residential	Commercial	Commercial	Industrial	Industrial	Agriculture
Observations	960	576	896	544	960	576	928
R-squared	0.126	0.177	0.094	0.086	0.181	0.156	0.097
Countries	30	18	28	17	30	18	29

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A2: Regression results: Electricity

	(1)	(2)	(3)
Short run (first differenced) terms			
Log real GDP per capita	0.7295**	-0.1243	-1.3509
	(3.4525e-01)	(2.0979e-01)	(1.0138)
$\overline{T} < 7.5$°C	0.0031**	0.0048**	-0.0532
	(1.0175e-03)	(7.9307e-04)	(1.6044e-01)
$7.5 < \overline{T} < 10$°C	0.0037**	0.0028**	0.0070
	(1.4675e-03)	(1.0189e-03)	(3.5702e-02)
$10 < \overline{T} < 12.5$°C		0.0030**	-0.0088
		(5.2804e-04)	(5.4163e-03)
$12.5 < \overline{T} < 15$°C		0.0024*	
		(1.2328e-03)	
$15 < \overline{T} < 17.5$°C		-0.0013**	
		(5.2972e-04)	
Long run (lagged) terms			
Log natural gas use per capita	-0.3297**	-0.1381**	-0.2439**
	(7.5189e-02)	(1.9666e-02)	(6.7592e-02)
Log real GDP per capita	0.5281**	0.1517**	-0.0468
	(1.6169e-01)	(5.3908e-02)	(2.7510e-01)
$\overline{T} < 7.5$°C	0.0026*	0.0021*	0.1047
	(1.4728e-03)	(1.1230e-03)	(1.3260e-01)
$7.5 < \overline{T} < 10$°C	0.0035*	0.0027*	0.0737
	(1.8183e-03)	(1.5222e-03)	(7.4061e-02)
$10 < \overline{T} < 12.5$°C		-0.0003	-0.0238
		(8.4876e-04)	(1.4310e-02)
$12.5 < \overline{T} < 15$°C		0.0024	
		(1.8068e-03)	
$15 < \overline{T} < 17.5$°C		-0.0015**	
		(6.9057e-04)	
Constant	-6.7276**	-2.1588**	-1.0740
	(1.8694)	(7.2832e-01)	(1.9878)
Region	World	Temperate	Tropical
Sector	Commercial	Residential	Residential
Observations	552	552	168
R-squared	0.233	0.329	0.189
Countries	23	23	7

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A3: Regression results: Natural gas

	(1)	(2)	(3)	(4)
Short run (first differenced) terms				
Log real GDP per capita	0.7719**	-0.1271	0.9535	-0.3727
	(1.8955e-01)	(4.7807e-01)	(5.4536e-01)	(7.5888e-01)
$\overline{T} < 7.5$°C	0.0021	0.0405	0.0043	0.0076**
	(1.3246e-03)	(4.6819e-02)	(4.4752e-03)	(2.3848e-03)
$10 < \overline{T} < 12.5$°C	0.0013	0.0153		
	(1.7803e-03)	(1.9918e-02)		
Long run (lagged) terms				
Log fuel oil use per capita	-0.0709**	-0.2812**	-0.1433**	-0.0633**
	(3.2236e-02)	(9.1887e-02)	(5.5244e-02)	(2.4646e-02)
Log real GDP per capita	-0.0936*	-0.1735*	-0.0589	-0.2093*
	(5.4031e-02)	(8.6125e-02)	(6.7081e-02)	(9.6522e-02)
$\overline{T} < 7.5$°C	0.0042**	0.0754	0.0066*	0.0063
	(1.5737e-03)	(8.6954e-02)	(3.3152e-03)	(3.6669e-03)
$7.5 < \overline{T} < 10$°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)	(1.0737)
Region	Temperate	Tropical	World	World
Sector	Industry	Industry	Agriculture	Residential
Observations	928	512	384	240
R-squared	0.044	0.130	0.071	0.061
Countries	29	16	12	8

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A4: Regression results: Fuel oil

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log real GDP per capita	0.8628**	0.8996**	0.7456**	1.1343**	0.9804**	0.7342**	0.2527
	(3.0171e-01)	(1.9771e-01)	(1.5440e-01)	(3.3948e-01)	(1.7433e-01)	(2.3051e-01)	(3.0838e-01)
$\overline{H} < 4$ g/kg	0.0021**	0.0083*	-0.0019	0.0029	-0.0017	-0.0261**	0.0047**
	(7.8961e-04)	(4.3952e-03)	(1.2245e-03)	(5.7806e-03)	(1.2716e-03)	(1.1283e-02)	(1.1418e-03)
$\overline{H} > 14$ g/kg	-0.0040**	0.0003	-0.0020	0.0024	-0.0019	0.0013	-0.0094**
	(1.2974e-03)	(1.4018e-03)	(1.5749e-03)	(3.2262e-03)	(1.7413e-03)	(3.1171e-03)	(3.4176e-03)
$\overline{T} < 12.5$°C	0.0013	0.0014	0.0004	0.0027	0.0001	0.0103**	0.0009
	(8.2399e-04)	(1.0695e-03)	(9.0056e-04)	(3.7391e-03)	(8.8446e-04)	(3.9733e-03)	(1.8630e-03)
$\overline{T} > 27.5$°C	0.0117**	-0.0003	0.0035**	0.0014	0.0109**	-0.0020	0.0137**
	(3.2316e-03)	(5.9671e-04)	(1.4761e-03)	(9.7955e-04)	(3.3840e-03)	(1.8462e-03)	(3.7585e-03)
Constant	-11.5157**	-12.2313**	-9.2324**	-14.5077**	-12.5701**	-11.5668**	-8.5224**
	(2.7993)	(1.6315)	(1.5769)	(3.1705)	(1.6631)	(2.0585)	(2.7705)
	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
Sector	Residential	Residential	Industry	Industry	Agriculture	Commercial	Commercial
Region	Temperate	Tropical	Temperate	Tropical	World	Tropical	Temperate
Observations	960	576	960	576	896	544	928
R-squared	0.720	0.866	0.640	0.652	0.806	0.719	0.393
Countries	30	18	30	18	28	17	29

	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Log real GDP per capita	1.1898**	0.5448*	1.6162*	-0.0311	1.0240**	-2.1610	1.4020**
	(2.0218e-01)	(2.8298e-01)	(7.0227e-01)	(1.0546)	(2.2537e-01)	(1.2945)	(4.4996e-01)
$\overline{T} < 7.5$°C	0.0037	0.1288	0.0335**	0.0086	0.0067**	0.3792	0.0010
	(2.8303e-03)	(7.8901e-02)	(1.1837e-02)	(1.1014e-02)	(1.7046e-03)	(2.4096e-01)	(2.3969e-03)
$7.5 < \overline{T} < 10$°C	0.0004	0.0451**			0.0018	-0.1254	0.0017
	(1.7205e-03)	(2.0149e-02)			(1.7651e-03)	(8.7510e-02)	(3.3085e-03)
$10 < \overline{T} < 12.5$°C					0.0025	-0.0304**	-0.0037
					(1.7710e-03)	(1.1054e-02)	(4.3679e-03)
Constant	-13.3912**	-8.0340**	-24.0529**	-6.4788	-13.7512**	11.8386	-17.7958**
	(1.8242)	(2.3360)	(7.6523)	(9.5676)	(2.2492)	(1.1163e+01)	(4.1936)
	Fuel oil	Fuel oil	Fuel oil	Fuel oil	Natural gas	Natural gas	Natural gas
Sector	Industry	Industry	Residential	Agriculture	Residential	Residential	Commercial
Region	Temperate	Tropical	World	World	Temperate	Tropical	World
Observations	928	512	240	384	529	161	552
R-squared	0.701	0.303	0.556	0.218	0.523	0.299	0.434
Countries	29	16	8	12	23	7	23

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A5: Robustness check: Static model

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log real GDP	0.1961**	0.1852*	0.4587**	0.6958**	0.4897**	0.2269	0.2094
per capita	(9.1488e-02)	(9.5626e-02)	(6.7223e-02)	(1.4973e-01)	(6.4303e-02)	(1.5282e-01)	(2.8210e-01)
$\overline{H} < 4$ g/kg	0.0004**	0.0019*	0.0001	0.0029**	0.0002	-0.0047*	0.0009**
	(1.0659e-04)	(9.1853e-04)	(9.4431e-05)	(7.9287e-04)	(3.9933e-04)	(2.6679e-03)	(4.1250e-04)
$\overline{H} > 14$ g/kg	-0.0000	0.0004	0.0000	0.0004	0.0005	-0.0008	0.0000
	(3.1955e-04)	(4.5645e-04)	(2.1721e-04)	(3.4386e-04)	(4.9702e-04)	(6.3979e-04)	(1.5030e-03)
$\overline{T} < 12.5°$C	0.0006**	0.0003	-0.0000	0.0005	-0.0003	-0.0008	-0.0001
	(1.5023e-04)	(2.8342e-04)	(1.0413e-04)	(6.9381e-04)	(2.3893e-04)	(6.5735e-04)	(6.2759e-04)
$\overline{T} > 27.5°$C	0.0005*	0.0004**	0.0002	-0.0002	0.0005	0.0005**	0.0024**
	(2.3577e-04)	(1.4762e-04)	(1.7956e-04)	(2.4348e-04)	(4.1611e-04)	(1.7953e-04)	(7.8118e-04)
Constant	0.0440**	0.0716**	0.0445**	0.1406**	0.0190*	0.0737**	0.0572*
	(5.5610e-03)	(1.5892e-02)	(7.4565e-03)	(3.1542e-02)	(1.0518e-02)	(2.7714e-02)	(3.0498e-02)
	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity
Region	Temperate	Tropical	Temperate	Tropical	World	Tropical	Temperate
Sector	Residential	Residential	Industry	Industry	Agriculture	Commercial	Commercial
Observations	960	576	960	576	896	544	928
R-squared	0.118	0.120	0.299	0.171	0.079	0.065	0.051
Countries	30	18	30	18	28	17	29

	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Log real GDP	0.2277	0.2640	0.1778	0.6919	-0.0078	-0.3979	0.1555
per capita	(2.1238e-01)	(3.6200e-01)	(7.0579e-01)	(6.5998e-01)	(1.9433e-01)	(1.3652)	(3.4668e-01)
$\overline{T} < 7.5°$C	0.0001	0.0285	0.0046**	0.0017	0.0036**	-0.0188	0.0005
	(1.1212e-03)	(2.8220e-02)	(1.3835e-03)	(3.9060e-03)	(4.4639e-04)	(2.0658e-01)	(1.2778e-03)
$7.5 < \overline{T} < 10°$C	-0.0011	0.0035			0.0011*	-0.0823**	0.0017
	(1.1090e-03)	(7.0246e-03)			(5.3202e-04)	(3.1540e-02)	(1.9931e-03)
$10 < \overline{T} < 12.5°$C					0.0032**	0.0009	-0.0031
					(4.2603e-04)	(4.6141e-03)	(3.6548e-03)
Constant	0.0067	0.0919	0.0117	-0.0212	0.0651**	0.0841	0.0951**
	(1.8957e-02)	(5.7302e-02)	(1.0166e-01)	(7.2701e-02)	(2.2406e-02)	(4.5693e-02)	(4.2816e-02)
Fuel	Fuel oil	Fuel oil	Fuel oil	Fuel oil	Natural gas	Natural gas	Natural gas
Sector	Industry	Industry	Residential	Agriculture	Residential	Residential	Commercial
Region	Temperate	Tropical	World	World	Temperate	Tropical	World
Observations	928	512	240	384	529	161	552
R-squared	0.066	0.081	0.101	0.110	0.239	0.163	0.039
Countries	29	16	8	12	23	7	23

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A6: Robustness check: First difference model

Short run (first differenced) terms								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log real GDP	0.2699***	0.1847*	0.2501***	0.2329***	0.2839***	0.1772*	0.2851***	0.1609
per capita	(7.7713e-02)	(9.0975e-02)	(8.5588e-02)	(7.2379e-02)	(9.2262e-02)	(8.7128e-02)	(8.0774e-02)	(1.0688e-01)
$\overline{H}$ <4 g/kg x x	0.0000**	0.0003***	0.0000***	0.0001***	0.0000**	0.0001**	0.0000**	0.0001**
	(1.8676e-05)	(8.2463e-05)	(7.3215e-06)	(2.9891e-05)	(9.4846e-06)	(4.6993e-05)	(6.4559e-06)	(3.5275e-05)
$\overline{H}$ >14 g/kg x x	0.0000	0.0001*	0.0000	0.0000**	0.0000	0.0000	0.0000	0.0000
	(3.3948e-05)	(3.9278e-05)	(1.3376e-05)	(9.4714e-06)	(1.6476e-05)	(2.3825e-05)	(6.1533e-06)	(1.5942e-05)
$\overline{T}$ < 12.5°C x x	0.0001***	0.0000	0.0000***	0.0000**	0.0000***	0.0000	0.0000***	-0.0000
	(2.0585e-05)	(4.1096e-05)	(8.5532e-06)	(7.3127e-06)	(8.5493e-06)	(1.5921e-05)	(7.6098e-06)	(1.7910e-05)
$\overline{T}$ > 27.5°C x x	0.0001***	0.0001***	0.0000**	0.0000***	0.0000***	0.0000***	0.0000**	0.0000***
	(3.3071e-05)	(1.2952e-05)	(1.1461e-05)	(5.2357e-06)	(1.5094e-05)	(6.7252e-06)	(1.4491e-05)	(5.4491e-06)
Long run (lagged) terms								
Log electricity use	-0.0633***	-0.0785***	-0.0595***	-0.0853***	-0.0734***	-0.0988***	-0.0701***	-0.0676***
per capita	(1.3459e-02)	(1.1181e-02)	(1.1376e-02)	(1.4450e-02)	(1.2904e-02)	(1.4198e-02)	(1.3208e-02)	(4.1722e-03)
Log real GDP	0.0455**	0.0740***	0.0479**	0.0761***	0.0549**	0.0978***	0.0587**	0.0794***
per capita	(2.0458e-02)	(1.9124e-02)	(2.2117e-02)	(1.8390e-02)	(2.3070e-02)	(1.9802e-02)	(2.2475e-02)	(1.5175e-02)
$\overline{H}$ <4 g/kg x x	0.0000	0.0002**	0.0000	0.0001***	0.0000	0.0001**	0.0000	0.0000
	(2.1355e-05)	(8.6332e-05)	(8.9672e-06)	(2.2448e-05)	(1.0691e-05)	(4.3611e-05)	(7.4029e-06)	(4.2459e-05)
$\overline{H}$ >14 g/kg x x	-0.0000	0.0001**	-0.0000	0.0000*	-0.0000	0.0000***	-0.0000	0.0000
	(2.4227e-05)	(3.2537e-05)	(9.1092e-06)	(1.6897e-05)	(1.4146e-05)	(1.4284e-05)	(1.0117e-05)	(1.4733e-05)
$\overline{T}$ < 12.5°C x x	0.0001**	-0.0000	0.0000	0.0000*	0.0000	-0.0000	0.0000**	-0.0000*
	(2.9165e-05)	(5.5115e-05)	(1.1162e-05)	(1.0386e-05)	(9.8593e-06)	(1.7452e-05)	(1.0581e-05)	(1.9097e-05)
$\overline{T}$ > 27.5°C x x	0.0001**	0.0000**	0.0000**	0.0000*	0.0000**	0.0000	0.0000	0.0000*
	(3.5265e-05)	(2.0222e-05)	(1.5117e-05)	(8.0131e-06)	(1.6426e-05)	(1.0153e-05)	(1.8711e-05)	(7.6682e-06)
Constant	-0.7056***	-1.0740***	-0.6844**	-1.1504***	-0.7147***	-1.3903***	-0.8433***	-1.0691***
	(2.4850e-01)	(1.9012e-01)	(2.5882e-01)	(2.1914e-01)	(2.5132e-01)	(2.3511e-01)	(2.8471e-01)	(1.0767e-01)
z	Log real GDP per capita	Log real GDP per capita	Machinery and transport eq.	Machinery and transport eq.	Heating and cooling eq.	Heating and cooling eq.	Capital stock	Capital stock
Region	Temperate	Tropical	Temperate	Tropical	Temperate	Tropical	Temperate	Tropical
Observations	960	576	866	514	921	506	919	445
R-squared	0.124	0.176	0.126	0.177	0.136	0.183	0.130	0.143
Countries	30	18	30	18	30	18	29	14

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A7: Regression results: Further analysis on the extensive margin

	(1)	(2)
Short run (first difference) terms		
Log real GDP per capita	0.2010**	0.1989**
	(7.3875e-02)	(7.5095e-02)
Log electricity price		-0.0036
		(1.1258e-02)
$\overline{H} < 4$ g/kg	0.0005**	0.0005**
	(9.7759e-05)	(9.5469e-05)
$\overline{H} > 14$ g/kg	0.0004*	0.0005*
	(2.1714e-04)	(2.2204e-04)
$\overline{T} < 12.5°$C	0.0006**	0.0006**
	(1.8355e-04)	(1.8350e-04)
$\overline{T} > 27.5°$C	0.0012**	0.0013**
	(2.3151e-04)	(2.1736e-04)
Long run (lagged) terms		
Log electricity demand per capita	-0.0322**	-0.0281**
	(8.6086e-03)	(8.9745e-03)
Log real GDP per capita	0.0066	0.0286**
	(9.4076e-03)	(7.3679e-03)
Log electricity price		-0.0199**
		(6.2189e-03)
$\overline{H} < 4$ g/kg	0.0001	0.0001
	(1.3065e-04)	(1.2293e-04)
$\overline{H} > 14$ g/kg	-0.0002	-0.0002
	(2.4472e-04)	(2.7477e-04)
$\overline{T} < 12.5°$C	0.0001	0.0001
	(2.7968e-04)	(2.6707e-04)
$\overline{T} > 27.5°$C	0.0006*	0.0006*
	(3.3143e-04)	(3.4423e-04)
Constant	-0.1387	-0.2149**
	(1.2802e-01)	(8.5546e-02)
Observations	558	558
R-squared	0.220	0.240
Number of countries	18	18

** $p<0.05$, * $p<0.1$, Robust standard errors in parentheses

Table A8: Robustness check: inclusion of residential electricity prices

	RCP 4.5				RCP 8.5			
	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*
	A. Current energy system: sensitivity to temperature elasticities							
	Tropical							
Agriculture	[0.19,1.05]	–	[-0.01,0.00]	*[0.19,1.04]*	[0.32,2.41]	–	[-0.01,0.00]	*[0.32,2.40]*
Commercial	–	[-0.07,0.00]	–	*[-0.07,0.00]*	–	[-0.10,0.00]	–	*[-0.10,0.00]*
Industrial	[1.04,1.56]	–	–	*[1.04,1.56]*	[1.88,2.70]	–	–	*[1.88,2.70]*
Residential	[0.22,1.43]	–	–	*[0.22,1.43]*	[0.35,2.58]	–	–	*[0.35,2.58]*
Total	*[1.45,4.04]*	*[-0.07,0.00]*	*[-0.01,0.00]*	*[1.45,3.96]*	*[2.55,7.69]*	*[-0.10,0.00]*	*[-0.01,0.00]*	*[2.55,7.58]*
	Temperate							
Agriculture	[0.07,0.31]	–	[-0.02,0.00]	*[0.07,0.29]*	[0.12,0.59]	–	[-0.02,0.00]	*[0.12,0.57]*
Commercial	[2.45,3.39]	[-1.51,0.04]	–	*[1.88,2.49]*	[3.44,5.44]	[-1.97,0.07]	–	*[3.48,3.51]*
Industrial	–	–	[-1.08,-0.14]	*[-1.08,-0.14]*	–	–	[-1.26,-0.21]	*[-1.26,-0.21]*
Residential	[-1.81,-0.38]	[-4.55,-1.05]	[-0.03,0.00]	*[-6.40,-1.43]*	[-2.22,-0.47]	[-5.39,-1.38]	[-0.03,0.00]	*[-7.64,-1.85]*
Total	*[1.89,2.14]*	*[-6.06,-1.01]*	*[-1.13,-0.14]*	*[-5.31,0.99]*	*[3.09,3.81]*	*[-7.36,-1.31]*	*[-1.31,-0.21]*	*[-4.85,1.57]*
	World							
Agriculture	[0.26,1.36]	–	[-0.03,0.00]	*[0.26,1.33]*	[0.44,3.00]	–	[-0.03,0.00]	*[0.44,2.97]*
Commercial	[2.45,3.39]	[-1.58,0.04]	–	*[1.81,2.49]*	[3.44,5.44]	[-2.07,0.07]	–	*[3.38,3.51]*
Industrial	[1.04,1.56]	–	[-1.08,-0.14]	*[0.48,0.90]*	[1.88,2.70]	–	[-1.26,-0.21]	*[1.44,1.67]*
Residential	[-0.38,-0.16]	[-4.55,-1.05]	[-0.03,0.00]	*[-4.97,-1.21]*	[-0.12,0.36]	[-5.39,-1.38]	[-0.03,0.00]	*[-5.06,-1.50]*
Total	*[3.59,5.93]*	*[-6.13,-1.01]*	*[-1.14,-0.14]*	*[-1.35,2.44]*	*[5.64,11.50]*	*[-7.46,-1.31]*	*[-1.32,-0.21]*	*[2.73,4.12]*
	B. 2050 Baseline energy system: sensitivity to GDP elasticity							
	Tropical							
Agriculture	[0.97,4.83]	–	–	*[0.97,4.82]*	[1.84,9.05]	–	[-0.01,-0.01]	*[1.83,9.04]*
Commercial	–	[-0.82,-0.21]	–	*[-0.82,-0.21]*	–	[-1.06,-0.28]	–	*[-1.06,-0.28]*
Industrial	[7.31,52.82]	–	–	*[7.31,52.82]*	[12.02,83.46]	–	–	*[12.02,83.46]*
Residential	[7.32,20.33]	–	–	*[7.32,20.33]*	[12.37,34.24]	–	–	*[12.37,34.24]*
Total	*[15.60,77.98]*	*[-0.82,-0.21]*	–	*[15.39,77.15]*	*[26.23,126.75]*	*[-1.06,-0.28]*	*[-0.01,-0.01]*	*[25.94,125.68]*
	Temperate							
Agriculture	[0.27,1.44]	–	[-0.02,-0.02]	*[0.26,1.42]*	[0.50,2.58]	–	[-0.02,-0.02]	*[0.48,2.56]*
Commercial	[9.65,30.73]	[-12.00,-3.15]	–	*[6.50,18.72]*	[14.86,49.29]	[-15.57,-4.12]	–	*[10.74,33.73]*
Industrial	–	–	[-0.61,-0.11]	*[-0.61,-0.11]*	–	–	[-0.77,-0.13]	*[-0.77,-0.13]*
Residential	[-3.25,-2.31]	[-25.52,-6.40]	[-0.03,0.00]	*[-28.80,-8.71]*	[-3.24,-2.75]	[-30.28,-7.73]	[-0.03,0.00]	*[-33.55,-10.49]*
Total	*[7.61,28.92]*	*[-37.52,-9.55]*	*[-0.66,-0.13]*	*[-9.27,-2.06]*	*[12.61,48.63]*	*[-45.85,-11.85]*	*[-0.82,-0.15]*	*[0.60,1.97]*
	World							
Agriculture	[1.24,6.27]	–	[-0.02,-0.02]	*[1.23,6.24]*	[2.34,11.63]	–	[-0.03,-0.03]	*[2.31,11.60]*
Commercial	[9.65,30.73]	[-12.82,-3.36]	–	*[6.29,17.90]*	[14.86,49.29]	[-16.63,-4.40]	–	*[10.46,32.67]*
Industrial	[7.31,52.82]	–	[-0.61,-0.11]	*[7.20,52.21]*	[12.02,83.46]	–	[-0.77,-0.13]	*[11.89,82.69]*
Residential	[5.01,17.08]	[-25.52,-6.40]	[-0.03,0.00]	*[-8.47,-1.39]*	[9.62,31.00]	[-30.28,-7.73]	[-0.03,0.00]	*[0.69,1.88]*
Total	*[23.21,106.90]*	*[-38.34,-9.76]*	*[-0.66,-0.13]*	*[13.33,67.88]*	*[38.84,175.38]*	*[-46.91,-12.13]*	*[-0.83,-0.16]*	*[26.54,127.65]*

Table A9: Sensitivity Analysis: Sectoral and aggregate energy demand responses (EJ) for world regions for different warming scenarios circa 2050.

	RCP 4.5				RCP 8.5			
	Electricity	Natural Gas	Fuel Oil	*Total*	Electricity	Natural Gas	Fuel Oil	*Total*
	C. 2050 energy system: sensitivity to temperature elasticities							
	Tropical							
Agriculture	[0.76,4.16]	–	[-0.01,0.00]	*[0.76,4.15]*	[1.28,9.32]	–	[-0.01,0.00]	*[1.28,9.31]*
Commercial	–	[-0.77,0.02]	–	*[-0.77,0.02]*	–	[-0.98,0.03]	–	*[-0.98,0.03]*
Industrial	[13.19,26.62]	–	–	*[13.19,26.62]*	[21.08,44.90]	–	–	*[21.08,44.90]*
Residential	[3.38,23.08]	–	–	*[3.38,23.08]*	[5.36,41.80]	–	–	*[5.36,41.80]*
Total	*[17.33,53.86]*	*[-0.77,0.02]*	*[-0.01,0.00]*	*[17.35,53.08]*	*[27.72,96.02]*	*[-0.98,0.03]*	*[-0.01,0.00]*	*[27.75,95.03]*
	Temperate							
Agriculture	[0.24,1.08]	–	[-0.02,0.00]	*[0.24,1.05]*	[0.41,2.07]	–	[-0.03,0.00]	*[0.41,2.05]*
Commercial	[11.61,22.94]	[-11.21,0.37]	–	*[11.73,11.98]*	[16.41,39.67]	[-14.36,0.59]	–	*[17.00,25.31]*
Industrial	–	–	[-0.34,-0.05]	*[-0.34,-0.05]*	–	–	[-0.39,-0.06]	*[-0.39,-0.06]*
Residential	[-4.59,-0.83]	[-18.94,-4.38]	–	*[-23.54,-5.20]*	[-5.10,-0.87]	[-21.91,-5.69]	–	*[-27.01,-6.56]*
Total	*[11.02,19.43]*	*[-30.15,-4.01]*	*[-0.36,-0.05]*	*[-11.10,6.97]*	*[15.95,36.64]*	*[-36.27,-5.10]*	*[-0.42,-0.06]*	*[-0.04,10.79]*
	World							
Agriculture	[1.00,5.24]	–	[-0.03,0.00]	*[1.00,5.20]*	[1.69,11.39]	–	[-0.04,0.00]	*[1.69,11.36]*
Commercial	[11.61,22.94]	[-11.98,0.39]	–	*[10.96,12.00]*	[16.41,39.67]	[-15.34,0.62]	–	*[17.03,24.33]*
Industrial	[13.19,26.62]	–	[-0.34,-0.05]	*[13.14,26.28]*	[21.08,44.90]	–	[-0.39,-0.06]	*[21.02,44.51]*
Residential	[2.55,18.49]	[-18.94,-4.38]	–	*[-1.82,-0.46]*	[4.49,36.70]	[-21.91,-5.69]	–	*[-1.20,14.79]*
Total	*[28.35,73.29]*	*[-30.92,-3.99]*	*[-0.37,-0.05]*	*[24.32,41.98]*	*[43.67,132.66]*	*[-37.25,-5.07]*	*[-0.43,-0.06]*	*[38.54,94.99]*
	D. 2050 energy system: joint sensitivity to GDP and temperature elasticities							
	Tropical							
Agriculture	[0.34,9.32]	–	[-0.01,0.00]	*[0.34,9.31]*	[0.58,20.58]	–	[-0.01,0.00]	*[0.58,20.57]*
Commercial	–	[-1.54,0.01]	–	*[-1.54,0.01]*	–	[-1.95,0.02]	–	*[-1.95,0.02]*
Industrial	[5.46,77.48]	–	–	*[5.46,77.48]*	[9.15,130.02]	–	–	*[9.15,130.02]*
Residential	[2.05,38.89]	–	–	*[2.05,38.89]*	[3.26,70.40]	–	–	*[3.26,70.40]*
Total	*[7.85,125.69]*	*[-1.54,0.01]*	*[-0.01,0.00]*	*[7.86,124.14]*	*[12.99,221.00]*	*[-1.95,0.02]*	*[-0.01,0.00]*	*[13.01,219.04]*
	Temperate							
Agriculture	[0.11,2.49]	–	[-0.02,0.00]	*[0.10,2.47]*	[0.18,4.77]	–	[-0.03,0.00]	*[0.18,4.74]*
Commercial	[7.45,45.77]	[-23.07,0.19]	–	*[7.64,22.70]*	[10.49,81.04]	[-29.46,0.30]	–	*[10.78,51.57]*
Industrial	–	–	[-0.87,-0.02]	*[-0.87,-0.02]*	–	–	[-1.00,-0.03]	*[-1.00,-0.03]*
Residential	[-5.35,-0.73]	[-39.64,-2.30]	[-0.03,0.00]	*[-45.03,-3.03]*	[-5.28,-0.84]	[-45.58,-3.00]	[-0.04,0.00]	*[-50.89,-3.84]*
Total	*[6.83,42.91]*	*[-62.71,-2.11]*	*[-0.92,-0.02]*	*[-20.73,4.69]*	*[9.83,80.53]*	*[-75.04,-2.70]*	*[-1.07,-0.03]*	*[4.42,7.09]*
	World							
Agriculture	[0.45,11.81]	–	[-0.03,0.00]	*[0.44,11.78]*	[0.76,25.35]	–	[-0.04,0.00]	*[0.76,25.31]*
Commercial	[7.45,45.77]	[-24.61,0.20]	–	*[7.65,21.16]*	[10.49,81.04]	[-31.41,0.32]	–	*[10.80,49.62]*
Industrial	[5.46,77.48]	–	[-0.87,-0.02]	*[5.44,76.61]*	[9.15,130.02]	–	[-1.00,-0.03]	*[9.12,129.02]*
Residential	[1.32,33.54]	[-39.64,-2.30]	[-0.03,0.00]	*[-6.14,-0.98]*	[2.42,65.12]	[-45.58,-3.00]	[-0.04,0.00]	*[-0.58,19.51]*
Total	*[14.68,168.60]*	*[-64.25,-2.10]*	*[-0.93,-0.02]*	*[12.55,103.41]*	*[22.82,301.53]*	*[-76.99,-2.68]*	*[-1.08,-0.03]*	*[20.10,223.46]*

Table A9 (Continued): Sensitivity Analysis: Sectoral and aggregate energy demand responses (EJ) for world regions for different warming scenarios circa 2050.

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