Global Energy Consumption in a Warming Climate

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Abstract We combine econometric analysis of the response of energy demand to temperature and humidity exposure with future scenarios of climate change and socioeconomic development to quantify the impacts of future climate warming on final energy consumption across the world. Globally, changes in climate circa 2050 have a moderate impact on energy consumption of 7–17%, depending on the degree of warming. Impacts vary in sign and magnitude across regions, fuels, and sectors. Climatically-induced changes in energy use are larger in tropical regions. Almost all continents experience increases in energy demand, driven by the commercial and industrial sectors. In Europe declines in energy use by residences drive an overall reduction in aggregate final energy. Energy use increases in almost all G20 economies located in the tropics, while outside of Europe G20 countries in temperate regions experience both increasing and declining total energy use, depending on the incidence of changes in the frequency of hot and cold days. The effect of climate change is regressive, 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 Classification N5 · O13 · Q1 · Q54

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1 Introduction

How climate change will impact the way we use energy is an important topic in environmental economics. Demand for energy is directly affected by changes in weather and climatic conditions. In addition to being the major source of greenhouse gases (GHGs) that drive climate warming, energy is a necessary input to the production of space conditioning services, which in turn are a critical margin of adaptation to high and low temperatures. Relative to the current climate, global warming will cause more frequent high temperature extremes—increasing demands for cooling services and the energy necessary to produce them, while simultaneously decreasing the frequency of low temperature extremes—reducing the demand for heating and its associated energy use. As the world warms, the central question is whether, and if so by what margin, the former effect might outweigh the latter. The answer is complicated by dependence of shifts in energy consumption on the ways in which changes in weather interact with changes in socioeconomic conditions across different locations. 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 sectors’ demands for individual fuels respond to future meteorological exposures.

A large and growing literature attempts to project future energy use 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 integrated assessment models (IAMs) sophisticated numerical simulations 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; Riahi et al. 2017). 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 investigated. However, empirical assessments at broad geographic scales are comparatively rare (see De Cian et al. 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 sectors and fuels is also limited, emphasizing electricity and, less commonly, natural gas, while prioritizing the residential sector over other parts of the economy (Auffhammer and Mansur 2014; Schaeffer 2012). This omission is potentially significant given 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. 2011; Wilbanks et al. 2012).

Turning to (ii), the precise manner in which empirical studies articulate the response of energy demand to meteorology directly affects how their results can be combined with projections of future meteorology to characterize climate change impacts. Energy consumption 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, with the exception of load on electricity grids (e.g., Scapin et al. 2015; Auffhammer et al. 2017; Wenz et al. 2017). Temperature is the meteorological driver that has been most widely considered, with other
potentially relevant variables (e.g., humidity) receiving less attention (Barreca 2012). Empirical studies have estimated 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 et al. 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; Auffhammer et al. 2017; Wenz et al. 2017). 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 affecting the use of such estimates to construct impact projections is consistent aggregation of current and future meteorological data across spatial and temporal scales. Earth system models (ESMs)—the principal tool for projecting future climates—simulate meteorological variables on time steps of hours to months at geographic scales of hundreds of kilometers. Averaging ESM outputs over space and time is inevitable, but often has the unpleasant side-effect of shrinking the tails of the distribution of meteorological drivers of energy demand, leading analyses to understate the large impacts that can arise from convolving nonlinear demand responses with extreme weather exposures. 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 sign. Effectively capturing the impacts of future extremes thus requires an empirical strategy 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.

Here 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 climate change on energy use that reflects 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 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 pathway scenarios (RCPs—van Vuuren et al. 2011) indicative of a high-warming scenario in which climate change is unabated and moderate-warming scenario in which mitigation policies are pursued. These are augmented with a shared socioeconomic pathway scenario (SSP—Kriegler et al. 2012; Van Vuuren et al. 2014) that assumes a future world in which there is conventional economic development, slow population growth, international convergence, and rapid increase in final energy consumption. Comprehensive assessment of energy futures under different climate and socioeconomic assumptions is left to future work.

The rest of the paper is organized as follows. Section 2 provides the background and develops the 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 compares our results to the
existing literature. Section 5 concludes with a brief summary of our findings and their major caveats, and potential directions for future research.

2 Methods

2.1 Modeling the Long-Run Demand for Energy

We model the final demand for three energy commodities (electricity, petroleum products, and natural gas) in five economic sectors (residential, commercial, industrial, agriculture, transportation—see Table 7 in “Appendix”), with the goal of elucidating the response of per capita consumption to temperature, humidity and income. As shown schematically in Fig. 1, the response of energy demand ($Q$) to temperature ($T$) differs by region and eco-

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1 Here, “petroleum” refers to a composite of heterogeneous fuels that includes refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gasoline and diesel, fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes, petroleum coke and other oil products. The last category encompasses products which can be obtained by distillation of crude oil but are normally used outside the refining industry, and exclude finished products classified as refinery feedstocks.

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Economic sector. Energy demand responses are thought to 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; Arroonruengsawat and Auffhammer 2011; Auffhammer and Arroonruengsawat 2011; Deschenes and Greenstone 2013; Auffhammer et al. 2017; Wenz et al. 2017). These attributes vary according to the prevailing climate and the extent to which the energy using activity is exposed to weather. The height of the gray area \((Q_0)\) indicates the magnitude of climate-invariant consumption, which is largest (smallest) in the parts of the economy that are least (most) exposed to weather—typically the industrial (residential) sector. The decrease in average year-round temperatures with latitude suggests that residential balance point temperatures in the tropics exceed those in temperate regions \((T_{\text{Res, Tropical}} > T_{\text{Res, Temperate}})\).

Responses are also likely to be asymmetric, with tropical regions’ use of energy for cooling (heating) varying elastically (inelastically) with high (low) temperatures, and temperate regions exhibiting the opposite pattern. Given such potential 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 energy consumption changes as an adaptation to climatic shifts because they capture adjustments along the intensive margin, namely, changes in energy consumption that are conditional on the stock of energy-using durable goods. Over the long time horizon on which the climate changes, a key additional influence on energy demand will be movements along the extensive margin—i.e., adjustments in the quantity and efficiency of the energy-using capital stock (Auffhammer and Mansur 2014). There is particular concern that the diffusion of air conditioning (AC) equipment throughout the developing world will amplify electricity demand responses to higher summer temperatures, and, further, that warming will itself accelerate the accumulation of AC capital stocks beyond the levels of penetration determined solely by economic forces such as income growth and the cost and efficiency of AC units, endogenizing the amplification of demand. Modeling such extensive-margin adjustments typically necessitates information on stocks of energy-using durables (Sailor and Pavlova 2003; McNeil and Letschert 2008; Mansur et al. 2008; Davis and Gertler 2015), but at the global scale such data are not available. Our workaround is to statistically capture the effects of unobserved extensive margin adjustments by employing an error correction modeling (ECM) framework that distinguishes the short-run effects of weather shocks from the long-run responses to climate (Masish and Masish 1996; De Cian et al. 2013). While ECMs have been used to understand non-stationarity, endogeneity and causality in the relationship between energy use and income (Stern 2000; Masish and Masish 1996; Chontanawat et al. 2008), to our knowledge, only Beenstock et al. (1999) and De Cian et al. (2013) have employed them to study the relationship between energy and weather. The latter findings that contemporaneous temperature shocks tend to have persistent effects is what motivates our approach.

Importantly, the ECM is the solution to the two-stage optimization problem of achieving a target level of thermal regulation in the face of weather fluctuations. Motivated by Hunt and Ryan (2015), we consider a model of an economy in which each sector is a representative agent who derives utility \((U)\) from the consumption of three types of commodities: a com-

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2 We assume that per capita GDP causes energy use, especially at the level of individual sectors Medlock and Soligo (2001). Aggregate per capita GDP can be considered an exogenous driver of the sectoral demand of a specific fuel, and an individual sector’s demand for a specific fuel is unlikely to exert substantial feedbacks on GDP.
posite good \((z)\), a generic energy service \((v)\), and a weather sensitive “thermal regulation” service \((r)\).\(^3\) Thermal regulation generates utility by shielding the agent from exogenous weather exposures \((E)\). It is provided by combining quantities \(W_f\) of \(f = \{1, \ldots, F\}\) distinct fuels with the sector’s stock of durable goods \((X)\) to produce the appropriate amount of thermal regulation service conditional on \(E\) (e.g., heating, cooling and humidification):

\[
 r = \mathcal{R}[W_1, \ldots, W_F, X; E]
\]

By contrast, generic energy services are a function of non-weather sensitive fuel consumption \((N_f)\) and the durables stock:

\[
 v = \mathcal{V}[N_1, \ldots, N_F, X]
\]

The agent’s first-stage problem is at the intensive margin:

\[
 \max_{w_f, n_f, z} \begin{cases} 
 U[r, v, z] \\
 Y \geq \sum_f p_f (W_f + N_f) + z
 \end{cases}
\]

where \(Y\) and \(p_f\) denote the agent’s income and the relative prices of fuels. The solution is the optimal unconditional demands for weather responsive and non-weather responsive energy:

\[
 W_f^* = \mathcal{W}_f[p_1, \ldots, p_F, X, Y; E] \quad \text{and} \quad N_f^* = \mathcal{N}_f[p_1, \ldots, p_F, X, Y; E]
\]

that in turn determine the utility-maximizing quantities of thermal regulation and generic energy services, \(r^*\) and \(v^*\), which are not observed.

Complete reversibility in the production of \(r\) and \(v\) allows the agent’s demands for energy to shift smoothly in response to weather shocks. However, short-run fixity of durable stocks constrains the agent’s ability to adjust instantaneously, causing actual energy use to depart from its target equilibrium level. We model this process assuming that the agent follows a separable two-stage decision process: first determining static optimal energy service demands, and then determining the speed of adjustment of energy service flows to their equilibrium levels.\(^4\) We model the second stage using a dynamic adjustment cost framework (e.g., Fanelli 2006). We let \(t\) index time periods, \(b' = [r, v]'\) denote the vector of energy services (with optimal target values \(b^*\)), and assume that the agent selects a sequence of future service flows that minimizes expected discounted adjustment costs, conditional on the information available at each time step. Adjustment costs are represented by the quadratic loss function

\[
 \min_b \mathcal{K} = \mathbb{E}_t \sum_{\tau=0}^{\infty} \rho^\tau \left[ (b_{t+\tau} - b^*_t)' \Lambda_0 (b_{t+\tau} - b^*_t) + (b_{t+\tau} - b_{t+\tau-1})' \Lambda_1 (b_{t+\tau} - b_{t+\tau-1}) \right]
\]

where \(\rho \in (0, 1)\) is a time-invariant discount factor, and \(\Lambda_0\) and \(\Lambda_1\) are positive definite matrices. Equation (1) is a rational expectations model whose first term is the cost of missing the target level of energy services and whose second term is the cost of adjusting the level

\(^3\) The character of \(r\) varies by sector: in residential and commercial sectors it is primarily the maintenance of physiologically comfortable indoor temperature and humidity through the use of space conditioning, in agriculture it encompasses the shielding of crops from extreme heat by pumping irrigation water, or from extreme cold by using sprinklers, heaters or foggers, while in industry it is optimization of temperature-sensitive production processes.

\(^4\) The separability assumption allows the adjustment trajectory to be specified independently from the target level of the control variable.
of services from one period to the next. Using $\Delta$ to indicate first differences, the first-order necessary conditions are the Euler equations,

$$\Delta b_t = \rho E_t \Delta b_{t+1} - \Lambda (b_t - b_t^*)$$

where $\Lambda = \Lambda_0^{-1} \Lambda_1$. Because $E_t b_{t+1} = b_t^*$ and $E_t b_t = b_t$, the first-order condition implies the partial adjustment rule

$$b_t - b_{t-1} = - (\rho + \Lambda) (b_t - b_t^*)$$

whose error-correcting form is the solution to the second stage problem:

$$\Delta b_t = (\rho + \Lambda) b_t^* - (\rho + \Lambda) (b_t - b_t^*)$$

(2)

The first- and second-stage solutions may be straightforwardly connected by expressing the optimal quantities of energy services and energy use as stochastic linear functions:

$$r_t^* = \phi^0 R + \phi^E R \varepsilon_t + \phi^X R X_t + W_t^* \phi^W R + \epsilon_t^R$$

(3a)

$$v_t^* = \phi^0 V + \phi^E V \varepsilon_t + \phi^X V X_t + N_t^* \phi^N V + \epsilon_t^V$$

(3b)

$$W_{f,t}^* = \omega_f^0 W + \omega_f^E W \varepsilon_t + \omega_f^X W X_t + \omega_f^P W + \omega_f^Y W Y_t + \epsilon_t^W$$

(4a)

$$N_{f,t}^* = \omega_f^0 N + \omega_f^E N \varepsilon_t + \omega_f^X N X_t + \omega_f^P N + \omega_f^Y N Y_t + \epsilon_t^N$$

(4b)

where the vectors $\phi$ and $\omega$ are parameters, and $\epsilon$ denotes random disturbances. Equations (2), (3) and (4) suggest that the demands for a particular fuel ($f'$) also have an error-correcting form:

$$\Delta W_{f',t}^* = \omega_{f'}^0 W + \omega_{f'}^E W \varepsilon_t + \omega_{f'}^X W X_t + \Delta p_{f'} \omega_{f'}^P W + \omega_{f'}^Y W Y_t$$

$$+ \chi_{f'}^W \left( W_{f',t-1}^* - \psi_{f'}^W \varepsilon_{t-1} - \psi_{f'}^X W X_{t-1} - p_{t-1} \psi_{f'}^P W - \psi_{f'}^Y W Y_{t-1} \right) + \nu_{f',t}^W$$

(5a)

$$\Delta N_{f',t}^* = \omega_{f'}^0 N + \omega_{f'}^E N \varepsilon_t + \omega_{f'}^X N X_t + \Delta p_{f'} \omega_{f'}^P N + \omega_{f'}^Y N Y_t$$

$$+ \chi_{f'}^N \left( N_{f',t-1}^* - \psi_{f'}^E N \varepsilon_{t-1} - \psi_{f'}^X N X_{t-1} - p_{t-1} \psi_{f'}^P N - \psi_{f'}^Y N Y_{t-1} \right) + \nu_{f',t}^N$$

(5b)

parameterized by the vectors of coefficients $\omega$, $\psi$ and $\chi$, and errors $\nu$. Sparsity of data on the components of energy demand $W_f$ and $N_f$ makes it impossible to directly estimate the

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5 We first substitute (3) into (2) and rearrange the result to obtain the interperiod adjustment in the demands for $f'$:

$$\Delta W_{f',t}^* = \xi_{f'}^0 W + \xi_{f'}^E W \varepsilon_t + \xi_{f'}^X W X_t + \Delta W_{f',t-1}^* \xi_{f'}^W W$$

$$+ \epsilon_{f'}^W \left( W_{f',t-1}^* - \xi_{f'}^E W \varepsilon_{t-1} - \xi_{f'}^X W X_{t-1} - W_{f',t-1}^* \xi_{f'}^W W \right) + \mu_{f',t}^W$$

$$\Delta N_{f',t}^* = \xi_{f'}^0 N + \xi_{f'}^E N \varepsilon_t + \xi_{f'}^X N X_t + \Delta N_{f',t-1}^* \xi_{f'}^N N$$

$$+ \epsilon_{f'}^N \left( N_{f',t-1}^* - \xi_{f'}^E N \varepsilon_{t-1} - \xi_{f'}^X N X_{t-1} - N_{f',t-1}^* \xi_{f'}^N N \right) + \mu_{f',t}^N$$

whose coefficients $\xi$ and $\zeta$ are functions of the parameters $\rho$, $\Lambda$, $\phi$, $\omega$, and the error terms $\mu$ are functions of the parameters and the disturbances. We simplify the foregoing expression by using (4) to eliminate the right-hand side quantities of non-local fuels ($\sim f'$), yielding (5).
system of equations (5). However, the total consumption of each fuel, \( Q_f = W_f + N_f \), is readily available. Suppressing fuel subscripts, we model inter-period adjustment in \( Q \) as the sum of (5a) and (5b), yielding the specification we take to the data:

\[
\Delta Q_t = \omega^0 + \omega^E \Delta \varepsilon_t + \omega^X \Delta X_t + \Delta p_t \omega^P + \omega^Y \Delta Y_t
+ \chi \left\{ Q_{t-1} - \psi^E \varepsilon_{t-1} - \psi^X X_{t-1} - p_{t-1} \psi^P - \psi^Y Y_{t-1} \right\} + \nu_t
\]  

(6)

We recast the dependent variable as the interannual difference in the logarithm of fuel consumption and the prior levels of the covariates. The variables are derived from global gridded meteorological reanalysis data in two steps. First, for the \( j \)th temperature interval with support \( \langle T_{j-1}, T_j \rangle \), and the \( k \)th humidity interval with support \( \langle H_{k-1}, H_k \rangle \), year \( t \) exposure at the \( c \)th grid cell is the accumulated count of days whose average temperature and humidity \( (T_c \text{ and } H_c) \) fall into the appropriate ranges:

\[
\varepsilon_{j,c,t}^T = C \left[ T_c \in \langle T_{j-1}, T_j \rangle \right] \quad \text{and} \quad \varepsilon_{k,c,t}^H = C \left[ H_c \in \langle H_{k-1}, H_k \rangle \right]
\]  

(7)

where \( C \) is the count operator. For each country, \( i \), exposures are computed as the population-weighted sum of exposures over the country’s constituent grid cells \( c \in i \):

\[
\varepsilon_{j,i,t}^T = \sum_{c \in i} w_{c,i,t} \varepsilon_{j,c,t}^T \quad \text{and} \quad \varepsilon_{k,i,t}^H = \sum_{c \in i} w_{c,i,t} \varepsilon_{k,c,t}^H
\]  

(8)

where the weights, \( w_{c,i,t} = \text{pop}_{c,i,t} / \text{pop}_{i,t} \), are the ratio of the grid cell to national population. Statistical controls include log per capita GDP \( (y) \), log real prices of electricity, natural gas, and petroleum \( (p_f) \), and the log of the aggregate capital stock per capita \( (x) \). Combining these elements, we obtain a country-specific time series error-correction model:

\[
\Delta q_{i,t} = \alpha_i + \left[ \sum_{j=1}^J \beta_{j,i}^T \Delta \varepsilon_{j,i,t}^T + \sum_{k=1}^K \beta_{k,i}^H \Delta \varepsilon_{k,i,t}^H + \sum_f \beta_{f,i}^P \Delta p_{f,i,t} + \beta_i^Y \Delta y_{i,t} + \beta_i^X \Delta x_{i,t} \right]
+ \theta_i \left\{ q_{i,t-1} - \frac{1}{J} \sum_{j=1}^J \gamma_{j,i}^T \varepsilon_{j,i,t-1}^T - \frac{1}{K} \sum_{k=1}^K \gamma_{k,i}^H \varepsilon_{k,i,t-1}^H - \sum_f \gamma_{f,i}^P p_{f,i,t-1} - \gamma_i^Y \Delta y_{i,t-1} - \gamma_i^X \Delta x_{i,t-1} \right\} + \nu_{i,t}
\]  

(9)

in which \( \nu_{i,t} \) is a random disturbance term.

Equation (9) 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 the interannual differences of energy consumption and the regressors. The latter are identified from the co-variation between lagged energy consumption and the prior levels of the covariates.

The error-correction speed of adjustment parameter, \( \theta \), measures each country’s rate of adjustment toward its own long-run equilibrium. The parameter vectors \( \beta^T \) and \( \beta^H \) capture the short-run disequilibrium demand response to meteorology, while \( \gamma^T \) and \( \gamma^H \) capture the feedback effect of the divergence between observed energy consumption and long-term

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6 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.
equilibrium energy use predicted by the covariates. 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 $\gamma^T$ and $\gamma^H$ flexibly capture temperature and humidity long-run effects as a piecewise linear spline, whose shape is determined by the covariation between observed demand and meteorology within each interval, as well as by 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 and Empirical Approach

Our dataset is an unbalanced panel of countries varying by fuel × sector combination\textsuperscript{7}, over the period 1970–2014. Our dependent variable is final energy consumption from the ENERDATA database (Table 1). Of the 219 exajoules (EJ) consumed by our sample of countries in 2010,\textsuperscript{8} countries in temperate regions accounted for 77% of the total. In both temperate and tropical regions demand is concentrated in the transportation and industry, with residences coming in a close third in temperate countries and a distant third in the tropics. In both regions petroleum (used overwhelmingly by transportation) makes up around half of total consumption, while electricity accounts for roughly a quarter of tropical countries’ use and more than a third temperate countries’ use. Aside from transportation’s use of petroleum, tropical countries’ industrial sectors’ use of all fuels, and temperate countries’ industrial, commercial and residential sectors’ electricity consumption, as well as residences’ use of natural gas, are particularly important.

Meteorological covariates are calculated from 3-h fields of surface temperature and specific humidity on a 0.25° grid from the Global Land Data Assimilation System (GLDAS) dataset (Rodell et al. 2004). We first temporally aggregate the raw temperature and humidity fields to construct gridded daily averages, which we bin into 14 temperature ranges and 10 specific humidity ranges over the course of each year. The resulting annual counts of daily exposures are then spatially aggregated to the country level using geospatially referenced population for the year 2000 from the Global Rural-Urban Mapping Project (GRUMPv1) database.\textsuperscript{9} Our statistical controls are countries’ annual real PPP GDP per capita and real energy prices from the ENERDATA database\textsuperscript{10}. Data on real capital stocks are obtained from Berlemann and Wesselhoft (2014) and expressed in per capita terms. All variables are in logarithms. All values have been converted in constant PPP 2005USD using the ENERDATA GDP deflator. Descriptive statistics are summarized in the “Appendix” (Table 8).

Data gaps—particularly in developing countries—forced a tradeoff between capturing heterogeneity in weather impacts and generating estimates with sufficient fuel, sectoral and

\textsuperscript{7} The number of countries varies between 6 in the gas, commercial, tropical combination and 49 in electricity, agriculture, tropical countries.

\textsuperscript{8} Global total final energy consumption in 2010 was 376 EJ. Our smaller total reflects countries excluded because of missing data as well as the exclusion of other energy sources.

\textsuperscript{9} As dynamic population maps were not available, we assume identical weights for all years in our sample, $\bar{w}_{c,i,Current}$.

\textsuperscript{10} As fuel price series for the agriculture and commercial sectors were not available, industrial fuel prices were used. The transportation sector includes the price of gasoline only, Enerdata, Grenoble, France, 2016.
|                  | Tropical |                  | Temperate |                  | World    |                  |
|------------------|----------|------------------|-----------|------------------|----------|------------------|
|                  | Electricity | Natural gas | Petroleum | Total | Electricity | Natural gas | Petroleum | Total | Electricity | Natural gas | Petroleum | Total |
| Agriculture      | 0.8      | 0                | 1.5       | 2.3  | 0.9        | 0.3        | 3.2        | 4.4  | 1.6        | 0.3        | 4.7        | 6.6    |
| Industrial       | 4.5      | 6.8              | 4.6       | 15.9 | 21.6       | 12.9       | 8          | 42.5 | 26.1       | 19.7       | 12.7       | 58.5   |
| Residential      | 3.5      | 2                | 3         | 8.5  | 14         | 15.9       | 5.4        | 35.3 | 17.5       | 18         | 8.4        | 43.9   |
| Commercial       | 2.6      | 0.3              | 0.7       | 3.6  | 14.1       | 7.4        | 3.2        | 24.7 | 16.7       | 7.7        | 3.9        | 28.3   |
| Transportation   | 0.1      | 0.6              | 19.4      | 20.1 | 0.8        | 0.6        | 60         | 61.4 | 0.9        | 1.2        | 79.4       | 81.5   |
| Total            | 11.5     | 9.7              | 29.2      | 50.4 | 51.4       | 37.1       | 79.8       | 168.3 | 62.8       | 46.9       | 109.1      | 218.8  |
Global Energy Consumption in a Warming Climate

regional coverage to construct global projections. The time dimension of our sample was not sufficiently large to permit estimation of the heterogeneous slopes model (9). Our remedy was to partition our sample by climatic regime, designating countries as tropical or temperate according to their Köppen-Geiger classification (Table 8), which resulted in 30 fuel × sector × climate combinations. For each of these subsamples we estimated a fixed-effects panel ECM in which \( \alpha_i \) captured the influence of unobserved time-invariant country-specific factors on the subsample’s average growth rate of energy demand. Panel unit root tests indicated that the resulting log per capita fuel demand and GDP panels contain unit roots, but the temperature and humidity panels are stationary. Panel cointegration tests of regressions of log per capita fuel demand on log per capita GDP and weather almost always reject the null of no cointegration against the alternative hypothesis of some or all panels being cointegrated (Westerlund 2007; Persyn and Westerlund 2008). We initially sought to explicitly model short-run heterogeneity via the pooled mean-group (PMG) estimator (Pesaran and Smith 1995; Pesaran et al. 1999; Blackburne and Frank 2007) in which all countries share a common long-run relationship but have varying short-run dynamics and speed of adjustment to equilibrium:

\[
\gamma^T_{j,i} = \gamma^T_j, \quad \gamma^H_{k,i} = \gamma^H_k, \quad \gamma^P_{f,i} = \gamma^P_f, \quad \gamma^Y_i = \gamma^Y, \quad \gamma^X_i = \gamma^X
\]  

However, the PMG model yielded estimates for only 12 fuel × sector × region combinations, and does not include energy price covariates, see Table 10 in “Appendix”. We therefore ultimately relied on the restrictive assumption of homogeneous short and long-run coefficients as well as speeds of adjustment within each subsample:

\[
\beta^T_{j,i} = \beta^T_j, \quad \beta^H_{k,i} = \beta^H_k, \quad \beta^P_{f,i} = \beta^P_f, \quad \beta^Y_i = \beta^Y, \quad \beta^X_i = \beta^X, \quad \theta_i = \theta
\]  

Combining Eqs. (9), (10) and (11) yields our preferred specification: a fixed-effects model that achieved the broadest coverage in terms of identification, and which we estimate via OLS. Even so, small sample sizes limited identification of the per capita energy demand responses to all but a few of the 14 temperature intervals. Given the collinearity between the fixed effects and moderate temperature and humidity intervals, our remedy was to drop these middle bins and aggregate adjacent extreme bins to focus the analysis on the effects of exposure to extreme hot and cold days \((T < 12.5^\circ C \text{ and } T > 27.5^\circ C)\). Gaps in ENERDATA’s energy price series in developing countries further reduced our sample sizes in the tropics, while collinearity between country GDP and capital stock series prevented the use of both variables as independent controls.

We pursued the general-to-specific modeling strategy shown in Table 2. First, we dropped the capital stock variable and estimated our preferred specification with temperature, humidity, the full vector of energy prices and GDP per capita as our base specification (M1). We then estimate specifications with the additional exclusion of cross-price terms (M2), humidity bins (M3), and finally both cross price and humidity terms (M4). The combination of 4 models, 3 fuels, 5 sectors and 2 regions yields 120 regressions. There were insufficient observations of natural gas use by agriculture, residential, transportation, of petroleum by residential in the tropics, and in temperate countries of petroleum by agriculture and of natural gas in transportation. We end up with 24 fuel × sector × region combinations for models M1-M4. For

---

11 The following subsamples had insufficient data: residential, commercial, transportation and industrial natural gas use and transportation electricity use in the tropics, and commercial petroleum use in temperate regions. We fail to reject null of no cointegration for natural gas (electricity and petroleum) use in tropical (temperate) agriculture, as well as industrial natural gas use in temperate regions, see Table 9 in “Appendix”.
Table 2  Econometric modeling strategy

|   | Exclude capital stocks                        | Exclude capital stocks, cross-price terms | Exclude capital stocks, humidity | Exclude capital stocks, cross-price terms, humidity |
|---|-----------------------------------------------|------------------------------------------|---------------------------------|--------------------------------------------------|
| M1 | $\beta^X = \gamma^X = 0$                     | $\beta^X = \gamma^X = \beta^P_f \neq \text{Focal fuel} = \gamma^P_f \neq \text{Focal fuel} = 0$ | $\beta^X = \gamma^X = \beta^H = \gamma^H = 0$ | $\beta^X = \gamma^X = \beta^P_f \neq \text{Focal fuel} = \gamma^P_f \neq \text{Focal fuel} = \beta^H = \gamma^H = 0$ |

each unique combination, our preferred long-run elasticity values are taken from the least restrictive specification yielding estimates that are significant at the 10% level.\footnote{If there are no estimates significant at 10\% but there are estimates significant at 15\% level, we use them.}

Collinearity of our capital stocks with GDP created an insurmountable obstacle to identifying the impact on the average set-point energy consumption in Fig. 1 of capital deepening—or unpacking the effect of the latter into the influences of increasing quantity or changing characteristics of energy-using durables. Both influences are subsumed within the error-correcting speed of adjustment parameter and the long-run income elasticity. Nevertheless, we are able to elucidate the net impact of increases in the capital stock per person on the marginal response of energy demand to weather, by interacting the log capital stock per person with bins of temperature. The result is the extensive margin specification:

$$
\Delta q_{i,t} = \alpha_i + \left[ \sum_{j=1}^{J} \left( \beta^X_j \Delta (E^T_{j,i,t} x_{i,t}) + \beta^{TT}_j \Delta E^T_{j,i,t} \right) + \sum_{k=1}^{J} \beta^H_k \Delta E^H_{k,i,t} \right] + \sum_f \beta^P_f \Delta p_{f,i,t} + \beta^Y \Delta y_{i,t}
$$

$$
+ \theta \left\{ q_{i,t-1} - \sum_{j=1}^{J} \left( \gamma^X_j (E^T_{j,i,t-1} x_{i,t-1}) + \gamma^{TT}_j E^T_{j,i,t-1} \right) - \sum_{k=1}^{J} \gamma^H_k E^H_{k,i,t-1} - \sum_f \gamma^P_f p_{f,i,t-1} - \gamma^Y y_{i,t-1} \right\} + v_{i,t}
$$

which facilitates decomposition of the previously-estimated temperature elasticities into baseline responses ($\gamma^{TT}$) and the modulating effects of capital ($\gamma^X T$):

$$
\gamma^T_j = \gamma^{TT}_j + \gamma^X_j x
$$

Capital’s net influence is captured by the parameter $\gamma^X T$. Positive values suggest that the amplifying effect of a larger stock of energy-using durables outweighs the attenuating effect of the diffusion of energy efficiency improvements embodied therein, making energy consumption more sensitive to exposure to hot or cold temperatures. Negative values indicate that the reverse is true, yielding an attenuating effect on demand. The direction and magnitude of the overall impact of temperature depends on the per-capita capital stock. Note that if $\gamma^{TT}$ and $\gamma^X T$ have different signs a given change in temperate exposure can lower energy demand.
demand in some locations while simultaneously raising it in others with larger or smaller ratios of capital per person.

2.3 Climate Change Impact Projections

The second phase of our analysis combines econometrically estimated long-run elasticities with scenarios of climate change and global socioeconomic development to characterize future impacts on energy demand, circa 2050. Projected changes in meteorology are simulated by runs of the CMCC-CM earth system model (Scoccimarro et al. 2011) under two a representative scenarios of moderate and high warming (RCP 4.5 and RCP 8.5, with radiative forcing of 4.5 and 8.5 W/m$^{-2}$, respectively, by century’s end)\textsuperscript{13}. ESM projections of climate are subject to considerable uncertainty, particularly in the vertical structure of water vapor which will influence sensible temperature and the demands for heating and cooling (Flato et al. 2013). Accordingly, we restrict our attention to temperature as the climatic predictor of energy consumption changes. Although ESM simulations exhibit skill relative to broad patterns of surface temperatures in the current climate, individual ESMs exhibit biases that tend to increase with spatial and temporal resolution. For this reason making direct comparisons between ESM simulations of future climate and historical reanalysis datasets such as GLDAS is not appropriate. Our solution is to employ the “delta” method, which consists of applying Eq. (7) to CMCC-CM gridded model output to construct annualized PDFs of temperature exposures over the current and projection periods 2006–2015 and 2046–2055, denoted as $\tilde{\varepsilon}_{T,j,c,\text{Current}}$ and $\tilde{\varepsilon}_{T,j,c,\text{Future}}$, respectively. These two fields of temperature exposure can be validly compared for the purpose of constructing impact projections (Fig. 2). Relative to the 2006–2015 climate, circa 2050 the majority of grid cells will experience increased (decreased) frequency of hot days $>27.5^\circ$C (cold days $<0^\circ$C). The geographic incidence of these changes in uneven, with increased frequency of hot days in the tropics and areas such as southern Europe, as well as decreased frequency of cold days concentrated at high latitudes. In countries with large latitudinal extents (e.g., the U.S., China, Australia, and Brazil) increasing heat exposures and declining cold exposures are localized in different sub-national zones.

Our climate change impact metric is the change in per capita energy demand at the level of each grid-cell, $c$, which we calculate by combining the fitted long-run climatic estimates in (9) with our synthetic historical and future exposure series:

$$\phi_{\text{Climate}}^{c,f,s} = \exp \left\{ \sum_{j=1}^{J} \gamma_{j,f,s} \left( \tilde{\varepsilon}_{T,j,c,\text{Future}} - \tilde{\varepsilon}_{T,j,c,\text{Current}} \right) \right\}$$

(14)

The index $\phi_{\text{Climate}}$ can be interpreted as the ratio of per-capita fuel $\times$ sector energy consumption in a future climate relative energy use under the current climate. It is straightforward to use this kind of metric to quantify the effects that climatic shifts would have on today’s economy. For example, using current energy consumption ($\tilde{Q}_{i,f,s,\text{Current}}$) as the base, and assuming that sub-national per capita energy demand is uniformly distributed and equal to the national average, the net impact on contemporary country-level final energy demand, $i$, is found by aggregating across grid cells, fuels and sectors:

\textsuperscript{13} Relative to other ESMs participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5), CMCC-CM generally exhibits less warming in the tropics and more cold days in the mid-latitudes (Bas van Ruijven, personal communication).
Fig. 2 CMCC-CM simulated changes in future temperature exposure for different warming scenarios, 2046–2055 relative to 2006–2015. a Absolute change in the distribution of daily temperatures (outliers suppressed) and b % change in and future exposure to hot (left) and cold (right) days, RCP 4.5 (top) and RCP 8.5 (bottom). (Color figure online)

\[
\Phi_{i,Current} = \frac{\sum_f \sum_s \left\{ \sum_{c \in i} \tilde{w}_{c,i,Current} \Phi_{c,f,s}^{\text{Climate}} \right\}}{\sum_f \sum_s \tilde{Q}_{i,f,s,Current}}
\]  

(15)

The caveat is that the future global energy system is likely to differ substantially from the present, due especially to the growth of population and GDP anticipated in developing countries over the coming decades. The broader implication is that assessments should
account for the character of vulnerable human systems in the future periods when climatic changes arise (Kriegler et al. 2012). Here the latter correspond to gridded fields of population and “business as usual” (BaU) fuel × sector per-capita energy demand circa 2050, which we construct using the Shared Socioeconomic Pathways. Using SSP5, we obtain gridded and national population distributions, \( \text{pop}_c, \text{Future} \) and \( \text{Pop}_i, \text{Future} \) from Jones et al. (2015), as well as the logarithms of countries current and future average per-capita GDP, \( \tilde{y}_i, \text{Current} \) and \( \tilde{y}_i, \text{Future} \). Combining the latter with our estimated long-run income elasticities \( \hat{\gamma}_{f,s} \), we enable economic growth to scale the country-level per capita energy demands

\[
\phi_{E,ct}^{\text{Economy}} = \exp \left\{ \hat{\gamma}_{f,s}^Y \left( \tilde{y}_i, \text{Future} - \tilde{y}_i, \text{Current} \right) \right\}
\]

yielding future country-level energy consumption in the absence of climate change:

\[
Q_{i, f, s, \text{BaU}} = \phi_{E,ct}^{\text{Economy}} \tilde{Q}_{i, f, s, \text{Current}}
\]

Using future population to calculate grid-cell level weights, \( \bar{w}_{c, i, \text{Future}} = \text{pop}_c, \text{Future} / \text{Pop}_i, \text{Future} \), our analogue of (15) that accounts for future expansion in energy consumption is:

\[
\Phi_{i, \text{Future}} = {\sum f \sum s} \left( \frac{\sum_{c \in j} \bar{w}_{c, i, \text{Future}} \phi_{c, f, s}^{\text{Climate}} \tilde{Q}_{i, f, s, \text{BaU}}}{\sum f \sum s \tilde{Q}_{i, f, s, \text{BaU}}} \right)
\]

The corresponding changes in energy use at the grid cell-level are summarized by the fuel, sector, and fuel × sector margins of (18):

\[
\begin{align*}
\varphi_{c, f, \text{BaU}} & = \frac{\sum s \delta_{i,c} \phi_{c, f, s}^{\text{Climate}} \tilde{Q}_{i, f, s, \text{BaU}}}{\sum s \delta_{i,c} \tilde{Q}_{i, f, s, \text{BaU}}} \quad (19a) \\
\varphi_{c, s, \text{BaU}} & = \frac{\sum f \delta_{i,c} \phi_{c, f, s}^{\text{Climate}} \tilde{Q}_{i, f, s, \text{BaU}}}{\sum f \delta_{i,c} \tilde{Q}_{i, f, s, \text{BaU}}} \quad (19b) \\
\varphi_{c, \text{BaU}} & = \frac{\sum f \sum s \delta_{i,c} \phi_{c, f, s}^{\text{Climate}} \tilde{Q}_{i, f, s, \text{BaU}}}{\sum f \sum s \delta_{i,c} \tilde{Q}_{i, f, s, \text{BaU}}} \quad (19c)
\end{align*}
\]

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

Lastly, it is not straightforward to use our extensive margin specification (12) to construct detailed projections of climate change impacts on either the current or future energy system. The obstacle is absence of data on capital stocks at the grid cell level for the current period, and particularly for future periods consistent with the SSP scenarios. There is the potential to calculate an analogue of Eq. (14) to assess the-present day impacts of future climate change, using a spatially downscaled capital stock proxy, \( \tilde{x} \), e.g., derived from the global exposure database (De Bono and Mora 2014). However, such an assessment is beyond the scope of the present study.

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14 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 mostly through fossil fuels (O’Neill et al. 2014).
3 Results

3.1 Empirical Energy Demand Responses to Temperature and Income

Table 3 summarizes our empirical estimates. Out of 30 subsamples, our main specification yields estimates for 12, the no cross-price effects model yielded a further 6 estimates, the no-humidity model 4 more, and the model omitting both cross-price effects and humidity model, two more. Weather has a significant influence on energy consumption in less than 40% of fuel × sector × region combinations. Temperature semi-elasticities indicate that fuel demands tend to increase with hot days, an effect whose magnitude ranges in from 0.004 to 0.047 with larger values skewed toward temperate regions, and varies among fuels and sectors. These values generally exceed short-run elasticities estimated on aggregate data (e.g., Deschenes and Greenstone 2013), and, for some fuel × sector combinations, attain magnitudes similar to those estimated by micro studies (Davis and Gertler 2015; Auffhammer and Aroonruengsawat 2011). Responses to hot and cold days are asymmetric (cf Fig. 1). Either the heating or the cooling response is significant—but not both—in most fuel × sector combinations (exceptions are electricity in commerce and industry, as well as petroleum in commerce and transportation).

Several weather elasticities are negative, mostly for low temperatures and especially in the tropics, suggesting that with high average temperatures, only extreme cold exposures induce changes in thermal regulation services large enough to permit identification of energy demand responses. While the aggregate nature of our data preclude our ability to pinpoint the precise mechanisms at work, we note that tropical countries predominantly represent developing economies with unreliable electricity distribution systems and consequent extensive use of distributed petroleum-fired generators to satisfy final electricity demand. Thus, while the declines in commercial and transportation electricity use seen in temperate countries are likely due to reduced AC usage during spring and fall, in tropical countries declines in commercial petroleum use may reflect a similar seasonal phenomenon, via the channel of reduced autoproducer electricity supplies. Declines in (non-autoproducer) electricity consumption by industry and agriculture in the tropics could reflect reduced AC use for occupational health and safety in heavy industries (particularly those with high temperature processes), as well as reduced irrigation water conveyance during the growing season or post-harvest refrigeration or processing of crops.

It is more challenging to explain the other patterns of elasticity values, which we speculate could reflect fuel switching associated with seasonal variations in sectors’ economic activity. In the agriculture-intensive developing economies that are concentrated in the tropics, increased demand for transport of harvested agricultural products during the relatively hot growing season accounts for the estimated increase (decrease) in transportation sector petroleum use in response to hot (cold) days. This also helps explain the increase in agricultural petroleum use with cold days as reflecting the switch from growing season use of off-farm (e.g., transport sector) motive power to on-farm alternatives related to out-of-season field operations. And while in tropical countries increased exposure to hot days is associated with switching between petroleum and electricity in the commercial and transportation sectors, the underlying drivers remain opaque.

The table also summarizes our long-run income elasticities, which are positive except for electricity use by agriculture in tropical countries and petroleum use by commerce in temperate countries. In line with expectations, demand in most fuel × sector × region combinations exhibit income responses that are relatively inelastic (absolute magnitude in the range 0.2-
Table 3  Long-run semi-elasticities of energy demand with respect to temperature exposures and income: preferred specification

| Region          | Sector   | Response to cold days \((T < 12.5 \, ^\circ C)\) | Response to hot days \((T > 27.5 \, ^\circ C)\) | Log real GDP per capita elasticity | Own price elasticity | Error-correcting speed of adjustment | Time to equilibrium (years) |
|-----------------|----------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|----------------------|--------------------------------------|----------------------------|
| **Temperate regions** |          |                                               |                                               |                                   |                      |                                       |                            |
| Agriculture     | Electricity | M4  –                                          | 0.008                                          | 0.645                             | – 0.410              | – 0.107                              | 9.4                        |
|                 | Natural gas | M1  – 0.0195\(^+\)                          | 0.033                                          | 1.320                             | –                    | – 0.188                              | 5.3                        |
|                 | Petroleum  | n.d.                                          |                                                |                                   |                      |                                       |                            |
| Industrial      | Electricity | M2  –                                          | 0.009                                          | 0.363                             | – 0.232              | – 0.175                              | 5.7                        |
|                 | Natural gas | M2  –                                          | 0.033                                          | –                                 | –                    | – 0.216                              | 4.6                        |
|                 | Petroleum  | M2  –                                          | –                                              | 1.089                             | –                    | – 0.068                              | 14.6                       |
| Residential     | Electricity | M3  –                                          | 0.0146\(^+\)                                  | 0.366                             | – 0.412              | – 0.194                              | 5.15                       |
|                 | Natural gas | M1  – 0.023                                    | 1.433                                          | –                                 | –                    | – 0.117                              | 8.5                        |
|                 | Petroleum  | M4  0.0207\(^+\)                               | –                                              | –                                 | – 1.328              | – 0.056                              | 17.9                       |
| Commercial      | Electricity | M1  –                                          | 0.047                                          | 0.864                             | –                    | – 0.150                              | 6.7                        |
|                 | Natural gas | M1  –                                          | 0.970                                          | –                                 | –                    | – 0.240                              | 4.2                        |
|                 | Petroleum  | M3  0.012                                       | –                                              | –                                 | 0.795                | – 0.537                              | 2.9                        |
| Transportation  | Electricity | M1  – 0.003\(^+\)                            | 0.260                                          | –                                 | –                    | – 0.173                              | 5.8                        |
|                 | Natural gas | n.d.                                          |                                                |                                   |                      |                                       |                            |
|                 | Petroleum  | M1  –                                          | 0.821                                          | –                                 | – 0.292              | – 0.235                              | 4.3                        |
| **Tropical regions** |          |                                               |                                               |                                   |                      |                                       |                            |
| Agriculture     | Electricity | M1  – 0.008\(^+\)                            | –                                              | – 0.701                           | –                    | – 0.939                              | 1.1                        |
|                 | Natural gas | n.d.                                          |                                                |                                   |                      |                                       |                            |
|                 | Petroleum  | M1  0.066                                       | –                                              | –                                 | 1.084                | – 0.217                              | 4.6                        |
| Industrial      | Electricity | M1  – 0.028                                   | 0.008\(^+\)                                   | 0.478                             | –                    | – 0.157                              | 6.4                        |
|                 | Natural gas | M2  0.010                                       | –                                              | –                                 | –                    | – 0.150                              | 6.6                        |
|                 | Petroleum  | M2  0.005                                       | –                                              | –                                 | –                    | – 0.206                              | 4.8                        |
| Residential     | Electricity | M2  –                                          | –                                              | 1.287                             | –                    | – 0.092                              | 10.9                       |
|                 | Natural gas | n.d.                                          |                                                |                                   |                      |                                       |                            |
|                 | Petroleum  | n.d.                                          |                                                |                                   |                      |                                       |                            |
| Commercial      | Electricity | M1  –                                          | 0.008                                          | 0.702                             | –                    | – 0.218                              | 4.6                        |
|                 | Natural gas | M1  –                                          | –                                              | –                                 | –                    | – 0.239                              | 4.2                        |
|                 | Petroleum  | M3  0.014                                       | –                                              | 0.017                             | –                    | – 0.239                              | 4.2                        |
1. Natural gas in agricultural and residential sectors in temperate countries, and electricity in residential and transportation sectors in the tropics, increase elastically, while industrial petroleum use in temperate countries declines elastically. Comparing magnitudes across climates more broadly, elasticities of electricity use by residential, industrial and transportation sectors tend to be larger in the tropics, whereas those for commerce and agriculture tend to be larger in temperate regions. These values fall within the general range of estimates from previous aggregate analyses.

We obtain significant long-run own-price elasticities for only a handful of fuel × sector combinations, almost all of which are for temperate countries. Results are in line with previous estimates, see for example (Labandeiraa et al. 2017). In tropical countries prices appear not to influence energy demand, reflecting the imperfection of energy markets in those regions, which cover a smaller fraction of total final consumption and tend to be distorted.

The effects of humidity and other covariates are reported in the online Appendix. Exposure to high humidity days increases industrial and commercial electricity use, and agricultural petroleum use in temperate regions, as well as residential and agricultural natural gas use in the tropics. Exposure to low humidity days increases use of electricity and natural gas in agriculture. The latter result likely indicates the correlation between low humidity and drought conditions that increase demands for irrigation, which in some countries is a major source of agricultural electricity consumption (Maddigan et al. 1982; Shah et al. 2008). Temperate countries are generally more sensitive to high humidity levels, reflecting the fact that their climates tend to be less humid than the tropics. Long-run demand responses to temperature are uniformly larger in magnitude than their short-run counterparts.

Lastly, Table 3 records the error-correcting speed of adjustment coefficients and the implied length of time for energy demand to re-equilibrate after a shock. The coefficients, which are uniformly significant and less than unity, suggest that sectoral agents close anywhere from 7 to 94% of the disequilibrium gap between $q$ and $q^*$ in a year, confirming that energy consumption adjustments to contemporaneous weather shocks exert persistent effects on demand. The degree of persistence varies substantially. For agricultural electricity use in the tropics, full adjustment to a shock is practically instantaneous, taking about a year. But at the other extreme, residential energy use in temperate countries re-equilibrates very gradually, adjusting fully only after two decades. Across fuels and sectors it takes 7 years on average to fully adjust, but countries in the tropics adjust faster (5 years, as opposed to 8.6

---

**Table 3 continued**

|                  | Response to cold days ($T < 12.5 \degree C$) | Response to hot days ($T > 27.5 \degree C$) | Log real GDP per capita elasticity | Own price elasticity | Error-correcting speed of adjustment | Time to equilibrium (years) |
|------------------|--------------------------------------------|---------------------------------------------|-----------------------------------|---------------------|-------------------------------------|-----------------------------|
| **Transportation** |                                            |                                             |                                   |                     |                                     |                             |
| Electricity      | M3 –                                       | −0.011                                      | 1.93                              | −                   | −0.192                              | 5.2                         |
| Natural gas      | n.d.                                       |                                             |                                   |                     |                                     |                             |
| Petroleum        | M1 −0.009                                   | 0.004+                                      | 0.678                             | −                   | −0.206                              | 4.8                         |

Specification (M1) includes the full vector of energy prices, temperature and humidity terms; (M2) excludes cross-price terms; (M3) excludes humidity terms; (M4) excludes both cross-price terms and humidity terms. All estimates significant at the 10% level, except where indicated: $+p < 0.15$, $-p > 0.15$, n.d. insufficient observations.
years in temperate countries), consistent with the fact that they tend to be poorer economies with smaller (and thus more easily adjusted) stocks of energy-using capital.

Table 4 summarizes our long-run results at the extensive margin. Where $\gamma_{TT}$ and $\gamma_{XT}$ were both significant their estimates were always opposite in sign. Regarding the latter parameter, in temperate countries, capital deepening attenuates the demand response to cold days (rendering their positive effect less positive) and amplifies the demand response to hot days (rendering their negative effect less negative, or outright positive). In the tropics the signs of the interaction estimates are mixed, especially for demand responses to cold days, while responses to hot days are more strongly weighted toward amplification of the kind described above. These results suggest that the aforementioned temperature elasticities reflect the average of heterogeneous country responses that differ in sign and magnitude. Temperate-zone elasticities of heating (cooling) energy use are positive and significant for small to moderate (moderate to large) values of capital stock per person. Similar responses in tropical countries are not cleanly delineated by temperature: positive for low to moderate levels of capital stock per person and negative otherwise (demands for petroleum in agriculture and natural gas in commerce with low temperatures, as well as natural gas and petroleum in industry with high temperatures), and vice versa (demands for electricity in agriculture and industry with low temperatures, as well as for petroleum and electricity in agriculture and commerce with high temperatures). The biggest difference from Table 3 is that income elasticities are now only significant for a few fuel × sector combinations, mostly in temperate countries. Notwithstanding this, the error-correcting speed of adjustment coefficients and associated equilibrium adjustment periods change only slightly in most cases, giving us confidence in the consistency of our intensive- and extensive-margin results.

Our finding that increased capital intensity amplifies the rate at which temperate-zone residential electricity increases in response to heat vindicates our motivating concern about the consequences of AC penetration as poor countries develop. Already, our temperate-zone results encompass China (cf Auffhammer 2014), and although we do not identify similar historical responses in the tropics, countries such as Brazil and India following similar development trajectories in the future will likely portend substantial climate-driven increases in electricity consumption. It is this issue to which we now turn.

### 3.2 The 2050 Baseline: Energy Consumption and Vulnerability to Climate Change

Using Eqs. (16) and (17), we combine our preferred estimates with projected per capita GDP growth and gridded population from SSP5 to calculate BaU energy consumption circa 2050. The results, summarized in Table 5, indicate that in the absence of climate change global energy consumption will reach 677.7 EJ, a three-fold increase over 2010. This figure is in general agreement with IAM simulations of final energy under the SSP scenarios, falling just short of the lower end of the 709–895 EJ multimodel ensemble range (Riahi et al. 2017). Mirroring the range of our income elasticities, there is substantial heterogeneity in the extent of change in energy consumption across regions, sectors and fuels. We project a fourfold increase in final energy in tropical (generally emerging) economies, and a threefold increase in temperate (mostly advanced) economies, which shifts developing countries’ share of global energy use from the current 23–29% by mid-century. Electricity accounts for the bulk of the expansion in energy use in the tropics, with rapid increases outside of agriculture, concentrated in the transportation and residential sectors. In temperate regions increases in energy consumption are driven by natural gas. Compared with the current energy system, the global final energy mix is slightly more skewed toward electricity and natural gas at the
Table 4  Long-run semi-elasticities of energy demand with respect to temperature exposures and income: extensive margin specification

|                        | Response to cold days ($T < 12.5^\circ C$) | Response to hot days ($T > 27.5^\circ C$) | Log real GDP per capita elasticity | Error-correcting speed of adjustment | Time to equilibrium (years) |
|------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------|--------------------------------------|----------------------------|
|                        | Base Interaction @ %-iles of 2005 K per capita | Base Interaction @ %-iles of 2005 K per capita |                                   |                                      |                            |
|                        | 50% 5% 95%                                | 50% 5% 95%                                |                                   |                                      |                            |
| **Temperate regions**  |                                             |                                             |                                   |                                      |                            |
| **Agriculture**        |                                             |                                             |                                   |                                      |                            |
| Electricity M1         | 0.104                                     | 0.006                                     | −                                 | 1.172+                               | −0.127                     | 7.9                        |
| Natural gas M2         | −                                         | −                                         | −0.078 0.072                      | 0.171−0.259                         | −0.208                     | 4.8                        |
| Petroleum n.d.         |                                            |                                            |                                   |                                      |                            |
| **Industrial**         |                                             |                                             |                                   |                                      |                            |
| Electricity n.d.       |                                            |                                            |                                   |                                      |                            |
| Natural gas n.d.       |                                            |                                            |                                   |                                      |                            |
| Petroleum M1           | 0.130                                     | 0.007                                     | 0.025−−−−                          | −0.073−−−−                          | 13.8                       |
| **Residential**        |                                             |                                             |                                   |                                      |                            |
| Electricity M1         | 0.058                                     | 0.003                                     | 0.006 0.012−                       | −0.563 0.034 0.026−0.039 0.080 0.998 | −0.092                     | 10.9                       |
| Natural gas n.d.       |                                            |                                            |                                   |                                      |                            |
| Petroleum M2           | 0.271+                                    | 0.015                                     | −−−−                               | −−−−                                 | −0.049                     | 20.4                       |
| **Commercial**         |                                             |                                             |                                   |                                      |                            |
| Electricity n.d.       |                                            |                                            |                                   |                                      |                            |
| Natural gas n.d.       |                                            |                                            |                                   |                                      |                            |
| Petroleum M1           | 0.128                                     | 0.006+                                    | 0.018 0.030−                       | 0.069−−−−                            | −0.271                     | 3.7                        |
| **Transportation**     |                                             |                                             |                                   |                                      |                            |
| Electricity M2         | 0.049                                     | 0.003                                     | −−−−                               | 1.071−−−−                            | −0.145                     | 6.9                        |
| Natural gas n.d.       |                                            |                                            |                                   |                                      |                            |
| Petroleum n.d.         |                                            |                                            |                                   |                                      |                            |
Table 4  continued

|                      | Response to cold days ($T < 12.5^\circ C$) | Response to hot days ($T > 27.5^\circ C$) | Log real GDP per capita elasticity | Error-correcting speed of adjustment | Time to equilibrium (years) |
|----------------------|--------------------------------------------|-------------------------------------------|-----------------------------------|--------------------------------------|-----------------------------|
|                      | Base Interaction @ %-iles of 2005 K per capita | Base Interaction @ %-iles of 2005 K per capita |                                   |                                      |                             |
|                      | 50%  5%    95%                              | 50%  5%    95%                              |                                   |                                      |                             |
| Tropical regions     |                                            |                                            |                                   |                                      |                             |
| Agriculture          |                                            |                                            |                                   |                                      |                             |
| Electricity M2       | $-0.170$ $0.011$                          | $-0.235$ $0.015$                          | $-0.035$                          | $-0.390$                            | $3.3$                       |
| Natural gas n.d.     |                                            |                                            |                                   |                                      |                             |
| Petroleum M1         | $1.510$ $-0.092$                          | $0.109$ $0.302$                           | $-0.103$                          | $1.957$ $0.119$                     | $-0.139$ $0.390$ $0.135$ $-0$ | $-0.194$ $5.2$             |
| Industrial           |                                            |                                            |                                   |                                      |                             |
| Electricity M3       | $-0.886$ $0.053$                          | $-0.081$ $-0.191$                         | $0.302$                           | $-0.191$ $0.040$                    | $-0.132$                    | $7.5$                       |
| Natural gas M3       | $-0.232$ $0.047$                          | $0.127$ $-0.040$                          |                                   |                                      |                             |
| Petroleum M3         |                                            |                                            |                                   |                                      |                             |
| Residential          |                                            |                                            |                                   |                                      |                             |
| Electricity n.d.     |                                            |                                            |                                   |                                      |                             |
| Natural gas n.d.     |                                            |                                            |                                   |                                      |                             |
| Petroleum n.d.       |                                            |                                            |                                   |                                      |                             |
| Commercial           |                                            |                                            |                                   |                                      |                             |
| Electricity M1       | $-0.188$ $0.196$                          | $-0.237$ $0.591$                          | $-0.097$                          | $1.354$ $0.083$                     | $-0.472$                    | $2.1$                       |
| Natural gas M1       | $-0.466$                                 |                                           |                                   |                                      |                             |
| Petroleum M1         | $-0.472$                                 |                                           |                                   |                                      |                             |
### Table 4 continued

|                     | Response to cold days ($T < 12.5^\circ C$) | Response to hot days ($T > 27.5^\circ C$) | Log real GDP per capita elasticity | Error-correcting speed of adjustment | Time to equilibrium (years) |
|---------------------|-------------------------------------------|------------------------------------------|-----------------------------------|------------------------------------|---------------------------|
|                     | Base Interaction @ %-iles of 2005 K per capita | Base Interaction @ %-iles of 2005 K per capita |                                   |                                    |                           |
|                     | 50%  5%  95%                                 | 50%  5%  95%                              |                                   |                                    |                           |
| Transportation      |                                           |                                          |                                   |                                    |                           |
| Electricity         | M1 – – – –                                 | – 0.422 0.026 – 0.086 0.026             | – 0.020 0.002 0.004 – 0.007 0.698 | – 0.524                            | 1.9                       |
| Natural gas         | n.d.                                      |                                           |                                   |                                    |                           |
| Petroleum           | M1 – – – –                                 | – 0.020 0.002 0.004 – 0.007 0.698       | – 0.366                           |                                    | 2.7                       |

Specification (M1) includes the full vector of energy prices, temperature and humidity terms; (M2) excludes cross-price terms; (M3) excludes humidity terms; (M4) excludes both cross price and humidity terms.

All estimates significant at the 10% level, except where indicated: $+ p < 0.15, - p > 0.15, n.d.$ insufficient observations.
Table 5  Global weather-sensitive final energy consumption circa 2050 and change relative to 2010

|                | Tropical |                |                |                |                |                |                |
|----------------|----------|----------------|----------------|----------------|----------------|----------------|----------------|
|                | Electricity | Natural gas | Petroleum | Total | Electricity | Natural gas | Petroleum | Total |
| Agriculture    | 0.2      | 0              | 1.8          | 2     | 2.8         | 1.3          | 3.9          | 8     |
| Industrial     | 13.6     | 10.7           | 6.4          | 30.7  | 41.8        | 16.8         | 2.9          | 61.5  |
| Residential    | 51.7     | 2.5            | 3.8          | 58    | 26.7        | 108.8        | 6.7          | 142.2 |
| Commercial     | 11.4     | 0.4            | 0.9          | 12.7  | 46.1        | 24.5         | 1.9          | 72.5  |
| Transportation | 5.5      | 0.7            | 85           | 91.2  | 1.2         | 0.6          | 196.8        | 198.6 |
| Total          | 82.4     | 14.3           | 97.9         | 194.6 | 118.6       | 152          | 212.2        | 482.8 |

Energy consumption growth factor (2010 = 1.0)

|                | Tropical |                |                |                |                |                |                |
|----------------|----------|----------------|----------------|----------------|----------------|----------------|----------------|
|                | Agriculture | Industrial | Residential | Commercial | Transportation | Total |
| Agriculture    | 0        | 1              | 1              | 1              | 1              | 2              |
| Industrial     | 3        | 2              | 1              | 2              | 1              | 1              |
| Residential    | 15       | 1              | 1              | 7              | 2              | 1              |
| Commercial     | 4        | 1              | 1              | 4              | 3              | 1              |
| Transportation | 55       | 1              | 4              | 5              | 2              | 1              |
| Total          | 7        | 1              | 3              | 4              | 2              | 1              |
expense of petroleum, and toward the transportation and residential sectors at the expense of agriculture and industry.

Figure 3 highlights the consequences of the spatial intersection between these patterns of energy use and the climatic changes illustrated in Fig. 2b. More than half BaU final energy consumption (65%) is projected to occur in areas that will be exposed to either slight declines in cold temperatures or slight increases in high temperatures (fewer than ±5 extreme days). The largest absolute increases in hot days are concentrated in Southeast Asia, Latin America and Sub-Saharan Africa, regions where per capita and total final energy use are projected to still be small and whose frequency of hot days is already high in the current climate. The upshot is that the PDF of final energy’s vulnerability exhibits a long upper tail, with relatively small quantities of total consumption exposed to a wide range of increases in heat. By comparison the lower tail is more compact, with a concentration of advanced, high energy consuming economies at high latitudes experiencing moderate reductions in cold temperature exposures. This pattern is accentuated under rapid warming, with more widespread areas—and concomitantly larger quantities of total energy consumption—experiencing bigger absolute increases in hot days, and, especially, declines in cold days, increasing the variance of the vulnerability distribution.

3.3 Future Energy Consumption Impacts

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 changes in the energy consumed by developing (advanced) countries (cf Fig. 2). Figure 4 shows the changes in demand at the grid-cell level for our three fuels (panels A–C), five sectors (panels D–H), and total final energy (panel I) calculated using Eqs. (17) and (19).

Changes in the frequency of extreme days in Fig. 2, interacted with the elasticities in Table 3, result in fewer cold days in temperate regions inducing residential and commercial sectors to reduce their consumption of the major heating fuels, petroleum and natural gas. We see the opposite pattern in the tropics, where positive semi-elasticities of industrial and transportation consumption of petroleum and natural gas to hot days combine with increased frequency of hot days to expand consumption of these fuels. Impacts on natural gas use

![Fig. 3 Exposure of business as usual energy demand to temperature changes](image-url)
Fig. 4  CMCC-CM simulated impacts on final energy demand circa 2050. (Color figure online)
increase with latitude, whereas the strongest effects on petroleum use are largely in the tropics, reflecting the relatively larger share of petroleum products in the industrial and transportation sectors of tropical as compared to temperate countries (cf Table 5). Electricity consumption generally increases, with the commercial and industrial sectors worldwide and the residential sector in temperate regions demanding more energy to adapt to more frequent warm days.\textsuperscript{15}

Increased energy consumption for cooling prevails in the commercial and industrial sectors globally, and in the transport sector in the tropics, while reduced energy use for heating energy use prevails in the residential sector in temperate regions.\textsuperscript{16} Increased exposure to hot days could put a pressure on energy use for transportation in tropical countries, mostly through petroleum products, the predominant fuel in this sector. Understanding behavioural changes related to transportation as a mean of adaptation to climate change remains an important topic to be explored. Impacts on agricultural energy consumption are mixed: negligible effect in the tropics and high latitudes coincide with substantial reductions in overall energy use in the sub-tropics, where petroleum products have a high share, that transitions to modest increases in demand use at mid-latitudes.

The ultimate effect on the total consumption of energy use is the superposition of the above impacts according to the intersectoral distribution of baseline uses of each type of energy. The upshot is amplification of demand concentrated in tropical and mid-latitude zones (Sub-Saharan Africa, Central and Latin America, South- and South-East Asia and Oceania) coexisting with mixed but predominantly negative demand impacts in temperate regions (especially in the northern hemisphere). In the mid latitudes, higher consumption is prevalent where the effects of more frequent high temperature exposures on cooling demand is large enough to outweigh the effects of less frequent low temperature exposures on the demand for heating demand (e.g., southern U.S. and Europe, northern Australia). More rapid warming accentuates the magnitudes of both kinds of changes, but the broad geographic patterns of their net effects persist across warming scenarios.

Aggregating the grid-cell level impacts in Fig. 4 yields numerous insights. The first is the differential incidence of cooling-driven increases in energy consumption—and associated sectoral expenditures—relative to heating-driven savings. These are summarized by Fig. 5, which calculates their distribution across populations at the average income levels that correspond to the terciles of the SSP5 country per-capita GDP projections—low income: < $10,000, middle income: $10,000–$26,000 and high income: > $26,000. With both moderate and rapid warming more than 65\% of the world’s projected 8.5 billion people experience changes in weather-sensitive energy consumption in excess of ±5\% due to only to climate change, 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 96 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

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\textsuperscript{15} The tropics also experience the additional negative demand response of transportation, but the associated baseline electricity use and its elasticity to hot days are both too small to compensate for the increases described in the text.

\textsuperscript{16} For a few low-latitude temperate countries that experience substantially more hot days (e.g., South Africa, Cyprus) the cooling effect prevails despite their smaller high-temperature elasticities. Consequently, total commercial energy consumption in different countries at the same latitude can change in opposite directions, depending on the baseline mix of fuels. For example, Namibia’s commercial sector overwhelmingly uses petroleum, whose demand falls with the decline cold days in southern Africa.
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16% of the world’s population experiences a > 25% increase in demand due to climate change, a fraction which more than doubles with vigorous warming. Moreover, around 40% of individuals experiencing such large increases live in poor countries. These projected patterns are potential changes in energy demand because actual barriers to energy access or to expanding energy infrastructure to support the estimated energy needs are not considered. Therefore, Fig. 5 also highlights the higher vulnerability of especially low-income countries. Should those countries fail to meet the high adaptation challenge climate change could pose, residual impacts on their population and economy could be substantial, though yet to be quantified.

A second insight is the impacts on energy use across countries and geopolitical regions. This is shown in Fig. 6, which summarizes our sectoral and total results for the 20 largest economies that account for about 80% of global energy consumption. Total final energy goes up in almost all emerging G20 economies located in the tropics, whereas temperate G20 countries outside Europe can either increase (United States, Japan, Australia, South Africa, Turkey) or decrease (Argentina, Canada, South Korea and Russia) total final energy use, depending on the geographic incidence of climate change. Aside from Europe, Russia, South Korea, Canada and Argentina, impacts are positive and increase with the rate of warming. There are ubiquitous increases in industrial and commercial energy consumption, which are substantial, and in transportation fuel use, which is smaller, especially in high-latitude advanced countries. Residential energy declines in temperate countries, driven by reductions in natural gas and petroleum consumption with contracting demand for heating. The lone exception, South Africa, experiences an increase in hot days that is large enough to compensate for the relatively small positive response of electricity use for cooling. The absence of impact in the residential sector of developing countries reflects our lack of identification of weather responses in the tropics.

The sign and magnitude of economy-wide impacts reflect the balance between increased commercial, industrial and transportation sector demands, and declining residential demand, which is fundamentally determined by the intersectoral distribution of baseline energy use. As portended by Figs. 4 and 5, the flip in the direction of climate’s effect with latitude translates into a divide along income lines. Large developing economies (with the exception of Argentina) see significant increases in total energy consumption, while advanced economies (excepting Australia, Japan, and United States) see modest energy savings. Further aggregation reveals that every continent but Europe will face increased consumption of, and likely

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Fig. 5 Incidence of climate change impacts on energy demand relative to future baseline
Fig. 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. Percentage changes relative to the future baseline. (Color figure online)
larger expenditures on energy. Collectively, tropical and temperate countries both experience a modest rise in demand under both mild and vigorous warming scenarios, under which global energy consumption increases by 7 and 17%, respectively. The increase in final energy demand is mostly driven by the higher frequency of hot days (+19%), whereas fewer cold days mostly in temperate regions results in a reduction in energy demand (−3%), see Table 14 in “Appendix”.

Finally, we illustrate what these effects mean, in terms of the changes in the absolute quantities of the different kinds of energy being consumed. Table 6 compares the impacts, in physical units of consumption, of climatic changes circa 2050 on today’s energy system [panel A, following Eq. (15)] under future socioeconomic conditions (panel B, which has been the focus of this section). Accounting for the growth in the size of and the intersectoral and interfuel shifts in the global energy economy results in an almost threefold increase in impacts’ absolute magnitude. Consistent with our results thus far, most of that increase comes from developing countries in the tropics, concentrated in transportation and industry, while temperate countries see large commercial demand increases that are substantially offset by residential declines. Overall, climate change increases future global demand by 119 EJ, amplifying the effect of BaU economic expansion (from the current 219 EJ to 678 EJ in 2050) by an additional 26%. A comparison with Table 1 helps to put these numbers in context. Occurrence of vigorous climate change today would increase total energy consumption by 17% globally, 12% in temperate countries but 40% in tropical countries. However, if we express future changes from the BaU scenario as fractions of current demands, these numbers rise dramatically, to 50% globally, 30% in temperate countries, and 124% in countries in the tropics!

4 Discussion

4.1 Robustness of Empirical Estimates

Our projections of the energy system impacts of climate change impacts depend fundamentally on the quality of the underlying empirical estimates of demand responses to weather shocks and income. The fairly rapid adjustment of fuel demands to their long-run equilibrium levels in Sect. 3.1 raises the question of how sensitive our estimates are to the empirical specification of economic dynamics.

We begin by returning to our PMG model, whose long-run elasticities are summarized in Table 10 in “Appendix”. These estimates differ from Table 3, but the pattern of relative magnitudes shares many similarities. The estimated response function is in general asymmetric, with semi-elasticities to hot days generally larger in temperate countries. Elasticities to per capita GDP are uniformly positive, with the exception of petroleum in tropical countries, where they are also larger in magnitude compared to temperate regions. The median speed of adjustment is generally lower, leading to a slightly longer adjustment to equilibrium (8 vs. 7 years). Our preferred estimates always fall within the range from the model with heterogeneity. In each of the 12 subsamples for which we obtain estimates, at least one country’s speed of adjustment was not significantly different from zero, suggesting that shocks have a permanent effect.
Table 6  Sectoral and aggregate energy demand responses (EJ) for world regions for different warming scenarios circa 2050

| Region       | RCP 4.5      | RCP 8.5      |
|--------------|--------------|--------------|
|              | Electricity  | Natural gas  | Petroleum | Total | Electricity  | Natural gas  | Petroleum | Total |
|              |              |              |           |       |              |              |           |       |
| (A) Current energy system |              |              |           |       |              |              |           |       |
| World        |              |              |           |       |              |              |           |       |
| Agriculture  | 0.12         | 0            | −0.38     | −0.26 | 0.19         | 0            | −0.45     | −0.26 |
| Industrial   | 4.41         | 6.2          | 0.97      | 11.58 | 8.08         | 11.64        | 1.64      | 21.36 |
| Residential  | 1.63         | −4.96        | −1.57     | −4.9  | 2.61         | −5.82        | −2.05     | −5.26 |
| Commercial   | 10.08        | 0            | −0.78     | 9.3   | 19.74        | 0            | −1.03     | 18.71 |
| Transportation | 0.02        | 0            | 4.36      | 4.38  | 0.02         | 0            | 7.38      | 7.4   |
| Total        | 16.26        | 1.24         | 2.6       | 20.1  | 30.64        | 5.82         | 5.49      | 41.95 |
| Temperate    |              |              |           |       |              |              |           |       |
| Agriculture  | 0.07         | 0            | 0         | 0.07  | 0.12         | 0            | 0         | 0.12  |
| Industrial   | 1.81         | 3.3          | 0         | 5.11  | 2.91         | 6.19         | 0         | 9.1   |
| Residential  | 1.63         | −4.96        | −1.57     | −4.9  | 2.61         | −5.82        | −2.05     | −5.26 |
| Commercial   | 9.18         | 0            | −0.54     | 8.64  | 18.11        | 0            | −0.74     | 17.37 |
| Transportation | 0.03        | 0            | 0         | 0.03  | 0.04         | 0            | 0         | 0.04  |
| Total        | 12.72        | −1.66        | −2.11     | 8.95  | 23.79        | 0.37         | −2.79     | 21.37 |
| Tropical     |              |              |           |       |              |              |           |       |
| Agriculture  | 0.05         | 0            | 0         | 0.07  | 0.07         | 0            | −0.45     | −0.38 |
| Industrial   | 2.6          | 2.9          | 0.97      | 6.47  | 5.17         | 5.46         | 1.64      | 12.27 |
| Residential  | 0            | 0            | 0         | 0     | 0            | 0            | 0         | 0     |
| Commercial   | 0.9          | 0            | −0.23     | 0.67  | 1.63         | 0            | −0.29     | 1.34  |
| Transportation | −0.01       | 0            | 4.36      | 4.35  | −0.02        | 0            | 7.38      | 7.36  |
| Total        | 3.54         | 2.9          | 4.72      | 11.16 | 6.85         | 5.46         | 8.28      | 20.59 |
| (B) Energy system circa 2050 |              |              |           |       |              |              |           |       |
| World        |              |              |           |       |              |              |           |       |
| Agriculture  | 0.3          | 0            | −0.46     | −0.16 | 0.5          | 0            | −0.55     | −0.05 |
| Industrial   | 11.53        | 8.56         | 1.27      | 21.36 | 20.98        | 15.89        | 2.16      | 39.03 |
| Residential  | 3.34         | −32.63       | −1.97     | −31.26| 5.37         | −37.4        | −2.56     | −34.59 |
| Commercial   | 41.18        | 0            | −0.66     | 40.52 | 84.1         | 0            | −0.86     | 83.24 |
| Transportation | −1.15       | 0            | 19.56     | 18.41 | −1.66        | 0            | 32.56     | 30.9  |
| Total        | 55.2         | −24.07       | 17.74     | 48.87 | 109.29       | −21.51       | 30.75     | 118.53 |
| Temperate    |              |              |           |       |              |              |           |       |
| Agriculture  | 0.28         | 0            | 0         | 0.28  | 0.48         | 0            | 0         | 0.48  |
| Industrial   | 3.77         | 4.45         | 0         | 8.22  | 6.07         | 8.2          | 0         | 14.27 |
| Residential  | 3.34         | −32.63       | −1.97     | −31.26| 5.37         | −37.4        | −2.56     | −34.59 |
| Commercial   | 36.99        | 0            | −0.33     | 36.66 | 76.59        | 0            | −0.44     | 76.15 |
| Transportation | 0.05        | 0            | 0         | 0.05  | 0.06         | 0            | 0         | 0.06  |
| Total        | 44.43        | −28.18       | −2.3      | 13.95 | 88.57        | −29.2        | −3        | 56.37 |
| Tropical     |              |              |           |       |              |              |           |       |
| Agriculture  | 0.02         | 0            | −0.46     | −0.44 | 0.03         | 0            | −0.55     | −0.52 |
| Industrial   | 7.75         | 4.12         | 1.27      | 13.14 | 14.91        | 7.69         | 2.16      | 24.76 |
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Table 6 continued

|                | RCP 4.5 |          |          | Total | RCP 8.5 |          |          | Total |
|----------------|---------|----------|----------|-------|---------|----------|----------|-------|
|                | Electricity | Natural gas | Petroleum |       | Electricity | Natural gas | Petroleum |       |
| Residential    | 0       | 0        | 0        | 0     | 0       | 0        | 0        | 0     |
| Commercial     | 4.19    | 0        | −0.34    | 3.85  | 7.51    | 0        | −0.42    | 7.09  |
| Transportation | −1.2    | 0        | 19.56    | 18.36 | −1.72   | 0        | 32.56    | 30.84 |
| Total          | 10.76   | 4.12     | 20.03    | 34.91 | 20.73   | 7.69     | 33.75    | 62.17 |

Moving to the opposite extreme, we compare our preferred estimates to those generated by their corresponding static empirical specifications, namely,

\[ q_{i,t} = \alpha_i + g(t) + \sum_{j=1}^{J} \gamma_j^{T} E_{j,i,t} + \sum_{k=1}^{K} \gamma_k^{H} E_{k,i,t} + \sum_{f} \gamma_f^P P_{f,i,t} + \gamma_Y^Y Y_{i,t} + \lambda_{i,t} \]  

(21)

\[ q_{i,t} = \alpha_i + g(t) + \sum_{j=1}^{J} \left( \gamma_j^{TT} + \gamma_j^{XT} x_{i,t} \right) E_{j,i,t} + \sum_{k=1}^{K} \gamma_k^{H} E_{k,i,t} + \sum_{f} \gamma_f^P P_{f,i,t} + \gamma_Y^Y Y_{i,t} + \lambda_{i,t} \]  

(22)

in which \( g(t) \) represents a function of time (a time trend or year effects). The results are summarized in Tables 11 and 12. To facilitate comparison, we also estimate the short-run analogue of (21), a first-difference specification in which demand responses to weather and income are identified purely from interannual co-variation:

\[ \Delta q_{i,t} = \alpha_i + \sum_{j=1}^{J} \gamma_j^{T} \Delta E_{j,i,t} + \sum_{k=1}^{K} \gamma_k^{H} \Delta E_{k,i,t} + \sum_{f} \gamma_f^P \Delta P_{f,i,t} + \gamma_Y^Y \Delta Y_{i,t} + \lambda_{i,t} \]  

(23)

Our static and first-difference regression estimates are broadly similar to Table 3, with almost identical patterns of significance among elasticities. The first-difference model’s temperature elasticities are smaller in magnitude—which not surprising since they are identified from interannual weather variation, while the income elasticities understate our preferred estimates for some fuel × sector combinations and exceed them for others, but are of similar overall size. Similar patterns obtain in the static model, both in terms of the GDP elasticity (with the exception of agricultural electricity use), and the temperature elasticities, which tend to be somewhat smaller and more heavily weighted toward positive responses—especially to exposures to cold days in tropical countries.

These differences affect our estimates of adverse warming impact in opposite directions. On one hand, income elasticities that are bigger in magnitude and more uniformly positive tend to increase the baseline quantity of energy consumption, and the associated absolute magnitude of changes. On the other, smaller temperature elasticities translate into reduced impacts in percentage terms. Additionally, more positive demand responses to low temperature exposures—especially in the tropics where cold days decline markedly—mean that warming will generate larger offsetting energy savings and net adverse impacts of smaller magnitude.

Turning to our static extensive margin specification, baseline and interaction elasticities to hot and cold days are significant for several additional fuel × sector combinations, but many
of these are only at the 15% level, while some significant combinations in Table 3 become insignificant, particularly for heating responses. The remaining elasticities are almost all of the same sign as our previous estimates (exceptions are capital interaction effects of residential petroleum use in temperate countries and agricultural electricity use in the tropics), but, once again, generally smaller in magnitude—as expected. As well, income elasticities are significant for a larger number of combinations, and they are uniformly positive.

A final sensitivity check addresses the choice of variable used to weight our grid-cell level temperature and humidity exposures in agriculture. Instead of population we use average annual harvested area for all crops circa the year 2000 obtained from the MIRCA2000 database (Portmann et al. 2010). The resulting long-run elasticities, summarized in Table 13 in “Appendix”, are similar in sign and magnitude to our preferred estimates. Exceptions are the significance of the natural gas’ response to hot days in temperate countries, and the lack of significance of petroleum’ response to cold days in tropical countries, elasticity values which are both small.

4.2 Comparison with Previous Studies

Warming temperatures are expected to increase future global energy demand, but the magnitude of the rise depends on how socioeconomic conditions affect the future geographic patterns of energy use that will be exposed to climate change. The latter influence is minor relative to the pivotal effect of economic expansion: growth of per capita income increases energy consumption in the tropics by a factor of 4, compared with the additional factor 1.3 increase due to more frequent hot days. Isaac and Van Vuuren (2009), one of the few studies at global scale, reaches a similar conclusion in the context of residential heating and cooling energy demand. Future residential energy use will be driven by growing demand for cooling services associated with the growth of developing countries, mostly in the tropics, with the potential for a 20-fold increase in the global demand for AC by 2050 under a constant climate.

While corroborating income as a determinant of AC adoption (cf Sailor and Pavlova 2003; McNeil and Letscher 2008; Davis and Gertler 2015), our aggregate data are only able to partially identify how growth of capital stocks modulate the response of energy use to rising temperatures. Recent results based on micro data (Davis and Gertler 2015) show that explicitly modelling the extensive margin can lead to much higher impacts on future residential electricity demand, more than five times larger compared to considering only the intensive margin. In this regard, the lack of significant estimates of the effect of weather on residential use of energy in general—and electricity in particular—on either the intensive or extensive margins in the tropics is an important gap that remains to be addressed. Moreover, our estimates are silent on the endogenous effect of warming on the prevalence of AC in developing countries.

A related question is the stability of our income elasticities estimated for tropical countries, whether they might change over our projection horizon, and if so, in what direction. Over the very long run, energy services such as lighting and transportation exhibit declining income elasticities of demand (Fouquet 2014), however developing economies are subject to offsetting compositional changes and rebound effects that constrain their income elasticities to be similar in magnitude to those of richer nations (Van Benthem 2015). On the one hand, by 2050 elasticities can be larger because they implicitly account for the extensive margin. On the other, they can be smaller due to efficiency improvements in energy-using durables, energy conservation measures, or pollution control regulations. The lack of evidence of energy leapfrogging at the global scale, even with substantial improvements in energy efficiency, suggests that the historical record on which we rely offers scant guidance: characteristics
of future energy systems are beholden to intervening technological and structural changes whose implications can only be consistently elaborated using simulations such as IAMs.

The weather elasticities that we identify are generally larger than those previously found by applying static models to energy and weather data at the provincial level (Deschenes and Greenstone 2013). Comparisons between our weather semi-elasticities of electricity demand and previous studies are mixed. While we generally agree with findings derived from sub-national microdata (Davis and Gertler 2015) or sub-provincial (Auffhammer and Aroonruengsawat 2011) levels,17 our estimates are not directly comparable to those derived from hourly electricity load data at provincial (Auffhammer et al. 2017) and country (Wenz et al. 2017) scales.18 Our median estimate own-price elasticity across fuels and sectors (−0.41) is in excellent agreement with median value of −0.428 from a meta-analysis by Labandeira et al. (2017) and, compared to that study, has a lower spread, 0.66 standard deviation as opposed to 1.12 in the cited study.

Our results highlight the fact that modest global increases in energy consumption due to climate change arise out of offsetting changes in demand for a variety of fuels by multiple sectors in different regions (cf Isaac and Van Vuuren 2009). Substantial net reduction in residential energy demand at the global level, as well as in most countries, on account of reduced heating demand, is offset by increases in agriculture, transportation, industrial, and commerce of 7, 11, 42 and 98%, respectively, leading to 17% rise in global energy consumption under high warming. Regionally, the 32% increase in energy demand in the tropics is almost three times the 12% increase in temperate regions’ total final consumption. More energy for adaptation will be needed in the commercial, industrial, and transportation sectors across all continents, as perviously highlighted by country- or region-specific studies (Ruth and Lin 2006; Amato et al. 2005; Considine 2000).

The extent of adaptation found in this study is substantial, in contrast with the evidence from aggregate studies on the impact of temperature on macroeconomic productivity (Burke et al. 2015). While final energy use only represents a small share of the aggregate gross domestic product, divergence in results can also be driven by different econometric strategies.

5 Conclusion

This paper develops a methodology to characterize geographic variations, sectoral and fuel heterogeneity in climate change impacts on global energy demand that takes 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 socioeconomic 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, petroleum), five sectors (residential, agri-

17 Our intensive margin estimate for temperate residential electricity is slightly lower than Davis and Gertler’s range of 0.016–0.032, while our extensive-margin estimate at the 50th percentile of 2005 capital stock per person lies within the range of their estimates for the response to an additional day > 27.5°C for multiple levels of AC penetration—10% (0.010–0.026), 10–50% (0.017–0.029) and > 50% (0.019–0.042).

18 e.g., Wenz et al.’s normalized response shows an additional daily average degree above (below) 22°C increasing (decreasing) electric load by a fraction 0.35 (0.06) of the difference between average European loads at 14 and 4°C.
culture, industry, commercial, transportation), and in total. Future percentage and absolute changes (EJ) in energy demand due to socioeconomic development and changes in climatic conditions are calculated globally, for different world regions, and at the country-level.

Climate change redistributes energy consumption in multiple ways, geographically toward developing countries in the tropics where temperature increases will lead to relatively more hot days, seasonally toward summer when the frequency of hot days will rise the most, and across income groups, because hot and low-income countries will face the largest increase in energy use, raising the question whether climate change will amplify inequality. Global energy demand will increase by 7 and 17% under moderate (RCP4.5) and more significant (RCP8.5) warming, respectively, driven by tropical regions (18 and 32%, respectively). Almost all continents will see unequivocal increases in final energy demand with the exception of Europe. When aggregated to the country level, total final energy goes up in almost all emerging G20 economies located in the tropics, whereas temperate G20 countries outside Europe can either increase or decrease total final energy use depending on the geographic incidence of climate change.

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. Moreover, we have used global statistics on energy demand by sector and we cannot explicitly 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. Our analysis does not explain), illustrate the effect of price-based adaptation nor it discusses alternative energy efficiency scenarios. The fact that developing countries’ energy markets cover 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. Increases in energy prices that might result from the implementation of mitigation policies could further promote adaptation as well as improvements in efficiency, though they could also exacerbate the regressivity of impacts. How the estimated climate-driven energy needs could give rise to tensions between adaptation, mitigation, and sustainable development goals is left for future research, as answering these questions requires integrating the estimated shocks into integrated assessment models. While this paper establishes the methodology that can serve that purpose, incorporating additional GDP/temperature scenarios from SSP–RCP scenarios (Riahi et al. 2017) as well as from additional ESMs, which is critical for considering uncertainty, is left for future research.

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Appendix

See Tables 7, 8, 9, 10, 11, 12, 13 and 14.
Table 7  Sector definitions

Agriculture  ISIC 01–03: Agriculture/forestry includes deliveries to users classified as agriculture, hunting and forestry by the ISIC, and energy consumed by such users whether for traction (excluding agricultural highway use), power or heating (agricultural and domestic).

Commercial  ISIC 33; 36–39; 45–47; 53; 55; 56; 68–75; 77–82; 84 (excl. 8422); 85–88; 90–96; 99

Industry  ISIC 241, 2431: Iron and steel; 20–21: Chemical and petrochemicals excl. petrochemical feedstocks; 242, 2432: Non-ferrous metal basic industries; 23: Non-metallic minerals; 29–30: Transport equipment; 25–28: Machin ery, fabricated metal products, machinery and equipment other than transport equipment; 07, 08, 099: Mining (excl. fuels) and quarrying; 10–12: Food and tobacco; 17–18: Paper, pulp and print; 16: Wood and wood products (other than pulp and paper); 41–43: Construction; 13–15: Textile and leather; 22, 31–32: Manufacturing n.e.c.

Residential  ISIC 97–98: Heat pumps operated within the residential sector where heat is not sold are not considered a transformation process and are included here.

Transportation  ISIC 49–51: Consumption in transport covers all transport activity (in mobile engines) regardless of the economic sector to which it contributes.

Table 8  Descriptive statistics of the dataset

| Variable                               | Mean   | SD     | Min.  | Max.  | N. Obs |
|----------------------------------------|--------|--------|-------|-------|--------|
| Tropical countries                     |        |        |       |       |        |
| Population ('000)                       | 24,430.68 | 90,846.318 | 44,843.00 | 1,259,695 | 4972   |
| Real GDP per capita (2005 $)            | 9837.146 | 20,129,606 | 126,444.00 | 208,519,694 | 4657   |
| Total final energy (ktoe)              | 34,458.28 | 28,896,342 | 2637.30 | 144,905,703 | 264    |
| Electricity (ktoe) Agriculture         | 173.76  | 943.075 | 0.00  | 14,946.9 | 2361   |
| Electricity (ktoe) Industrial          | 539.245 | 2046.403 | 0.00  | 34,892.102 | 4938   |
| Electricity (ktoe) Residential         | 374.267 | 1190.863 | 0.00  | 19,319.699 | 4736   |
| Electricity (ktoe) Commercial          | 328.997 | 979.936 | 0.00  | 12,376.7 | 4112   |
| Electricity (ktoe) Transportation      | 7.4124  | 63.4874 | 0.00  | 1440.00  | 5032   |
| Petroleum (ktoe) Agriculture           | 384.218 | 1090.939 | 0.00  | 10,137.00 | 2537   |
| Petroleum (ktoe) Industrial            | 792.652 | 2135.38 | 0.00  | 22,321.9 | 4959   |
| Petroleum (ktoe) Residential           | 505.095 | 1858.905 | 0.00  | 25,628.699 | 4869   |
| Petroleum (ktoe) Commercial            | 202.645 | 503.901 | 0.00  | 4009.3 | 2425   |
| Petroleum (ktoe) Transportation        | 2368.638 | 6787.855 | 0.00  | 75,339.1 | 4938   |
| Natural gas (ktoe) Agriculture         | 25.954  | 82.476 | 0.00  | 670.5 | 309    |
| Natural gas (ktoe) Industrial          | 629.325 | 2436.445 | 0.00  | 32,946.699 | 5039   |
| Natural gas (ktoe) Residential         | 778.176 | 3689.99 | 0.00  | 37,642.801 | 1057   |
| Natural gas (ktoe) Commercial          | 168.221 | 595.958 | 0.00  | 5445.7 | 792    |
| Natural gas (ktoe) Transportation      | 26.1844 | 244.1962 | 0.00  | 6501.5 | 5034   |
| Electricity price (2005$/ktoe) Residential | 1274.646 | 857.184 | 0.00  | 6138.309 | 754    |
| Electricity price (2005$/ktoe) Industrial | 1136.988 | 982.700 | 0.00  | 14433.322 | 735    |
| Natural gas price (2005$/ktoe) Residential | 304.924 | 286.67 | 23.571 | 1000.811 | 85     |
| Natural gas price (2005$/ktoe) Industrial | 154.907 | 209.946 | 0.00  | 945.932 | 171    |
| Petroleum price (2005$/ktoe) Residential | 516.632 | 304.74 | 64.671 | 992.892 | 43     |
Table 8  continued

| Variable                        | Mean   | SD     | Min.   | Max.   | N. Obs |
|--------------------------------|--------|--------|--------|--------|--------|
| Petroleum price (2005$/ktoe) Industrial | 480.161| 271.26 | 10.928 | 2365.357| 349    |
| Premium gasoline price (2005$/ktoe) | 846.102| 446.5406| 5.078  | 3910.637| 1638   |
| $T < 12.5 \degree$C (population-weighted) | 12.65  | 33.189 | 0      | 204.695 | 4759   |
| $T > 27.5 \degree$C (population-weighted) | 64.406 | 72.73  | 0      | 332    | 4759   |
| $H < 4$ g/kg (population-weighted) | 10.458 | 25.629 | 0      | 199.982 | 4759   |
| $\bar{H} > 14$ g/kg (population-weighted) | 191.901| 114.322| 0      | 366    | 4759   |
| $T < 12.5 \degree$C (cropland-weighted) | 12.889 | 38.689 | 0      | 291.37 | 5073   |
| $T > 27.5 \degree$C (cropland-weighted) | 63.362 | 71.141 | 0      | 332    | 5073   |
| $T > 4$ g/kg (cropland-weighted) | 15.54  | 36.32  | 0      | 246.757| 5073   |
| $T > 14$ g/kg (cropland-weighted) | 177.224| 123.702| 0      | 366    | 5073   |
| Temperate countries             |        |        |        |        |        |
| Population ('000)               | 37,339.019 | 138,334.377 | 53 | 1,364,002.431 | 3168   |
| Real GDP per capita (2005 $)    | 15,510.819 | 11,547.56 | 431.082 | 72,680.162 | 3015   |
| Total final energy (ktoe)      | 45,183.796 | 108,088.769 | 417 | 713,541.188 | 1891   |
| Electricity (ktoe) Agriculture  | 251.218 | 763.200 | 0      | 8833.700 | 2510   |
| Electricity (ktoe) Industrial   | 5217.512 | 16,283.794 | 0 | 269,110.5 | 2801   |
| Electricity (ktoe) Residential  | 3370.783 | 11,785.393 | 0 | 124,331.203 | 2757   |
| Electricity (ktoe) Commercial   | 3024.977 | 11,598.494 | 0 | 130,601.602 | 2757   |
| Electricity (ktoe) Transportation| 200.1858 | 555.6779 | 0 | 5762.5 | 2801   |
| Petroleum (ktoe) Agriculture    | 1234.566 | 2762.615 | 0 | 24,388.4 | 2466   |
| Petroleum (ktoe) Industrial     | 3734.612 | 9006.767 | 0 | 98,447.602 | 2801   |
| Petroleum (ktoe) Residential    | 2543.193 | 6494.826 | 0 | 73,395.203 | 2757   |
| Petroleum (ktoe) Commercial     | 1715.746 | 4824.729 | 0 | 49,770.699 | 2460   |
| Petroleum (ktoe) Transportation | 17,078.38 | 63,994.43 | 0 | 606,586 | 2801   |
| Natural gas (ktoe) Agriculture  | 106.033 | 376.517 | 0 | 3243.3 | 1916   |
| Natural gas (ktoe) Industrial   | 4503.701 | 16,132.07 | 0 | 177,350.906 | 2841   |
| Natural gas (ktoe) Residential  | 5495.63 | 16,625.305 | 0 | 122,087.797 | 2211   |
| Natural gas (ktoe) Commercial   | 2614.686 | 9503.416 | 0 | 79,013.5 | 2192   |
| Natural gas (ktoe) Transportation| 59.3338 | 507.5102 | 0 | 13,399.8 | 2929   |
| Electricity price (2005$/ktoe) Residential | 1502.164 | 770.033 | 81.821 | 3732.609 | 1506   |
| Electricity price (2005$/ktoe) Industrial | 1031.863 | 561.905 | 83.562 | 12,662.016 | 1433   |
| Natural gas price (2005$/ktoe) Residential | 528.682 | 302.261 | 3.429 | 1635.434 | 1097   |
| Natural gas price (2005$/ktoe) Industrial | 312.815 | 191.476 | 17.024 | 1821.925 | 1110   |
| Petroleum price (2005$/ktoe) Residential | 780.008 | 354.645 | 32.831 | 1911.774 | 1043   |
| Petroleum price (2005$/ktoe) Industrial | 609.193 | 273.064 | 0.001 | 1495.268 | 942    |
| Premium gasoline price (2005$/ktoe) | 1367.345 | 534.5048 | 21.931 | 3150.702 | 1659   |
| $T < 12.5 \degree$C (population-weighted) | 187.781 | 67.232 | 0 | 362.61 | 3193   |
| $T > 27.5 \degree$C (population-weighted) | 9.611 | 22.23 | 0 | 169.825 | 3193   |
| $H < 4$ g/kg (population-weighted) | 71.008 | 51.734 | 0 | 264,811 | 3193   |
| $H > 14$ g/kg (population-weighted) | 15.979 | 26.439 | 0 | 127,867 | 3193   |
| $T < 12.5 \degree$C (cropland-weighted) | 195.657 | 76.835 | 0 | 356,535 | 3238   |
| $T > 27.5 \degree$C (cropland-weighted) | 12.76 | 28.898 | 0 | 165,623 | 3238   |
Table 8  continued

| Variable | Mean  | SD    | Min. | Max.  | N. Obs |
|----------|-------|-------|------|-------|--------|
| $\overline{H} < 4$ g/kg (cropland-weighted) | 84.686 | 59.963 | 0   | 270.921 | 3238   |
| $\overline{H} > 14$ g/kg (cropland-weighted) | 11.221 | 19.403 | 0   | 112.169 | 3238   |

Table 9  Cointegration test

|                      | Electricity | Natural gas | Petroleum |
|----------------------|-------------|-------------|-----------|
| Temperate regions    |             |             |           |
| Agriculture          | Reject $H_0$ |             | Reject $H_0$ |
| Industrial           | Reject $H_0$ | Reject $H_0$ | Reject $H_0$ |
| Residential          | Reject $H_0$ | Reject $H_0$ | Insuf. Obs. |
| Commercial           | Reject $H_0$ | Reject $H_0$ | Insuf. Obs. |
| Transportation       | Reject $H_0$ | Reject $H_0$ | Reject $H_0$ |
| Tropical regions     |             |             |           |
| Agriculture          | Reject $H_0$ |             | Reject $H_0$ |
| Industrial           | Reject $H_0$ | Insuf. Obs. | Reject $H_0$ |
| Residential          | Reject $H_0$ | Insuf. Obs. | Reject $H_0$ |
| Commercial           | Reject $H_0$ | Insuf. Obs. | Reject $H_0$ |
| Transportation       | Insuf. Obs. | Insuf. Obs. | Reject $H_0$ |

$H_0$: No Cointegration. $H_1$: All panels are cointegrated. Only for industrial petroleum in tropical countries we cannot reject $H_0$ against $H_1$: All panels are cointegrated but reject $H_0$ against $H_1$: Some panels are cointegrated.
Table 10  Long-run semi-elasticities of energy demand with respect to temperature exposures and income

|                     | Response to cold days ($T < 12.5 \, ^\circ C$) | Response to hot days ($T > 27.5 \, ^\circ C$) | Log real GDP per capita elasticity | Error-correcting speed of adjustment | Error-correcting speed of adjustment | Time to Equilibrium (years) | Range       |
|---------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|-------------------------------------|-------------------------------------|-----------------------------|-------------|
| **Temperate regions** |                                               |                                               |                                   |                                     |                                     |                             |             |
|  Industrial         |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | 0.0038                                        | 0.0061                                        | 0.369                             | -0.111                              | [-0.32, 0.00]                     | 9.017                        | [3.1, ∞]    |
| Residential         |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | -                                             | -                                             | 0.222                             | -0.104                              | [-0.37, 0.00]                     | 9.640                        | [2.7, ∞]    |
| Petroleum           | -0.0045                                       | -0.0068                                       | 0.568                             | -0.101                              | [-0.36, 0.09]                     | 9.872                        | [2.8, ∞]    |
| Transportation      |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | 0.0027                                        | 0.0158                                        | 0.867                             | -0.139                              | [-0.59, 0.00]                     | 7.179                        | [1.7, ∞]    |
| Petroleum           | 0.0031                                        | -                                             | 0.342                             | -0.129                              | [-0.39, 0.00]                     | 7.740                        | [2.5, ∞]    |
| **Tropical regions** |                                               |                                               |                                   |                                     |                                     |                             |             |
| Agriculture         |                                               |                                               |                                   |                                     |                                     |                             |             |
| Petroleum           | 0.0206                                        | 0.0069                                        | -0.723                            | -0.162                              | [-0.61, 0.07]                     | 6.177                        | [1.6, ∞]    |
| Industrial          |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | -                                             | 0.0007                                        | 0.825                             | -0.149                              | [-0.51, 0.00]                     | 6.734                        | [2.0, ∞]    |
| Petroleum           | 0.0384                                        | -                                             | 0.442                             | -0.192                              | [-0.58, 0.00]                     | 5.219                        | [1.7, ∞]    |
| Residential         |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | -                                             | -                                             | 1.466                             | -0.067                              | [-0.22, 0.08]                     | 14.948                       | [4.5, ∞]    |
| Petroleum           | 0.193                                         | -                                             | -0.193                            | -0.113                              | [-0.50, 0.00]                     | 8.873                        | [2.0, ∞]    |
| Commercial          |                                               |                                               |                                   |                                     |                                     |                             |             |
| Electricity         | -                                             | 0.001                                         | 1.117                             | -0.143                              | [-0.51, 0.00]                     | 6.983                        | [2.0, ∞]    |
| Transportation      |                                               |                                               |                                   |                                     |                                     |                             |             |
| Petroleum           | -                                             | -                                             | 1.035                             | -0.155                              | [-0.53, 0.00]                     | 6.447                        | [1.9, ∞]    |

The estimated model omits energy prices. All cross-sectional units are constrained to achieve the same long-run equilibrium, but each unit’s short-run dynamics and speed of adjustment varies. All estimates significant at the 10% level, except where indicated: $+ p < 0.15, - p > 0.15$
Table 11 Long-run estimated semi-elasticities of energy demand to temperature bins

|                        | First difference specification | Static specification | Preferred specification |
|------------------------|--------------------------------|----------------------|-------------------------|
|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|                        | Cooling response to T < 12.5 °C | Cooling response to T > 27.5 °C | Log real GDP per capita elasticity |
| Temperate Agriculture  |                                |                      |                          |
| Electricity            | –                               | 0.0005               | 0.4978                  | –                          | 0.0129                  | –                          | –                          | 0.0129                  | –                          | 0.0085                  | 0.6447                  |
| Natural gas            | 0.0018                          | –                    | 1.6591                  | –                          | 0.0023                  | –                          | 1.3856                  | –                          | 0.0195                  | –                          | 1.3202                  |
| Petroleum              | n.d.                            | n.d.                 | n.d.                    | n.d.                      | n.d.                    | n.d.                      | n.d.                    | n.d.                      | n.d.                    | n.d.                      | n.d.                    |
| Temperate Commercial  |                                |                      |                          |
| Electricity            | 0.0003                          | 0.0011               | 0.4912                  | –                          | 0.0005                  | 0.0103                  | 0.4584                  | –                          | 0.0062                  | 0.0467                  | 0.8645                  |
| Natural gas            | –                               | –                    | 1.0362                  | –                          | –                       | 0.6083                  | –                       | –                          | –                       | –                       | 0.9696                  |
| Petroleum              | 0.0015                          | –                    | 0.825                   | –                          | 0.0037                  | –                       | 1.524                   | –                          | 0.0118                  | –                       | –                       | 0.7947                  |
| Temperate Industrial  |                                |                      |                          |
| Electricity            | –                               | 0.0002               | 0.8672                  | –                          | 0.0033                  | 0.5393                  | –                       | 0.0089                  | 0.3628                  |
| Natural gas            | –                               | –                    | –                       | 0.014                     | –                       | –                       | 0.0334                  | –                       | –                       | –                       | –                       |
| Petroleum              | –                               | –                    | 1.0714                  | –                          | –                       | 0.2398                  | –                       | –                          | –                       | –                       | –                       | 1.0886                  |
| Temperate Residential |                                |                      |                          |
| Electricity            | –                               | 0.0015               | 0.1159                  | –                          | 0.0103                  | 0.3763                  | –                       | 0.146                    | 0.3665                  |
| Natural gas            | 0.0022                          | –                    | 0.6917                  | –                          | 0.0017                  | 0.9625                  | 0.023                   | –                       | 1.4331                  |
| Petroleum              | 0.0013                          | –                    | 0.0045                  | –                          | –                       | 0.0207                  | –                       | –                          | –                       | –                       | –                       |
| Temperate Transportation |                              |                      |                          |
| Electricity            | –                               | 0.0001               | 0.3575                  | –                          | 0.0005                  | 0.1215                  | –                       | 0.0026                  | –                       | 0.2597                  |
| Natural gas            | n.d.                            | n.d.                 | n.d.                    | n.d.                      | n.d.                    | n.d.                    | n.d.                    | n.d.                      | n.d.                      | n.d.                      | n.d.                      | n.d.                      |
| Petroleum              | –                               | –                    | 0.7362                  | –                          | –                       | 0.904                   | –                       | –                          | –                       | 0.8211                  |

Temperate Agriculture

|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|------------------------|--------------------------------|--------------------------------|----------------------------------|
| Electricity            | –                               | 0.0005                          | 0.4978                           |
| Natural gas            | 0.0018                          | –                               | 1.6591                           |
| Petroleum              | n.d.                            | n.d.                            | n.d.                             |

Temperate Commercial

|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|------------------------|--------------------------------|--------------------------------|----------------------------------|
| Electricity            | 0.0003                          | 0.0011                          | 0.4912                           |
| Natural gas            | –                               | –                               | 1.0362                           |
| Petroleum              | 0.0015                          | –                               | 0.825                            |

Temperate Industrial

|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|------------------------|--------------------------------|--------------------------------|----------------------------------|
| Electricity            | –                               | 0.0002                          | 0.8672                           |
| Natural gas            | –                               | –                               | 1.0714                           |
| Petroleum              | –                               | –                               | 1.0714                           |

Temperate Residential

|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|------------------------|--------------------------------|--------------------------------|----------------------------------|
| Electricity            | –                               | 0.0015                          | 0.1159                           |
| Natural gas            | 0.0022                          | –                               | 0.6917                           |
| Petroleum              | 0.0013                          | –                               | 0.0045                           |

Temperate Transportation

|                        | Heating response to T < 12.5 °C | Heating response to T > 27.5 °C | Log real GDP per capita elasticity |
|------------------------|--------------------------------|--------------------------------|----------------------------------|
| Electricity            | –                               | 0.0001                          | 0.3575                           |
| Natural gas            | n.d.                            | n.d.                            | n.d.                             |
| Petroleum              | –                               | –                               | 0.7362                           |

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Note: n.d. stands for "not determined."
|                          | First difference specification | Static specification | Preferred specification |
|--------------------------|-------------------------------|----------------------|------------------------|
|                          | Heating response to days with | Heating response to days with | Heating response to days with |
|                          | $T < 12.5 \, ^\circ C$       | $T > 27.5 \, ^\circ C$       | $T < 12.5 \, ^\circ C$       |
|                          | Cooling response to days with | Cooling response to days with | Cooling response to days with |
|                          | $T < 12.5 \, ^\circ C$       | $T > 27.5 \, ^\circ C$       | $T < 12.5 \, ^\circ C$       |
|                          | Log real GDP per capita elasticity | Log real GDP per capita elasticity | Log real GDP per capita elasticity |
| Tropical                 |                               |                       |                         |
| Agriculture              |                               |                       |                         |
| Electricity              | $-0.0054$                     | $-0.0248$             | $-0.0119$               |
| Natural gas              | n.d.                          | n.d.                  | n.d.                   |
| Petroleum                | $0.0003$                      | $0.0085$              | $0.0662$               |
| Commercial               |                               |                       |                         |
| Electricity              | $-0.0003$                     | $0.1897$              | $0.0021$               |
| Natural gas              | $0.0043$                      | $0.0022$              | $-0.0013$             |
| Petroleum                | $-0.0008$                     | $-0.0046$             | $-0.0311$             |
| Industrial               |                               |                       |                         |
| Electricity              | $-0.0024$                     | $0.0006$              | $-0.0053$             |
| Natural gas              | $0.0017$                      | $0.015$               | $-0.0011$             |
| Petroleum                | $0.0005$                      | $0.0022$              | $0.005$               |
| Residential              |                               |                       |                         |
| Electricity              | $-0.0004$                     | $1.0083$              | $-0.0004$             |
| Natural gas              | n.d.                          | n.d.                  | n.d.                  |
| Petroleum                | $0.0006$                      | $0.5605$              | $-0.0011$             |
| Transportation           |                               |                       |                         |
| Electricity              | $-0.0004$                     | $1.0083$              | $-0.0004$             |
| Natural gas              | n.d.                          | n.d.                  | n.d.                  |
| Petroleum                | $0.0006$                      | $-0.0001$             | $0.0019$              |

Robustness analysis to first-difference and static specifications
All estimates significant at the 10% level, except where indicated: $+ p < 0.15, - p > 0.15$, n.d. insufficient observations
Table 12  Static semi-elasticities of energy demand with respect to temperature exposures and income: extensive margin specification

| Region          | Sector          | Energy Source | Response to cold days ($T < 12.5 \degree C$) | Base | Interaction @ %-iles of 2010 K per capita | Response to hot days ($T > 27.5 \degree C$) | Log real GDP per capita elasticity |
|-----------------|-----------------|---------------|-------------------------------------------|------|------------------------------------------|-------------------------------------------|----------------------------------|
|                 |                 |               |                                           | Base | Interaction @ %-iles of 2010 K per capita |                                           |                                  |
|                 | Agriculture     | Electricity   |                                           | 0.105 | 0.006 0.003 0.014 0.007 |                                          | 0.022+ |                                  |
|                 | Agriculture     | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Agriculture     | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Industrial      | Electricity   |                                           | 0.017 | -0.001 -0.002 -0.001 |                                          | 0.04 | 0.002 0.003 0.006 | 0.754 |
|                 | Industrial      | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Industrial      | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Residential     | Electricity   |                                           | 0.018 | 0.012 0.016 0.008 |                                          | 0.38 | 0.020 | 0.102 | 0.207 |
|                 | Residential     | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Residential     | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Commercial      | Electricity   |                                           | 0.030 | 0.002 0.003 |                                          | 0.307 | 0.019 0.017 | 0.047 |
|                 | Commercial      | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Commercial      | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Transportation  | Electricity   |                                           | 0.025 | 0.001 0.003 0.002 |                                          | 0.071 | 0.004 | 0.008 0.007 | 0.968 |
|                 | Transportation  | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
| Temperate regions | Agriculture | Electricity   |                                           | 0.186 | 0.011 0.023 0.045 |                                          | 0.689 | 0.042 0.044 0.133 | 0.053 |
|                 | Agriculture     | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Agriculture     | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Industrial      | Electricity   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Industrial      | Natural gas   |                                           | –     | – – – – |                                          | –     |                                  |
|                 | Industrial      | Petroleum     |                                           | –     | – – – – |                                          | –     |                                  |

Global Energy Consumption in a Warming Climate
| Industry    | Sector     | Base | Interaction | 50%  | 5%  | 95%  | 50%  | 5%  | 95%  | Log real GDP per capita elasticity |
|-------------|------------|------|-------------|------|-----|------|------|-----|------|-----------------------------------|
| Industrial  | Natural gas| 0.394| −0.024      | 0.032| 0.082| −     | 0.754| −0.046| −    | 1.111                            |
| Industrial  | Petroleum  | n.d. |             |      |      |      |      |      |      |                                  |
| Residential | Electricity| n.d  |             |      |      |      |      |      |      |                                  |
| Residential | Natural gas| n.d  |             |      |      |      |      |      |      |                                  |
| Residential | Petroleum  | n.d  |             |      |      |      |      |      |      |                                  |
| Commercial  | Electricity| M1   | −           | −     | −   | −    | −    | 0.048| −0.049+| −0.150 0.062                    |
| Commercial  | Natural gas| M1   | −           | −     | −   | −    | −    | 4.034| −0.248 | 0.258 0.778                     |
| Commercial  | Petroleum  | M1   | −           | −     | −   | −    | −    | −0.953| 0.059  | −0.060+ −0.183 0.075            |
| Transportation | Electricity | M1 | −           | −     | −   | −    | −    | −0.143| 0.009  | −0.013+ −0.031                   |
| Transportation | Natural gas | n.d. |             |      |      |      |      |      |      |                                  |
| Transportation | Petroleum | M1   | −           | −     | −   | −    | −    | −0.018| 0.001  | 0.002  | 0.005+ 0.650                    |

All estimates significant at the 10% level, except where indicated: + $p < 0.15$, − $p > 0.15$, n.d. insufficient observations.
Table 13  Long-run estimated semi-elasticities of energy demand to temperature in the agricultural sector, country temperature exposures weighted by harvested area

|                      | Heating response to days with $T < 12.5\,^\circ C$ | Cooling response to days with $T > 27.5\,^\circ C$ | Log real GDP per capita elasticity |
|----------------------|--------------------------------------------------|--------------------------------------------------|----------------------------------|
| **Temperate regions**|                                                  |                                                  |                                  |
| Electricity          | –                                                | 0.0528                                           | 0.6388                           |
| Natural gas          | –                                                | 0.0673                                           | 1.6604                           |
| Petroleum            | –                                                | –                                                | –                                |
| **Tropical regions** | – 0.0599                                         | –                                                | – 0.8430                         |
| Electricity          | –                                                | –                                                | –                                |
| Natural gas          | –                                                | –                                                | –                                |
| Petroleum            | –                                                | –                                                | –                                |

Elasticities statistically significant at 10 and 15% significance level

Table 14  Aggregate energy demand responses (%) to cold and hot days for different warming scenarios

|                      | RCP 4.5 (%) | RCP 8.5 (%) |
|----------------------|-------------|-------------|
| **(A) Current energy system** |             |             |
| World                |             |             |
| Impacts due to cold days | – 1.6      | – 1.1       |
| Impacts due to hot days  | 10.5        | 19.3        |
| Total impacts        | 9.2         | 19.2        |
| **Temperate**        |             |             |
| Impacts due to cold days | – 3.3      | – 3.9       |
| Impacts due to hot days  | 8.3         | 15.7        |
| Total impacts        | 5.3         | 12.7        |
| **Tropical**         |             |             |
| Impacts due to cold days | 4.0         | 8.4         |
| Impacts due to hot days  | 17.8        | 31.6        |
| Total impacts        | 22.1        | 40.9        |
| **(B) Future energy system circa 2050** |             |             |
| World                |             |             |
| Impacts due to cold days | – 3.4      | – 3.1       |
| Impacts due to hot days  | 10.2        | 19.3        |
| Total impacts        | 7.2         | 17.5        |
| **Temperate**        |             |             |
| Impacts due to cold days | – 6.3      | – 7.0       |
| Impacts due to hot days  | 8.7         | 17.2        |
| Total impacts        | 2.9         | 11.7        |
| **Tropical**         |             |             |
| Impacts due to cold days | 3.7         | 6.8         |
| Impacts due to hot days  | 14.0        | 24.4        |
| Total impacts        | 17.9        | 31.9        |
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