OPEN ACCESS
Climate Change Economics, Vol. 15, No. 2 (2024) 2450005 (38 pages)
© The Author(s)
DOI: 10.1142/S2010007824500052

World Scientific
www.worldscientific.com

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

IMPACTS OF GLOBAL WARMING ON REGIONAL ENERGY AND ECONOMY: UNEVEN CONSEQUENCES ARISING FROM GLOBAL WARMING-INDUCED HEATING AND COOLING DEMAND OF HOUSEHOLDS

LIN MA[*], TAOYUAN WEI, KALLE NORDLING
and ASBJØRN AAHEIM

CICERO Center for International Climate Research
P. O. Box 1129 Blindern, 0318 Oslo, Norway
[*]lin.ma@cicero.oslo.no

Received 25 July 2023
Revised 7 March 2024
Accepted 7 March 2024
Published 22 May 2024

The impacts of global warming vary across regions. This paper studies the distributional implications of global warming impacts on household energy use for heating and cooling and the induced macroeconomic responses under different scenarios. Our research updates the direct impact of global warming on household energy demand in 140 regions worldwide by utilizing existing estimations of damage functions related to temperature changes. Subsequently, the updated direct impact is used in a global static computable general equilibrium (CGE) model to evaluate the macroeconomic responses. We find that at the global level, the market effects cause a reduction in the direct impact on the demand for oil and gas, while that for electricity displays a positive but moderate growth. Whereas the regional effects vary across countries and lead to changes in both directions, in which the autonomous adaptation embodied in the global market plays a vital role. Furthermore, we find strong inequality in the socioeconomic responses to global warming across regions. Notably, low-income countries are most strongly affected by increased primary energy use and decreased gross domestic product (GDP). Disparities in the impacts on carbon-based energy sources yield a near-perfect inequality as per the adjusted Gini index for CO_2 emission changes, which potentially intensify the distributional consequences of global climate change.

Keywords: Household energy demand; climate change impact; inequality; socioeconomic impact; macroeconomic model; climate simulation.

JEL Codes: Q40, Q41, Q43, Q51, Q54

---

[*] Corresponding author.

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 (CC BY-NC) License which permits use, distribution and reproduction in any medium, provided that the original work is properly cited and is used for non-commercial purposes.

1. Introduction

The increasing temperature caused by climate change has far-reaching consequences for global residents. These impacts can differ across geological regions and socioeconomic groups and significantly alter residents' way of living, including energy consumption patterns. This heterogeneous impact on residential energy usage and its subsequent effect on energy expenditure and income are among the issues faced by policymakers whose concern is to improve social equity and justice, especially with regard to the United Nations's 7th, 10th, and 13th Sustainable Development Goals (United Nations, 2023).

In this paper, we study the distributional implications of global warming impacts on household energy use for heating and cooling and the induced economic responses under different scenarios. As argued in Sec. 2, we contribute to the literature mainly in the following ways. First, while aligning with previous studies like those by Wilbanks *et al.* (2008), Dowling (2013), and Fan *et al.* (2019), which focus on local implementations in the US, Europe, and China, our research expands the scope to 140 global regions. We estimate the direct impact of global warming on the household energy demand for heating and cooling by considering various temperature changes across regions based on the latest climate and socioeconomic scenarios. Second, this research builds upon and updates the result in Roson and Sartori (2016) by incorporating the distributional impact of climate change on energy demand — a critical aspect that was not addressed in their study. Unlike Roson and Sartori (2016) who assumed a homogenized temperature increase across different regions, our approach recognizes regional variations associated with a given global warming level. Third, we extend the existing literature that assumes fixed prices (Emenekwe and Emodi, 2022) to investigate broader market impacts with endogenous price effects. We assess the macroeconomic implications of shifts in energy demand due to climate change, considering not only regional gross domestic products (GDPs) changes as in Tol (2013) and Hasegawa *et al.* (2016), but also variations in household energy use, regional primary energy use, and CO_2 emissions. Lastly, we employ an adjusted Gini index (Kilani, 2022) to address the distributional implications of the climate change impacts at the global level, even when dealing with a series with negative values. This approach diverges the study from Campagnolo and De Cian (2022) that applies conventional Gini index measures and focuses the analysis on individual countries only.

Global warming in the coming decades will vary depending on different socioeconomic pathways (SSPs). To capture potential global warming, climate models have been used to predict temperature and other climatic variables based on greenhouse gas (GHG) emissions derived from specific SSPs. In each scenario with a particular global warming level, the changes in temperature and other climatic variables vary across regions, implying a different impact on the residential demand for cooling and heating services. Consequently, the impact affects the entire economy through a changed demand for the energy used for household cooling and heating.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

This study computes seasonal temperature changes in 140 regions based on the predicted temperature data across models for a single representative ensemble from the Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations corresponding to the GHG emission levels implied by four SSP scenarios. The regional temperature changes are used to derive the direct impact on household energy use (i.e., how households modify their demand for the energy used for cooling and heating, assuming constant market prices). Following this, the direct impact on energy use is treated as an exogenous disturbance to the entire world economy, leading to changes in market prices and the associated supply and demand of economic agents for goods and services. The market responses are simulated as autonomous adaptation embodied in a global multi-region multi-sector computable general equilibrium (CGE) model in this study.

Our findings show that changes in household energy consumption for cooling and heating directly triggered by global warming vary across countries and energy sources. They reveal a considerable level of inequitable distribution in the affected residential energy consumption for cooling and heating. These direct impacts on household energy consumption shift the equilibrium of the economic system and engender a broad dispersion of impacts across countries, depending on the country-specific economic status and geographical characteristics. Higher-income countries, especially those located in cold regions, experience more significant reductions in household energy expenditures compared to the other countries. Moreover, the structure of an economy plays a vital role. Low-income countries, characterized mainly by industries that are heavily reliant on fossil fuels, witness a more considerable rise in primary energy expenditure and a decline in GDP. In contrast, high-income countries, characterized by the predominance of service-related sectors, experience GDP growth along with a decrease in primary energy consumption. Finally, the increase in the usage of fossil fuels is noticeable in low-income countries located in hot regions. This causes more intensive CO_2 emissions in these areas, whereas most rich regions exhibit dramatic decreases. Such development further intensifies the global disparity in emissions, which has the potential to exaggerate the uneven impacts of global climate change.

The remainder of this paper is structured as follows: Sec. 2 provides a brief literature review of the existing research on climate change impacts on the residential energy demand for cooling and heating and its economic effects. In addition, we present a brief overview of the methodology on the adjusted Gini index treating negative values. Sections 3 and 4 explain in detail the methodologies and data sources used in this study, respectively. Section 5 reports and discusses the findings regarding the direct impacts of global warming on household energy consumption, as well as the macroeconomic impacts coupled with autonomous adaptation. Finally, Sec. 6 presents the conclusion of the study.

2. Literature Review

There is extensive literature comprising national and regional studies on the impact of climate change on energy use; however, none of them investigate this impact across world regions on very detailed levels for climate changes derived from specific SSP scenarios. For example, Wilbanks *et al.* (2008) provided a detailed literature review of the global warming impact on the energy used for heating and cooling in the United States of America (USA). Several papers used models mapping climate metrics to energy use and expenditure for space conditioning (Rosenthal *et al.*, 1995; Sailor, 2001; Isaac and Van Vuuren, 2009; Tol *et al.*, 2012; Emenekwe and Emodi, 2022). However, in these studies, the market price of energy was employed as the social cost of energy and treated as an exogenous variable in the assessment.

We are not the first to study the macroeconomic impact while taking into account endogenous price effects related to market behavior. One example is Bosello *et al.* (2007), who utilized a global CGE model to estimate the energy use for cooling and heating resulting from climate change; they based this on an earlier econometric estimate of the damage function linking temperature changes to the energy used by households for cooling and heating by De Cian *et al.* (2007), which was updated considerably by De Cian *et al.* (2013). The approach used by Bosello *et al.* (2007) is similar to the one in our study; however, it focused on only eight regions, making it hard to derive the distributional impacts across regions, as found in our study.

Aaheim *et al.* (2012) also employed a global CGE model to consider the energy demand affected by temperature changes as part of the various economic impacts of climate change in Europe. Similar to Bosello *et al.* (2007), they evaluated the direct impact on energy consumption based on the earlier estimates of temperature elasticities by De Cian *et al.* (2007). With an explicit emphasis on geological variations, Aaheim *et al.* (2012) broke the European region into 85 subregions to study the economic impact of climate change under the autonomous adaptation embodied in the CGE model. However, they assumed a constant temperature change for all seasons and across relatively coarse regions[1] when assessing the direct impact. In addition, Bosello *et al.* (2012) employed a CGE model to study the impact of climate change on energy demand and economy by dividing the world into eight aggregated regions based on the aforementioned estimates of temperature elasticities. Compared to our study, these previous studies overlook both inter-temporal and spatial variations, thus potentially underestimating the spread of the direct impact on residential energy consumption and introducing bias into the assessment of economic impacts. In the updated damage function, De Cian *et al.* (2013) estimated the short- and long-term seasonal temperature elasticities of the energy used by households for cooling and heating in countries with cold, mild, and hot weather conditions. Building on the damage function updated in De Cian *et al.* (2013), Roson and Sartori (2016) conducted a series of meta-analyses and derived the long-run temperature elasticities of the household energy demand for cooling and heating, taking into account variations in energy sources, seasons, and climatic regions. Subsequently, the long-run elasticities were used to estimate percentage changes in household energy consumption corresponding to a given increase

---

[1] Aaheim *et al.* (2012) utilized temperature projected data for eight subregions in Europe.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

in the average temperature for every country in the world. However, Roson and Sartori (2016) did not estimate the macroeconomic impact related to the modified household energy use for cooling and heating, although they suggested addressing the issue via a global disaggregated macroeconomic model, as our study does.

Among the existing studies, only a few have emphasized the distributional consequences of climate change impacts on residential energy consumption; however, these have mainly focused on distributions within single countries. For example, Campagnolo and De Cian (2022) studied this topic for Italy using gridded climate information within the country and assessing the distributional effect on household energy expenditure using poverty gap and severity indexes. They used temperature elasticity estimates from De Cian and Sue Wing (2019). In addition, while not specifically emphasizing the impact on energy demand, Hsiang *et al.* (2019) reviewed the existing literature and determined that, qualitatively, the heterogeneous marginal impacts of climate change differ significantly across countries with different income levels. Our quantitative research shifts the focus to the impact on inequality in regions across the world. We use the Gini index as a measure of the disparity in climate impacts, providing a numerical depiction of the variations at the global level.

Previous studies focusing on regional distributional effects at the global level are scarce. Although such studies have been emerging, the scope is limited to a small number of countries, typically fewer than 20. Davis *et al.* (2021) and Pavanello *et al.* (2021) studied the global inequality of residential air conditioning using household-level data from several representative countries.[2] They employed econometric models to fit the demand for air conditioning for cooling purposes and found income to be the primary driver of disparities in the adoption of air conditioning. Moreover, Eboli *et al.* (2010) investigated the relative differences in general climate change impacts on the economic growth of developing and developed countries. As mentioned in the previous section, our study presents the distributional effect at the global level, including 140 countries and groups of countries which together cover the whole world as defined in the Global Trade Analysis Project (GTAP) database (Aguiar *et al.*, 2019).

Meanwhile, our research significantly contributes to the limited work on evaluating adjusted Gini coefficients plausible for a series with strictly negative values. This topic has been explored in only a few studies, including Chen *et al.* (1982), De Battisti *et al.* (2019), and Kilani (2022). Kilani (2022) builds upon the method established by Chen *et al.* (1982) and Berrebi and Silber (1985) with an extension on allowing general probability distributions. This method specifically addresses the way of correcting for the negative area under the Lorenz curve when computing the Gini index. In such a way, the index is normalized to fall within the range of [0,1]. Our study employs this approach and investigates empirically the dispersion of climate change impacts.

---

[2] The studies of Davis *et al.* (2021) and Pavanello *et al.* (2021) involved 16 countries and four emerging economies, respectively.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Last but not least, the paper also contributes to the growing literature on regional carbon emissions. For instance, Nie *et al.* (2023) study the carbon emissions from the residential energy sector in both China and Europe. Meanwhile, Mo *et al.* (2023) investigate the primary factors affecting carbon emissions in China. Furthermore, Osobajo *et al.* (2020), Chen *et al.* (2021), and Anser *et al.* (2021) expand their analysis to a multi-regional perspective, comparing carbon emissions to identify patterns and formulate optimal policy implications. Compared to these studies focused on specific regions, our study estimates carbon emissions from energy used by households in 140 regions from a consistent global perspective.

In sum, our study develops this line of research by updating Roson and Sartori's (2016) and Aaheim *et al.*'s (2012) results regarding the distributional impact of climate change in 140 global regions on energy demand and regional economy in four alternative climate scenarios simulated by state-of-the-art climate models for seasonal metrological simulations under given SSP scenarios. Additionally, our application of the adjusted Gini index provides updated insights on the inequality of global climate change impacts.

3. Methodology

This section summarizes the methodology utilized in our research. Figure 1 illustrates our methodology with a frame diagram mapping out the logical interconnections between the research methods and the outcomes of this study. First, we evaluate the direct impact of the household energy demand for cooling and heating (as shown in the green box in Fig. 1) by integrating temperature changes projected using climate models (as shown in the blue box in Fig. 1 and explained in Sec. 4.1) with the existing findings on the temperature elasticities in the damage functions. Subsequently, treating the direct impact on energy use as an exogenous disturbance, we employ a static CGE model to address the economic responses and resulting market effects (shown in the last two orange boxes in Fig. 1). In this research, we focus on the climate-induced impacts on household energy expenditure, GDP, primary energy use and CO_2 emissions. Finally, as part of the outcome measures of impacts (the box delineated by dashed lines in Fig. 1), we compute an adjusted Gini index as a measure of the disparity in climate impacts, revealing distributional implications regarding climate change effect at the global level.

3.1. *Direct impact on household energy use for cooling and heating*

To estimate the direct impact of climate change on the household energy used for cooling and heating, we use the damage function for household energy demand estimated by Roson and Sartori (2016). It is based on an approach combining the econometric estimation from De Cian *et al.* (2013) with a series of meta-analyses. In the aforementioned damage function, the average regional temperature change is linked to the change in the energy used for cooling and heating by the long-run

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

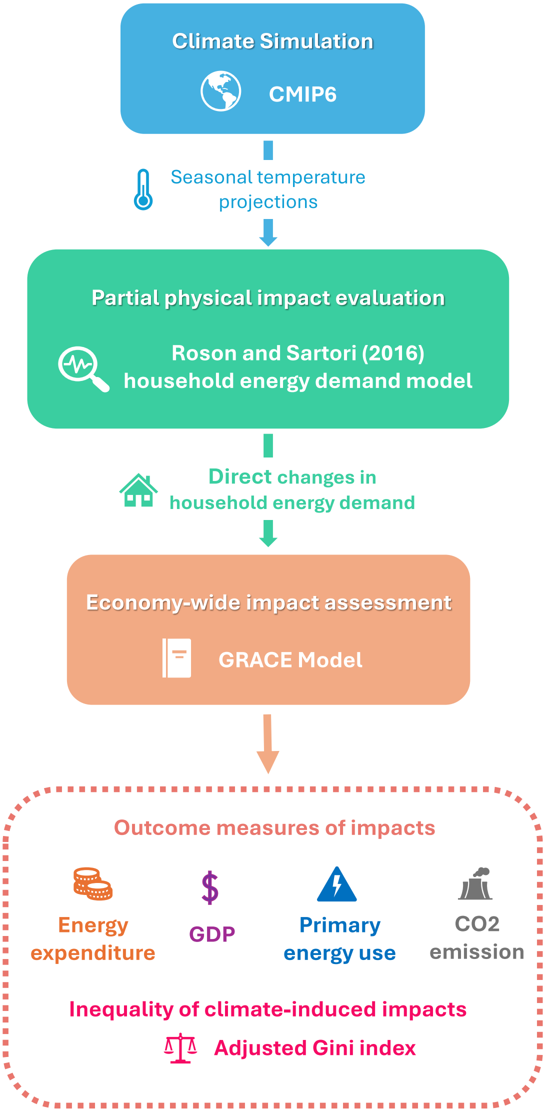


Figure 1. The frame diagram on the research models and outcomes.

temperature elasticities of the energy demand for cooling and heating. These elasticity estimates explain the changes in household energy demand in response to temperature fluctuations (expressed in °F), taking into account variations in energy sources, seasons, and climatic regions.

We compute the annual impact on energy demand for different energy sources in each country as follows:

$$\Delta y_{e,r} = \sum_{s} \sum_{c} \alpha_{s,c,e} \Delta T_{s,r} I_{c,r}. \tag{1}$$

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

In Eq. (1), $\Delta y_{e,r}$ represents the change in the demand for energy source e of country r, such that $e \in \{\text{electricity, gas, oil}\}$ and $r = 1, \ldots, n$ $(n = 140)$. $\Delta T_{s,r}$ denotes the rate of country-specific seasonal temperature change in Fahrenheit relative to the base year level, where s is the index of seasons, such that $s \in \{\text{Winter, Spring, Summer, Autumn}\}$. The parameter $\alpha_{s,c,e}$ denotes the estimated elasticity of energy demand for cooling and heating for energy source e, in season s, and for countries located in climate region c, where $c \in \{\text{Cold, Mild, Hot}\}$. These estimates $\alpha_{s,c,e}$ are reported in Roson and Sartori (2016) and as shown in Table 2 in this paper. $I_{c,r}$ is a dummy variable indicating the climate region in which the country is located.

According to Eq. (1), the annual impact on a country's household energy demand is calculated as the sum of its seasonal responses to the country-specific temperature change. It is important to note that, different from Roson and Sartori (2016) using uniform temperature changes across all countries, our method incorporates country-specific temperature variations (ΔT_s) under a range of scenarios. This method explicitly addresses the heterogeneity among countries, by considering temperature variations of each individual country, and therefore, ensuring a more accurate analysis of the climate change impacts.

3.2. *Macroeconomic impact while considering autonomous adaptation*

To assess the macroeconomic impact caused by global warming on the household energy demand for heating and cooling, we utilize a static global CGE model GRACE (Aaheim *et al.*, 2018). Global Responses to Anthropogenic Change in the Environment (GRACE) has been used for studies on climate impact, adaptation, mitigation, and the assessment of energy and climate policies (e.g., Carattini *et al.*, 2019; Orlov *et al.*, 2020; Zhang *et al.*, 2022). In this study focusing on regional differences and distributions, we use the static version of GRACE, which divides the world into 140 regions. Each regional economy consists of 15 production activities including five energy industries of coal, crude oil, natural gas, refined oil, and electricity. The static model simulates an initial equilibrium of the global economy considering the interactions between all the activities in all the regions by calibration around the 2014 global economy described by the GTAP database version 10 (Aguiar *et al.*, 2019), the latest version available at the time we wrote the paper. Figure 2 illustrates a diagram explaining the circular flow of economic activities and climate–economic interactions within the GRACE model. More details about GRACE are provided in Appendix B and below, we explain the market mechanism related to household energy use simulated in the model.

In the model, all households in a region maximize their aggregate utility by choosing the consumption of energy and other goods given a budget. A change in the consumption of energy by households due to, e.g., climate change, disturbs the energy market from the initial equilibrium by affecting energy demand and prices, which serve as a signal for energy producers that maximize profits to adjust energy supply.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

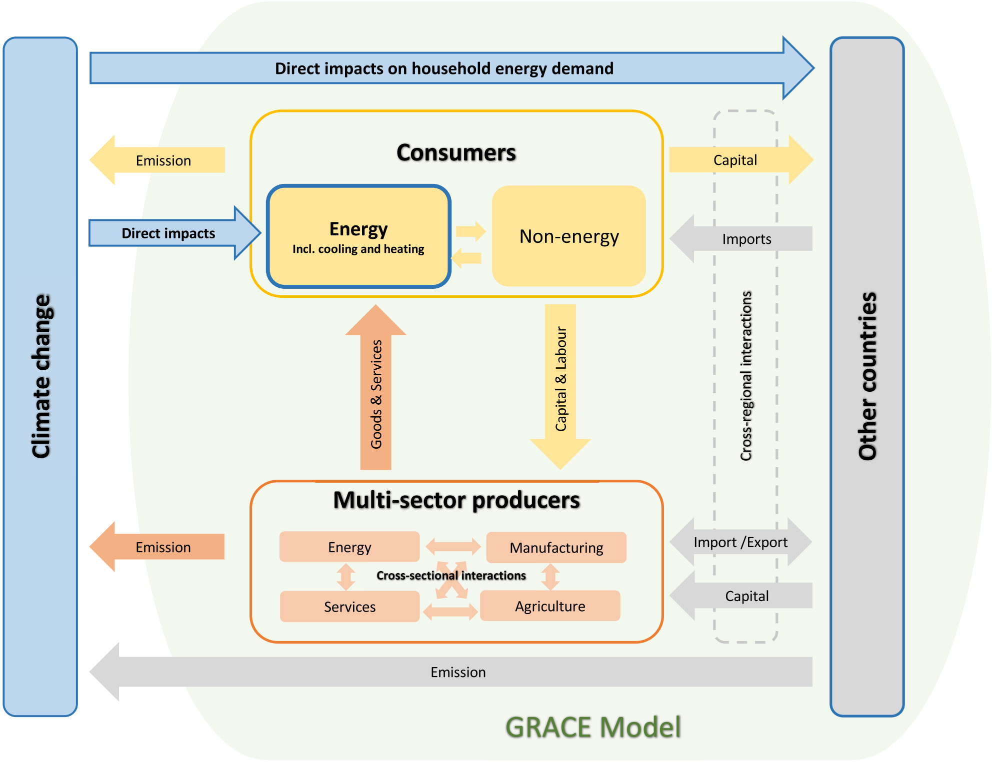


Figure 2. Diagram of the GRACE model. Revised based on Orlov *et al.* (2021).

Moreover, the markets of the other goods can be influenced by the disturbance as the markets of all goods in all regions are interlinked, e.g., households may reduce consumption of the other goods to increase energy consumption; and producers may need more inputs of the other goods to produce more energy. The influences on the other goods can also have a feedback effect on the energy market. Finally, all the markets will reach another equilibrium.

The direct impact on household energy demand estimated above is used as the input to GRACE to estimate the macroeconomic impact by considering the sectoral and regional interactions through market mechanisms, i.e., autonomous adaptation embodied in the CGE model as explained in Wei and Aaheim (2023). In GRACE, the direct impact on household energy demand by region and energy goods is interpreted as a direct reduction in energy consumption by households while all other factors remain equal. As the direct impact leads to changes in energy demand, which implies a deviation from the initial equilibrium, we then run the model to obtain a new equilibrium; this is compared to the initial equilibrium to identify the impact of climate change on households' cooling and heating after accounting for the autonomous adaptation.

It is notable that given the large number of regions (and sectors) we considered in this study, it would be very challenging to calibrate the static model to a future year or

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

develop a dynamic model to simulate a reasonable pathway considering regional and sectoral interactions in the coming decades. Hence, we use a static CGE model representing the present economy to examine the influence of future climate warming on the present economy. By doing so, we demonstrate the core climate impacts on energy use without confounding influences from time-dependent market dynamics in the growth process. Meanwhile, static approaches are also standard in studies of impacts and adaptation because they are often based on local observations without explicit links to aggregated levels.

3.3. *Gini index*

We employ the adjusted Gini index to explore the statistical dispersion of changes in the economy in response to climate-induced impacts across countries. The Gini index was originally developed to assess socioeconomic inequality, especially in income and wealth distribution. However, the application of the Gini index has been extensively used in several other areas. For instance, Dixon *et al.* (1988), Damgaard and Weiner (2000), Tol *et al.* (2004), Zimm and Nakicenovic (2020), and Dagdeviren *et al.* (2021), among others, used it to study inequality in climate change impacts.

In our research, we intend to highlight the disparities in the changes of economic variables among countries. Notably, these relative changes can sometimes become negative values. To quantify this, we adopt the most recent method proposed by Kilani (2022) and compute the adjusted Gini index for discrete distribution. We first sort the series values of a variable w in ascending order, for countries indexed by $i = 1, 2, \ldots, n$ (where $n = 140$).[3] Then, we determine the corresponding nonzero probability, p_i, for each element, w_i. In this work, we assess the empirical probability of each w_i, which is derived by dividing the number of occurrences of each unique value by the total number of observations n. Afterward, we compute the adjusted Gini index, $\tilde{G}$, using the formula as follows:

$$\tilde{G} = \frac{G}{1+\theta}. \tag{2}$$

In Eq. (2), G refers to the conventional Gini coefficient:

$$G = \sum_{i=1}^{n} \gamma_i - 1,$$

where $\gamma_i \equiv (2\pi_i - p_i)y_i$, for $i = 1, \ldots, n$. π_i denotes the cumulative probabilities of w_i, computed as $\pi_i \equiv \sum_{j=1}^{i} p_j$. The term y_i denotes the share of a country-specific impact relative to the total impact, where $y_i \equiv (p_i w_i)/\sum_{j=1}^{n} p_j w_j$.

---

[3] One prerequisite for computing the adjusted Gini index assumes that the series have a strictly positive mean, following Kilani (2022). However, we find the mean values of our variables of interest occasionally fall below zero. In order to implement the approach, we adjust the series by inverting the sign of all its values $-w_i$ for $i = 1, \ldots n$, if the mean value of the series is negative.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

According to Kilani (2022), θ refers to the adjustment term, correcting for the negative area beneath the Lorenz curve. It is computed as follows:

$$\theta = \sum_{i=1}^{k} \gamma_i + \left(\sum_{i=1}^{k} y_i\right)\left(\frac{\sum_{i=1}^{k} y_i}{y_{k+1}} p_{k+1} - 2\sum_{i=1}^{k} p_i\right),$$

where index k is defined at the point where the cumulative sum of y_i up to k is less than or equal to zero and the cumulative sum up to $k+1$ is great than 0.

The calculated adjusted Gini index still ranges from 0 to 1. A value of 0 indicates perfect equality in the distribution, while 1 indicates full inequality. The ranked series we use to calculate the adjusted Gini indexes include the relative changes in household energy expenditure, GDP, primary energy consumption, and CO_2 emissions due to regional average temperature changes. Hence, the adjusted Gini indexes indicate the extent of the equality of climate change impacts on the corresponding variables across regions.

4. Scenarios and Data

In this section, we explain the data sources utilized in this study and characterize the temperature development under different climate scenarios.

4.1. *Climate projections*

We employ simulations from the CMIP6 (Eyring *et al.*, 2016) for monthly temperature values across models for the representative ensemble "r1i1p1f1" under SSP Scenario 1 (following approximately RCP 2.6 global radiative forcing pathway), Scenario 2 (following RCP 4.5), Scenario 3 (following RCP 7.0), and Scenario 5 (following RCP 8.5), ensuring the inclusion of comprehensive model variation.[4] We compute the seasonal temperature[5] as the average value across models for 177 countries worldwide. These series of temperature projections are employed to calculate the rate of temperature changes, ΔT_s, for each country in Eq. (1) later. The historical CMIP6 simulations are based on the observational GHG data until 2014, and aerosol forcing is either described by historical optical properties or by mass-mixing rations (Eyring *et al.*, 2016). From 2015 onward, the simulations rely on forcing derived from different SSPs.

Uncertainties in this simulation arise from the following factors: (1) model uncertainty, which relates to varying subgrid parametrization between models and different implementation of numerical methods, (2) internal climate variability, and (3) scenario

---

[4] CMIP6 projection models used in this study are listed in Table C.1, Appendix C.

[5] The seasonal temperature is computed based on the empirical seasonal behavior across the Northern and Southern Hemispheres. We define that countries in the Northern Hemisphere have winter in December, January, and February; spring in March, April, and May; summer in June, July, and August; and autumn in September, October, and November. Whereas countries in the Southern Hemisphere have winter in June, July, and August; spring in September, October, and November; summer in December, January, and February; and autumn in March, April, and May.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

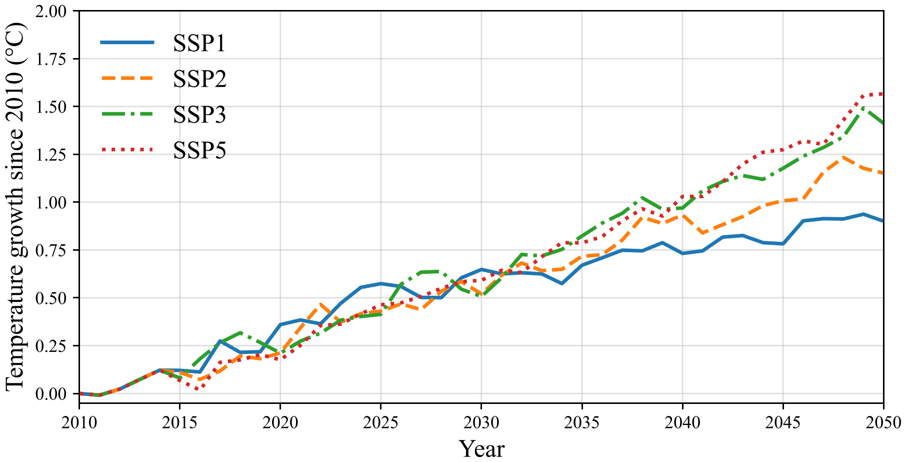


Figure 3. The global multi-model average annual temperature increase (base year 2010) under different scenarios. The temperature is the cross-model average from the CMIP6 simulations. The figure plots the annual temperature increase relative to the level in 2010.

uncertainty arising from lack of knowledge about how emissions will develop in the future. The effect of internal climate variability can be exploited by employing multiple ensembles from one model run; however, here, we employ the cross-model mean to reduce model bias and provide more robust values without eliminating the uncertainty associated with individual models.

Figure 3 presents the trajectory of the annual mean global temperature growth since 2010 under different SSP scenarios. By the year 2050, the increase in temperature from 2010 is projected to be 0.90 under SSP1, 1.15 under SSP2, 1.41 under SSP3, and 1.57 under SSP5.

Using monthly temperatures from historical and scenario simulations, we compute the 20-year multi-model average of seasonal temperature changes between the 2001–2020 and 2041–2060 periods based on the hemisphere information of each country. Table 1 shows the seasonal variation of global warming, in which the most significant temperature increase is predicted to take place in summer, with a summer temperature increase of 1.0°C in SSP1, 1.3°C in SSP2, 1.6°C in SSP3, and 1.8°C in SSP5 by 2050. Furthermore, a wide range of temperature distribution exists within each season across countries, particularly in summer. The coefficient of variation (C.V.) of temperature increases during summer ranges between 0.3 and 0.5 across SSPs.

The average temperature changes for each region under different SSP scenarios reveal a significant variance in the temperature increase across countries and seasons. Figure 4 indicates that, for most of the regions[6] in Africa, Asia, Oceania, Eastern and Western Europe, and South America, the highest temperature rise is expected to occur during summer. In particular, Central Asia will witness the most severe temperature

---

[6] The map of sub-regions is shown in Fig. A.1 in Appendix A.

Table 1. The statistics of temperature changes in 2050 under different SSP scenarios (°C). The temperature is the cross-model average from the CMIP6 simulations. The table presents the moments of seasonal temperature differences between the 2001–2020 and 2041–2060 periods. Std.dev. stands for standard deviation and C.V. denotes the coefficient of variation.

		Winter	Spring	Summer	Autumn
SSP1	Mean	0.737	0.884	1.020	0.825
	Std.dev.	0.286	0.243	0.508	0.309
	C.V.	0.388	0.275	0.498	0.375
SSP2	Mean	1.055	1.215	1.345	1.158
	Std.dev.	0.303	0.247	0.484	0.306
	C.V.	0.287	0.203	0.360	0.264
SSP3	Mean	1.348	1.429	1.590	1.418
	Std.dev.	0.323	0.265	0.511	0.310
	C.V.	0.240	0.185	0.321	0.219
SSP5	Mean	1.419	1.587	1.804	1.580
	Std.dev.	0.421	0.344	0.666	0.426
	C.V.	0.297	0.217	0.369	0.270

increase (1.9–2.9°C) in summer by 2050 under different scenarios. In contrast, North America exhibits a different pattern, with the largest temperature increase occurring during winter. Notably, the winter temperature increase may reach 1.6–2.8°C in Northern America under various scenarios. The seasonal temperature increases in various regions of Southeastern Asian, Southern Asia, Oceania, Northern Europe, Southern America, and sub-Saharan Africa appear to be relatively evenly distributed across seasons.

In this study, we follow Roson and Sartori (2016) and categorize countries into cold, mild, and hot climate regions.[7] As shown in Fig. 5, the temperature growth in cold regions is relatively high in summer under SSP1 scenario and in both winter and summer under SSP2, SSP3, and SSP5 scenarios. Furthermore, global warming engenders the highest summer temperature increment in mild climate regions, with temperature increases ranging between 1.48% and 2.34% under different SSPs. On the contrary, the temperature growth in hot climate regions appears relatively moderate compared to that in other climate zones. The highest increase takes place in spring. Nonetheless, this does not imply a cooler climate condition in these regions; rather, it indicates a limited increase resulting from an already extreme temperature level.

---

[7] The map of climate regions is shown in Fig. A.2 in Appendix A.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

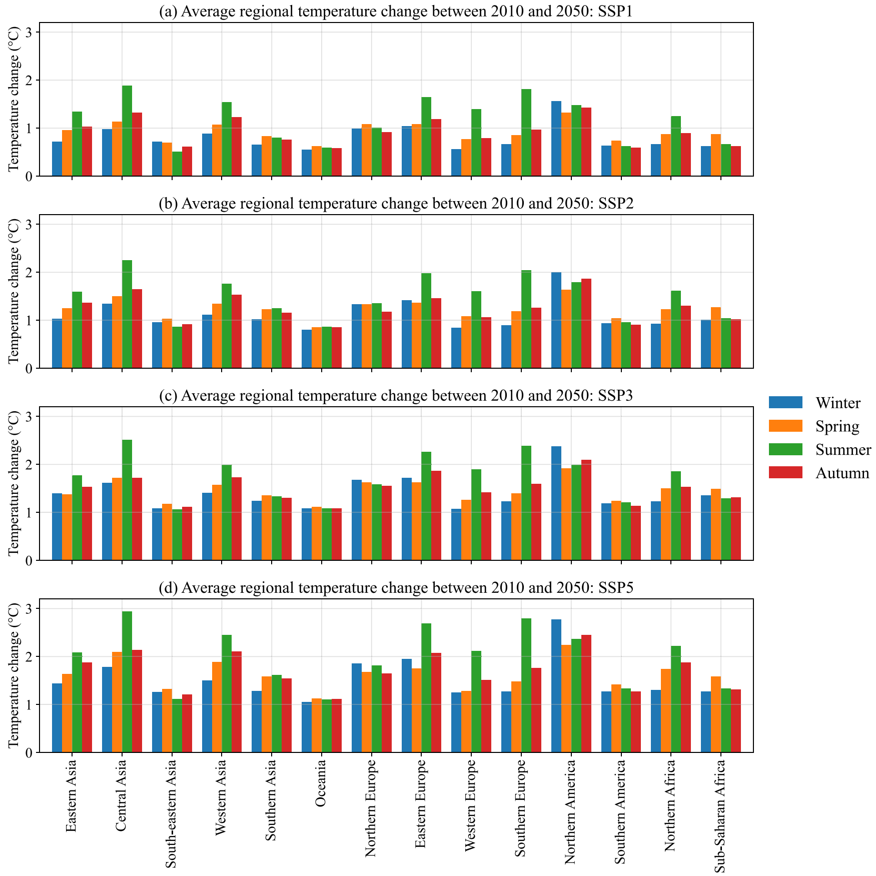


Figure 4. The average regional temperature changes from 2010 to 2050 under different scenarios (°C). The seasonal temperature difference is computed as the average regional temperature difference between the 2001–2020 and 2041–2060 periods.

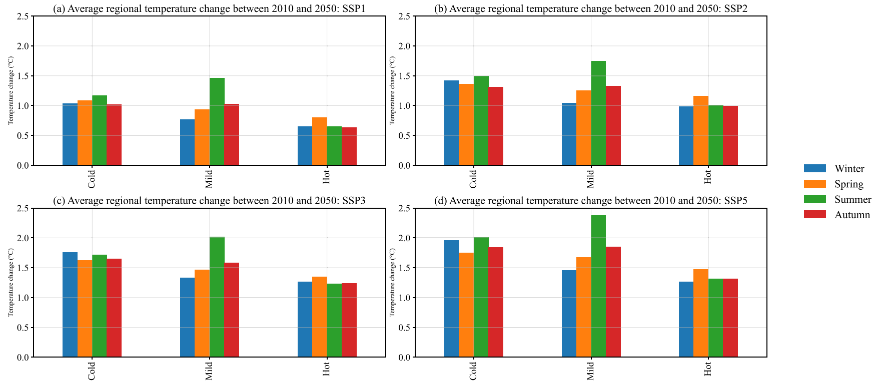


Figure 5. The temperature changes from 2015 to 2050 in different climate regions under the SSPs (°C). The seasonal temperature difference is computed as the average temperature difference between the 2001–2020 and 2041–2060 periods in cold, mild, and hot climate regions.

4.2. *Estimated temperature elasticity from Roson and Sartori (2016)*

Table 2 displays the long-run estimates of temperature elasticities from Roson and Sartori (2016), which is the parameter $\alpha_{s,c,e}$ in Eq. (1). These estimations have been conducted for different seasons, climate regions based on the latitude information of countries and regions, and diverse energy sources, including electricity, gas, and oil products, for cooling and heating purposes.

The seasonal variation of the estimates presents nonlinear relationships between temperatures and energy demands within a year for different energy sources and climate regions. The large negative elasticity for oil and gas reveals a substantial heating effect, especially during winter and summer. This suggests that a higher temperature corresponds to a reduction in the demand for oil and gas for household heating. This heating effect is stronger in the cold regions compared to the other two climate regions. In contrast, the relatively large and positive elasticity of electricity is associated with the cooling effect in mild and hot regions. Thus, as the temperature rises, the electricity demand for cooling purposes increases. Notably, the absolute values of the elasticities for gas and oil are larger than those for electricity demand. This indicates that gas demand and oil demand are more sensitive to temperature changes. Interestingly, higher spring temperatures lead to increased electricity demand, thus positive elasticities, in regions with extreme cold and hot climate conditions (see Table 2). According to De Cian *et al.* (2013), this can be attributed to the strong and positive annual effect of temperature changes on electricity demand, which dominates the estimated elasticity in spring.

Table 2. Roson and Sartori's (2016) estimates of long-run temperature elasticities of the household energy demand for cooling and heating.

Season	Climate	Electricity	Gas	Oil
Winter	Cold	−0.0111	−0.3053	−0.3558
	Mild	−0.0221	−0.2345	−0.3596
	Hot	−0.0300	−0.2008	−0.3596
Spring	Cold	0.0682	0.4962	−0.3462
	Mild	−0.0200	0.3812	−0.3401
	Hot	0.0929	0.3264	−0.3401
Summer	Cold	−0.0419	−0.7292	−0.7993
	Mild	0.0519	−0.5602	−0.7853
	Hot	0.0614	−0.4797	−0.7853
Fall	Cold	—	0.4955	0.0002
	Mild	—	0.3807	0.0002
	Hot	—	0.3260	0.0002

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

5. Results and Discussion

In this section, we begin by presenting and discussing our findings regarding the direct impact of climate change on the household energy demand for cooling and heating. After that, we focus on the economic responses toward climate change under different scenarios simulated by the static CGE model. These are the modified impacts after considering the autonomous adaptation embodied in GRACE through the subsequent economic responses across regions and sectors in response to climate change.

In the following analysis, we mainly present results under the SSP3 scenario as the primary showcase of our findings.[8] The overall results of the other scenarios largely remain the same qualitatively, but the exact impact level may differ. The detailed results for the other scenarios are shown in Appendix A for further reference.

5.1. *Direct impacts on household energy demand*

Employing the estimates in Roson and Sartori (2016) and the climate simulations from the CMIP6 models, we evaluate the direct impact of climate change on the household energy demand for cooling and heating $\Delta y_{e,r}$, following Eq. (1). As shown in Table 3, globally, the most significant reduction is observed in the household demand for oil products (−6.40% in SSP3) compared to that for gas and electricity. Canada and countries in the northern part of Eastern Europe exhibit the most marked decline in the demand for oil products (Fig. 6). This is mainly attributed to the significant temperature growth in the cold regions, particularly during summer and winter (Fig. 5), coupled with the relatively strong heating effect of oil products (large negative temperature elasticities of oil products; Table 2) in winter, spring, and summer.

Simultaneously, the global demand for gas exhibits a minor decrease, with a direct impact of −0.35% across different scenarios. Similar to the direct impact on oil demand, countries with a cold climate experience the highest reduction in gas demand. This is explained by the high sensitivity of gas demand with respect to temperature variations, in addition to a significant temperature rise in winter. Interestingly, we also

Table 3. The global average direct impact on the household energy demand for cooling and heating (%).

Energy sources	SSP1	SSP2	SSP3	SSP5
Oil products	−3.979	−5.347	−6.402	−6.890
Gas	−0.245	−0.275	−0.346	0.360
Electricity	0.140	0.186	0.212	0.196

---

[8] The results for other SSP scenarios are shown in Figs. A.3–A.9 in Appendix A. The spreadsheet "HED.xlsx" shows the computation of direct impacts on household energy demand as an update of Roson and Sartori's (2016) results.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

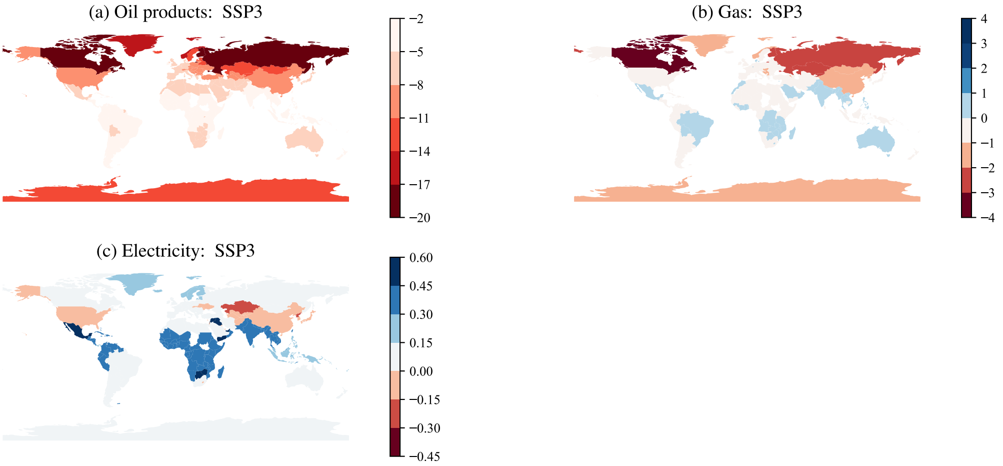


Figure 6. The direct impact on household energy consumption (%) under SSP3. These maps present the changes in household energy consumption on oil products, gas, and electricity due to climate changes relative to the business-as-usual case.

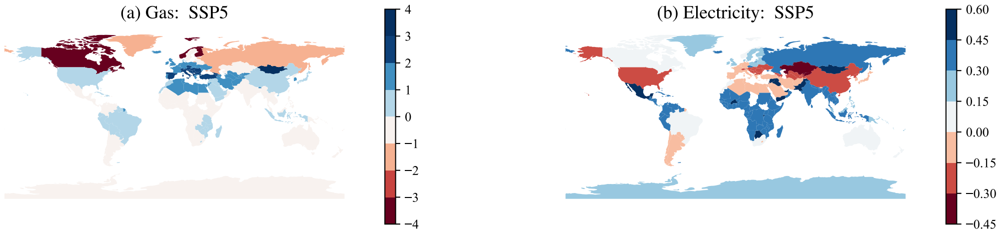
discover that certain areas with mild and hot climate conditions exhibit close to zero or even positive gas demand changes caused by climate warming. This is because of the positive temperature elasticity of gas demand during spring and autumn (Table 2), as well as a high-temperature growth in spring for countries in hot regions.

Notably, the direct impact on gas exhibits positive values at the global scale in the SSP3 scenario. As shown in Fig. 6, several countries — including Mongolia, Armenia, Georgia, Turkey, and countries in Western and Eastern Europe — experience a substantial decrease (over 2%) in gas demand. This can be largely attributed to the strong temperature increase in autumn under SSP3 compared with other scenarios.

Conversely, the global electricity demand exhibits positive growth but at a moderate level (no higher than 0.2%) across SSPs (Table 3). Figure 6 further illustrates the results of positive electricity demand as a result of the dominant cooling effect of electricity in cold and hot regions during spring, as well as in mild and hot regions during summer. Regions with a hot climate experience the highest surge in electricity demand, especially due to the large temperature increase during spring and the relatively large positive temperature elasticity for the region. Notably, a few areas with a mild climate experience a decrease in direct electricity demand. These areas include the USA, China, Argentina, and Chile, as well as countries in Central Asia and Northern Africa. The main reason is the negative temperature elasticity of the electricity demand in mild regions during spring, indicating that increasing temperature leads to decreasing electricity demand.

Under the SSP5 scenario in Fig. 7, we observe a considerably stronger positive impact on electricity demand in Russia and a few countries in Eastern Europe (0.30%) compared to the other scenarios. The reason is primarily explained as the substantial surge of summer temperature in these regions under SSP5.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.


(a) Gas: SSP5

(b) Electricity: SSP5

Figure 7. The direct impact on the household energy demand for gas and electricity under SSP5 (%). These maps present changes relative to the business-as-usual case.

5.2. *Impacts on household energy demand with autonomous adaptation*

Next, we incorporate the direct impacts on household energy use for each region into the GRACE model that leads us to the following findings.

Table 4 shows the global impacts when autonomous adaptation is taken into account. Under SSP1 and SSP5, the impacts on household oil and gas demand with autonomous adaptation display similar tendencies, but smaller absolute values, to those values in the direct effects at the global level. However, under SSP2 and SSP3, the impacts on gas demand with autonomous adaptation are larger than the outcome of direct impact. Notably, when moving from the direct impact to the equilibrium modeling, we observe a change from an increase to a decrease in the global average household electricity demand, as shown in Table 4. The direct impact at the global level under SSP3 is 0.21% (Table 3), whereas the impact from the equilibrium modeling is −0.07% (Table 4). One possible explanation is that lower oil and gas prices encourage more oil and gas use to replace more expensive electricity. It implies that referring to direct impact only in partial equilibrium models without considering autonomous adaptation may suggest misleading results for the electricity market. Meanwhile, the partial equilibrium models can underestimate the impacts on the demand of gas under certain scenarios.

Furthermore, Fig. 8 breaks these impacts down into groups of countries. The cross-country variations arise from the adjustments of each individual country in response to the systemic shifts in the global economy caused by climate change. We present the

Table 4. The global impact on the household energy demand for cooling and heating with autonomous adaptation (%).

Energy sources	SSP1	SSP2	SSP3	SSP5
Oil products	−2.018	−2.746	−3.294	−3.506
Gas	−0.242	−0.307	−0.384	0.015
Electricity	−0.025	−0.048	−0.070	−0.089

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

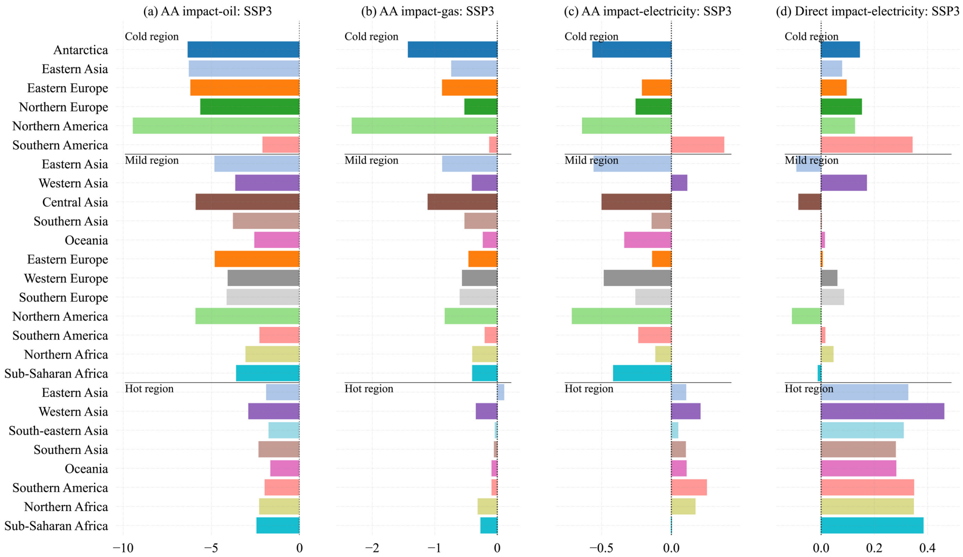


Figure 8. Impacts on household demand for oil, gas, and electricity under SSP3 scenario (%). Panels (a)–(c) show the impact along with autonomous adaptation (AA). Panel (d) shows the direct impact on household electricity demand. The figure presents the percentage change of each variable relative to the business-as-usual case solved from the GRACE model. It displays the average impact for each climate-subregion group, calculated using the individual country impact within those groups. The climate category is defined following Roson and Sartori (2016).

average impacts by grouping the countries into different geographical and climatic regions.[9]

Figures 8(a)–8(c) present the impact of climate change on the household demand for various energies while taking into account the effect of autonomous adaptation under the SSP3 scenario. As shown in Fig. 8(a), all regions show a decrease in household demand for oil. The largest decline in household oil demand is found in cold climate regions (−6.01%), followed by mild regions (−3.94%) and hot regions (−2.35%). The declining cross-region oil demand can be attributed to the sizable temperature increase in winter and summer, especially in cold regions such as Canada in Northern America. The large negative temperature elasticities of oil demand in winter, spring, and summer, as shown in Table 2, also play a significant role in this result.

Figure 8(b) displays a decreasing tendency in the household gas demand for most regions, with the exception of certain parts of Eastern Asia with a hot climate (e.g., Cambodia), where the household demand for gas exhibits a slight increase of 0.10%. This positive impact on gas demand is in line with the conclusions drawn from the direct impact. This is primarily because of the positive temperature elasticity of gas in

---

[9] The Online Appendix presents the impacts at the country level under different SSP scenarios.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

spring and autumn (Table 2) and the relatively high-temperature growth in spring for countries in this region.

Figure 8(c) illustrates the average impact of global warming on household electricity demand across climate-region groups, taking autonomous adaptation into account. Comparing this to the direct impact shown in Fig. 8(d), we find that this changing-sign impact mostly occurs in cold and mild climate regions, particularly certain parts of Northern America (Canada), Northern Europe, and Antarctica in the cold region and Western Europe in the mild region. This could partially result from the price changes in the electricity market. In this case, the direct increase in the global demand for electricity drives the electricity prices up and subsequently leads to a reduction in demand in equilibrium. The significant decreasing electricity demand can further be explained by the substitution effect on shifting from oil and gas to electricity driven by the lower oil and gas prices as explained below.

Compared to the direct impacts, the observed changes are largely driven by the market responses to price changes caused by the direct impacts on energy use. Globally, the total demand for oil and gas reduces in warmer climate regions, which in turn, lowers the prices of oil and gas in general. This price reduction encourages households to adapt by increasing oil and gas consumption. Conversely, the direct consequence of increased electricity demand pushes electricity prices upward, discouraging electricity use. Meanwhile, the relatively cheaper oil and gas becomes more affordable and induces shifts towards oil and gas over electricity. This dynamic reduces reliance on electricity, influenced by electricity price increases and the substitution effect favoring oil and gas. In cold regions, the substitution effect is particularly strong that households tend to decrease their electricity use, sometimes even below the levels than that in the warmer regions in relative terms.

5.3. *Impacts on household energy expenditure and GDP*

The strong decrease in the household demand for oil and gas and their weak prices strongly contribute to the reduction in household energy expenditures in all climate-region groups, as shown in Fig. 9(a). Northern America exhibits the most significant decline at -6.02%, followed by Central Asia at -3.88%. Globally, household energy expenditure decreases by 0.34%. As shown in Table 5, the impact intensity varies among countries of different income levels, with a tendency for greater reductions in high-income countries, although lower-middle countries face the lowest decline of 2.42%. The adjusted Gini index for relative changes in household energy expenditure, computed using Eq. (2), is reported at 0.18. This value indicates a relatively low inequality of the impact, yet it also signifies the cross-country distribution of climate impacts on household energy expenditure remains room from achieving the perfectly equitable dispersion.

As households save more on energy expenses and benefit from lowered energy prices, residents acquire more purchasing power for other consumer goods from

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

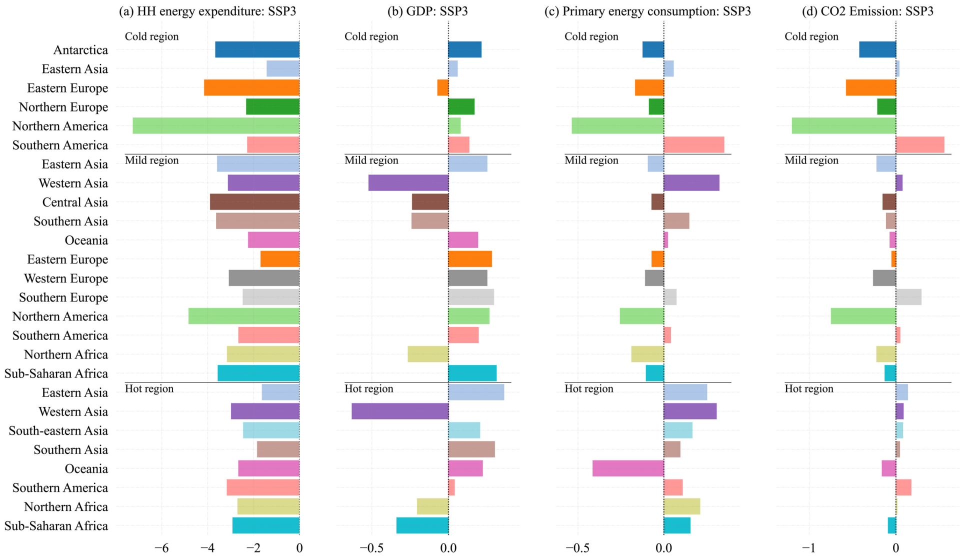


Figure 9. The impacts on household energy expenditure, primary energy consumption, GDP, and CO_2 emission in SSP3 (%). The figure presents the percentage change of each variable relative to the business-as-usual case solved from the GRACE model. It also presents the impact on the aggregate climate-subregion level. The climate category is defined following Roson and Sartori (2016).

various sectors and simulate the GDP simultaneously. As shown in Fig. 9(b), we observe positive impacts on the GDP in most of the countries and regions, especially Eastern Asian countries in mild climate regions (including China, Japan, and South Korea) and hot climate regions (including Taiwan).

However, we find a significant GDP contraction in Western Asian countries as of −0.4%. This trend is largely attributed to the income loss among the world's leading crude oil producers in the region, caused by the lowered global oil demand and declining oil prices. We also find negative GDP growth due to similar reasons for crude

Table 5. The impacts for different group levels (%) and the adjusted Gini index under SSP3 scenario.

Income level	HH energy exp.	GDP	Primary energy	CO_2 emission
Low (%)	−3.265	−0.433	0.458	−0.044
Lower-middle (%)	−2.419	0.053	0.088	−0.007
Upper-middle (%)	−3.545	0.102	−0.080	−0.207
High (%)	−3.689	0.209	−0.078	−0.389
Adj. Gini index	0.182[a]	0.955	0.891	0.999[a]

Note: [a]The series is adjusted by converting each element to its negative value, to ensure a positive mean value while computing the adjusted Gini index.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

oil and gas producers in Northern and sub-Saharan Africa, Central Asia, and Iran in Southern Asia with a mild climate.

The impact on GDP also differs among income groups. In particular, low-income countries face a GDP loss of 0.43%, while high-income countries experience a GDP growth of 0.21% (Table 5). Thus, these climate-induced impacts exacerbate the inequality in the change in global income, indicated by a substantial Gini index of 0.96 (Table 5).

Apart from the role of the energy sector in different countries, another explanation for why low-income countries are affected harder than high-income countries is related to the climate of these low-income countries, which tends to result in more energy demand for cooling and heating compared to high-income countries. It is difficult to distinguish clearly the roles of these two factors, however, because the climate (hot, mild, and cold) is highly correlated with the level of income. 67.9% of the 84 countries in hot regions are characterized as low-income countries and 32.1% as high-income countries. In the 65 countries in mild regions, 23.1% are characterized as low-income countries and 76.9% as high-income countries, while the corresponding figures for the 18 countries in cold regions are 5.6% and 94.4%, respectively.

5.4. *Impacts on primary energy consumption*

The additional purchasing power for consumption goods also potentially motivates sectoral production across various sectors and thus increases primary energy consumption. We observe an increase in primary energy usage in low and lower-middle-income countries (Table 5); most of these are located in hot climate regions, while some are located in mild climate regions (Fig. 9(c)).

In contrast, the upper-middle and high-income countries still experience a decrease in primary energy consumption. An explanation for this concerns the distinct economic structure in higher-income countries. In upper-middle and high-income countries, the service sector comprises a larger share of the economy; this is less energy intensive than the industrial activity-dominated lower-income countries. Consequently, a surge in the overall economic activity in rich countries does not necessarily lead to an increase in energy consumption. These varied impacts lead to a large adjusted Gini index of 0.89 for changes in energy use, implying a significant cross-country disparity.

Notably, our findings reveal a striking contrast: the low inequality in the impacts on the household energy expenditure transfers into a high disparity of impacts on primary energy consumption across countries (see Table 5). This result indicates the significant role of prices through market effects. Due to climate change, the global energy demand shrinks and results in a decline in the international energy prices. As low-income countries have lower domestic energy prices, the same decline in international energy prices leads to a larger energy price decrease in low-income countries relatively than in high-income countries. The enhanced affordability of energy in low-income countries stimulates the energy usage and leads to a greater increase in total energy consumption but with less energy expenditure. Specifically, low-income countries increasingly turn

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

to electricity (and oil) to replace coal and gas as the primary energy sources (as explained in Sec. 5.4). Conversely, such a rebound effect on energy use due to lower prices in high-income countries is not strong enough to cancel off the reduced turn in total energy consumption. The results are supported by a large literature of rebound effects if the reduced energy demand due to climate change is taken a type of energy efficiency improvement (Brockway *et al.*, 2021; Saunders *et al.*, 2021; Huang *et al.*, 2023).

Furthermore, Fig. 10 illustrates the detailed impact on the primary energy consumption from each energy source. Nearly all countries exhibit declines in coal usage, with the only exception in Taiwan in Eastern Asia's hot zone, as shown in Fig. 10(a). Canada in Northern America's cold region experiences the largest decrease (−0.87%). As coal is not one of the major sources for household cooling and heating in this research, the impact on coal consumption as a primary energy source in industrial production reveals the dynamic interactions in the economy due to autonomous adaptation.

Figure 10(c) reveals a downturn in the use of gas. Table 6 also shows that lower-income countries experience relatively lower impacts on gas consumption than higher-income countries. These marginal differences partially contribute to the differences in the substitution effect of energy sources and energy efficiencies across countries. Rich countries, which possess sufficient financial resources, can switch to other energy

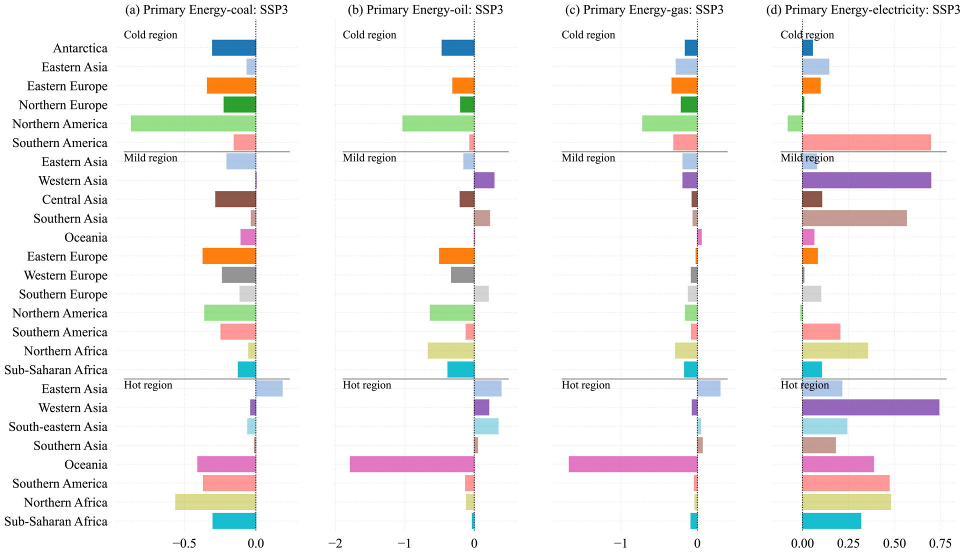


Figure 10. The impacts on primary energy sources namely coal, crude oil, gas, and electricity for different climate-region groups in SSP3. The figure presents the percentage change of each variable relative to the business-as-usual case solved from the GRACE model. It also presents the impact on the aggregate climate-subregion level. The climate category is defined following Roson *et al* (2016).

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Table 6. The impact on primary energy sources namely coal, crude oil, gas, and electricity for different income groups (%) based on Scenario SSP3.

Income level	Coal	Crude oil	Gas	Electricity
Low	−0.013	0.268	−0.125	0.796
Lower-middle	−0.064	0.058	−0.059	0.278
Upper-middle	−0.215	−0.215	−0.213	0.150
High	−0.235	−0.267	−0.174	0.074

sources more easily. In addition, these countries have better access to more energy-efficient technologies and equipment for both industrial production and household cooling and heating, thereby resulting in a further reduction in gas usage.

Interestingly, the effect on crude oil consumption varies across countries, as shown in Fig. 10(b). Table 6 indicates an increase in oil consumption in low and lower-middle-income countries, but a decrease in upper-middle- and high-income countries. Furthermore, lower-income countries exhibit a greater increase in electricity demand compared to higher-income countries. These patterns are consistent with the impact on the aggregate primary energy consumption, as shown in Fig. 9(c). They suggest that the increased purchasing power of households stimulates production in energy-intensive sectors, primarily in the oil industry and partially in electricity-intensive industries, in lower-income countries. This ultimately leads to a positive impact on the overall energy consumption in lower-income countries and a negative impact in higher-income countries.

5.5. *Impacts on CO_2 emissions*

The emission of CO_2 is closely tied to the consumption of carbon-based fuels, including oil, coal, and natural gas. Thus, the changes in CO_2 emissions are primarily driven by variabilities in the consumption of these primary energy sources. While the previous paragraphs show that the impact on energy consumption from various energy sources differs across countries, we also find a strong variation in emissions across countries, as shown in Fig. 9(d), although the overall impact levels are fairly moderate. Higher-income countries, including those in cold regions and the USA in the mild regions, present a significant reduction of emission (−0.38%), as shown in Table 3. This is largely due to the substantial decline in carbon-based fuels.

Nevertheless, we also find an increase in emissions in Southern Europe, a region with mainly high- and upper-middle-income countries. The pattern of positive impact on emissions is consistent with the growth in oil consumption in the region, as shown in Fig. 9(b). Countries in Southern Europe, including Greece, Italy, Spain, and Portugal, are characterized by energy-intensive industries, such as manufacturing, mining, and chemical industries.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

However, as shown in Table 5, the impact on emissions in low and lower-middle-income countries is very limited (−0.04% and −0.01%, respectively). This limited emission reduction can be explained by the increase in oil and gas consumption in these regions. Such varied results yield an adjusted Gini index close to 1 for changes in CO_2 emissions, indicating a nearly perfect inequitable distribution among countries in the world.

6. Conclusion

In this paper, we have studied the distributional implications of global warming impacts across countries and regions with regard to the global economy. We first assess the direct climate-induced impacts by incorporating climate model simulations from the CMIP6 on temperature changes under different projected scenarios alongside the existing knowledge on estimates of temperature elasticities. Subsequently, we employ a CGE model, GRACE, to evaluate the impacts on the global economy. Thanks to the detailed climate simulations and multi-region setup of our macroeconomic CGE model, we are able to quantify the impacts for 140 regions and, therefore, discuss the disparities of climate impact on the economy coupled with autonomous adaptation. We also report the adjusted Gini indexes for the impacts on household energy expenditure, total primary energy usage, GDP, and emissions, which reveal the degree of inequality of regional economic responses to global warming.

Our study shows that the direct impacts on the household energy demand for cooling and heating witness the largest reduction in oil products. This reduction occurs especially in cold regions due to the significant temperature increase in summer and winter. Additionally, the household demand for gas experience decreases slightly. In contrast, electricity demand exhibits positive but moderate growth, dominated by the cooling effect of electricity. Consequently, this leads to household energy expenditure reductions of 3% on average under SSP3, as derived from our CGE model.

Through the application of the CGE model, we find strong inequality in the impact of climate change, with the specific structure of the economy playing an important role. Low-income countries whose economies are heavily reliant on energy industries, primarily the oil industry and partially electricity-intensive industries, experience an increase in primary energy expenditure and a decline in the GDP. In contrast, high-income countries gain an advantage in decreasing primary energy usage and promoting GDP growth from lower energy prices, although some oil exporters witness a marginal drop in the GDP. The disparity in impacts on carbon-based energy leads to a nearly perfect inequality of CO_2 emissions distributed around the world. This could potentially exacerbate the distributional consequences of global climate change.

Our research is subject to certain limitations. One of those is the use of country average temperatures. This approach assigns equal weights to all regions and thus fails to account for the regional temperature heterogeneity within countries. The effect can be substantial for large countries like China. For future research, a more accurate

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

weighting methodology taking spatial differences into account could be a valuable extension.

Furthermore, we emphasize that the results in this study are derived from a static CGE model; it describes the current economy, which is heavily dependent on fossil fuels. In a sense, our study illustrates a pessimistic case with no dramatic change in the fossil-fuel-dominated energy industry in the coming decades. Hence, our results might be modified if fossil fuels are largely replaced by renewable energy in the coming decades. By reducing the number of regions, we could potentially update our results by forward recalibrating our static model based on a global economy with an energy industry dominated by renewable energies. We could also develop a dynamic version of our model to provide a better simulation of the energy and economic impacts of climate change through the modified residential demand for cooling and heating services over time. Moreover, our research can also be extended to derive policy implications. For instance, it could be used for the selection of policy instruments, particularly to mitigate the social inequality caused by climate-induced impacts.

Appendix A. Maps of Impacts

Region groups

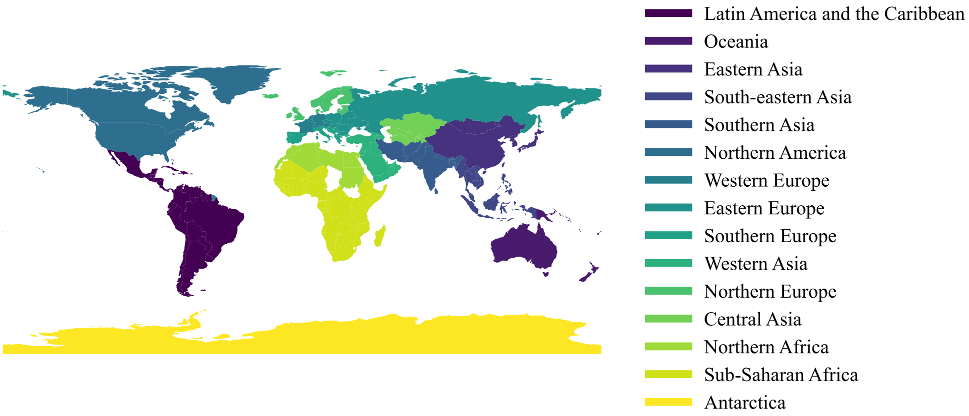


Figure A.1. Map of subregions.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

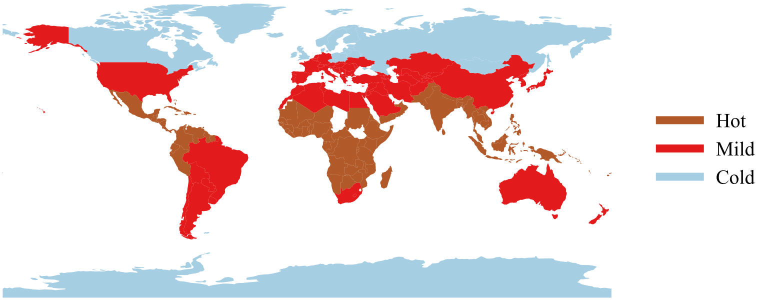


Figure A.2. Map of climate regions.

Direct impacts on the household energy demand

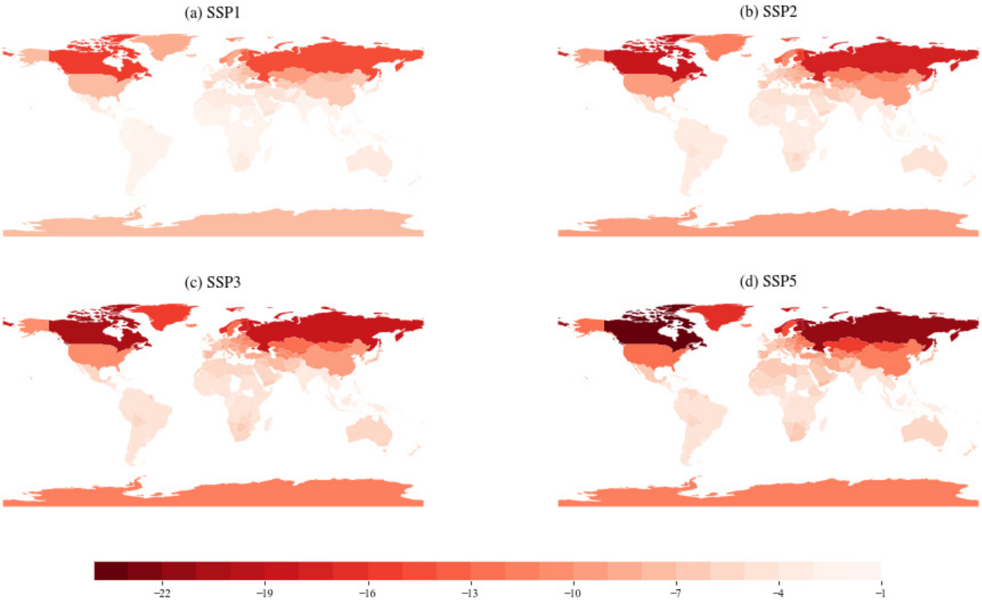


Figure A.3. Direct impact on the household demand for oil products under different SSP scenarios.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

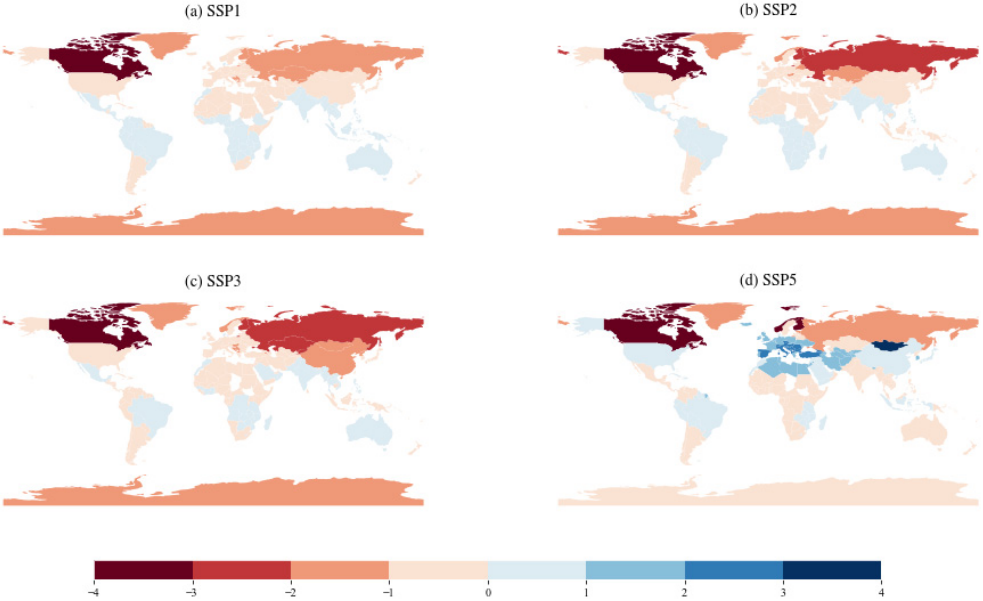


Figure A.4. Direct impact on the household demand for gas under different SSP scenarios.

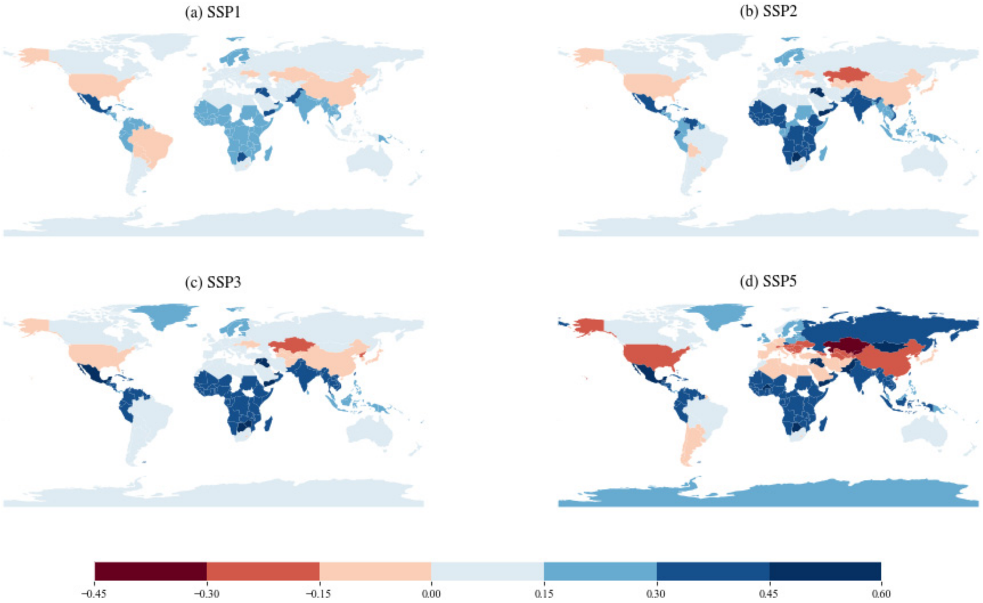


Figure A.5. Direct impact on the household demand for electricity under different SSP scenarios (%).

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Impacts on the household energy expenditure

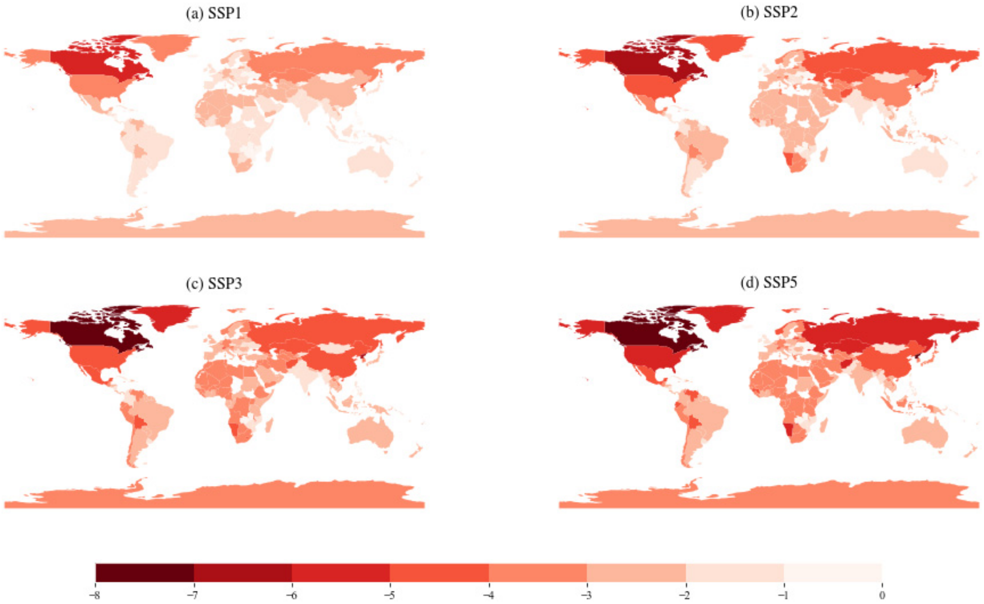


Figure A.6. Impacts on the household energy expenditure under different SSP scenarios (%).

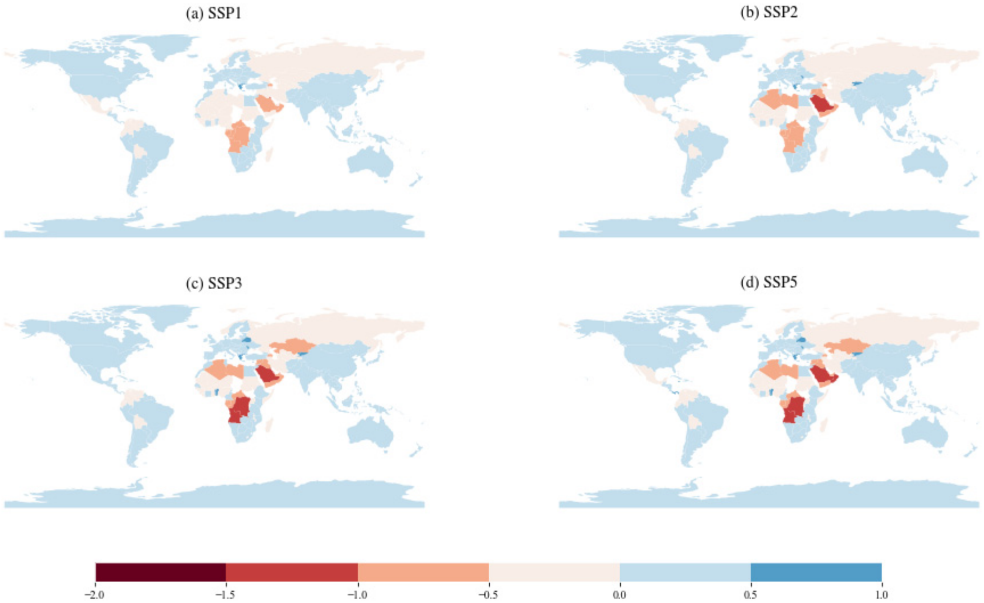


Figure A.7. Impacts on the GDP under different SSP scenarios (%).

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Impacts on primary energy consumption

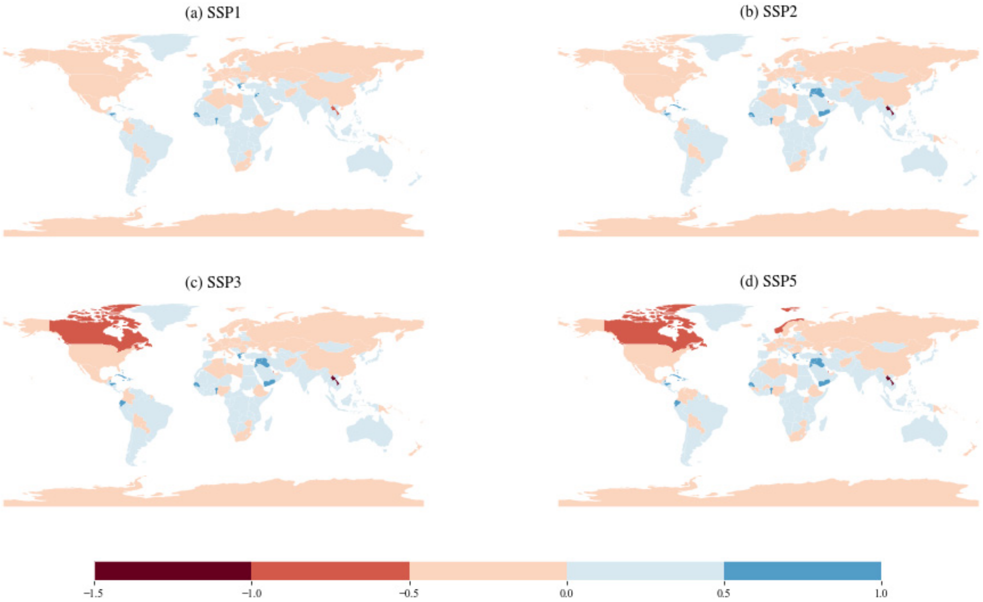


Figure A.8. Impacts on primary energy consumption under different SSP scenarios (%).

Impacts on emission

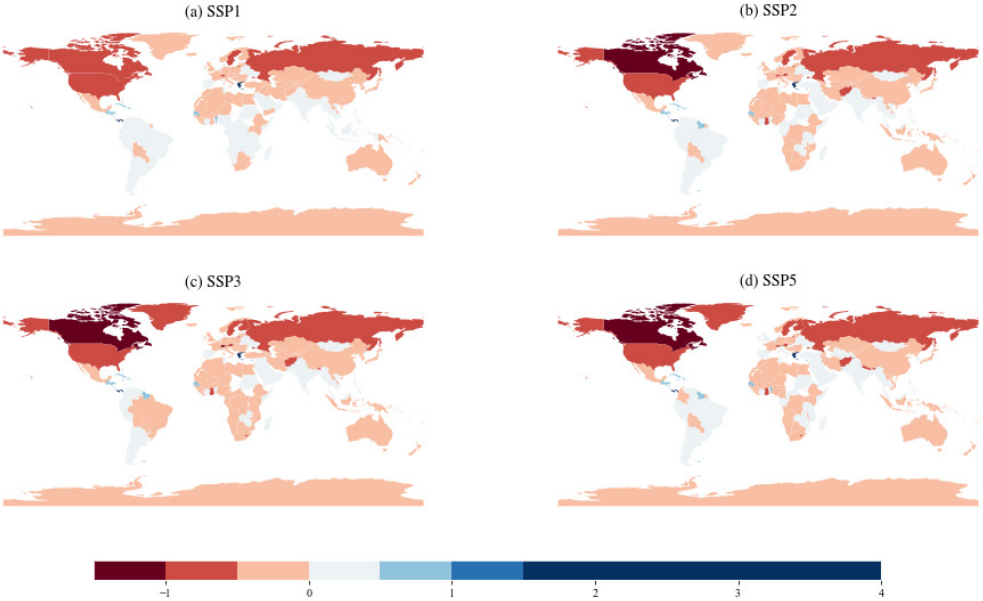


Figure A.9. Impacts on emission under different SSP scenarios (%).

Appendix B. A Brief Description of the GRACE Model[10]

The static GRACE model used in this study is a multi-region multi-sectoral recursively dynamic model and was based on the 2014 global economy described by the GTAP database version 10 (Aguiar *et al.*, 2019). As this study focuses on regional distributional effects, we follow the GTAP database to divide the world into 140 regions while aggregating the 65 production industries in a region into 15 industries (Agriculture, Forestry, Fishery, Iron & Steel, Cements, Other manufacturing, Services, and five energy sectors of coal, crude oil, natural gas, refined oil, and electricity).

In a regional economy simulated by the model, production activities are driven by the endowments of labor force, capital assets and natural resources, which are exogenous and immobile across the regional border. The labor force is indifferent and can participate in any production activities to achieve a uniform wage rate across industries. Capital assets and natural resources are activity-specific and immobile across industries. Competitive producers maximize their profits, determining the supply of products available for final consumers, who maximize their utility when making decisions on a bundle of products for consumption.

Figure B.1 illustrates a region's commodity flows of production and consumption activities. With intermediate inputs of goods and services, productive endowments are utilized to produce goods and services, which can be exported to other regions and satisfy the domestic demand from private and public consumption and investments with imported substitutes.

Sectoral production is simulated by two types of nested constant elasticity of substitution (CES) functions. One type is for production of primary fossil energy, i.e., crude oil, coal, and gas (Fig. B.2). To highlight the dependence on natural resources, the top level is a combination of natural resources and an aggregate of remaining

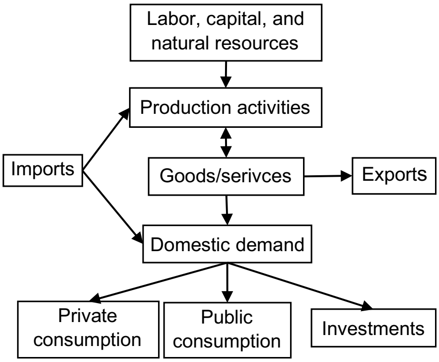


Figure B.1. Commodity flows of regional production and consumption activities in GRACE.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

---

[10] The text in the appendix was primarily taken from previous studies and documents, such as Wei and Liu (2017) and Aaheim *et al.* (2018).

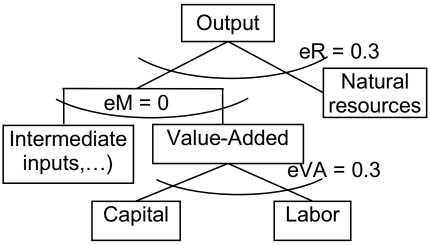


Figure B.2. Production of primary energy goods. The parameters starting with small letter "*e*" indicate the elasticities of substitution at the level where they stay.

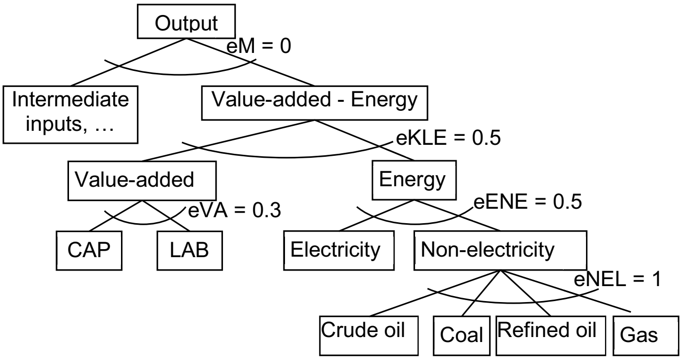


Figure B.3. Production of goods/services other than primary fossil energy. The parameters starting with small letter "*e*" indicate the elasticities of substitution at the level where they stay.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

inputs. At the middle level, the remaining inputs are a Leontief composite of intermediate goods and value added, where the value-added combines capital and labor.

The other type of production function (Fig. B.3) is for goods and services other than primary fossil energy. The top level is a Leontief composite of intermediate inputs other than energy and an aggregate of value-added and energy inputs. The next level combines value-added and energy inputs. The value added is further a combination of capital and labor. The energy inputs are a combination of electricity and other energy inputs, which is a Cobb–Douglas aggregate of crude oil, coal, refined oil, and gas.

Income generated from production activities and all taxes are collected by a virtual regional manager, who allocates the income and taxes to final consumers at fixed shares. Figure B.4 illustrates the demand structures of final consumers (including private and public consumers, and investors) in nested CES functions. At the top level, substitution can be made between energy and the other goods (nonenergy). At the bottom level, the energy combines five energy goods and the nonenergy combines all the other goods.

International trade is also modeled through a nested CES function (Fig. B.5). An Armington good combines domestic production and an aggregate of imports from all other regions. Exceptions of the elasticities are made for the following

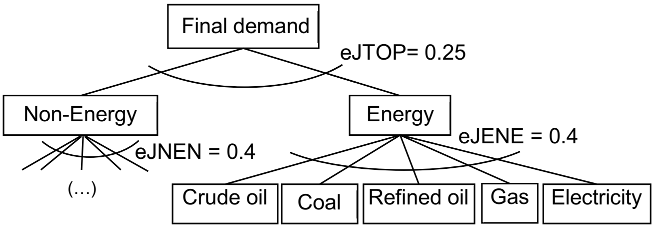


Figure B.4. Final demand structure in GRACE-EL. The parameters starting with small letter "*e*" indicate the elasticities of substitution at the level where they stay.

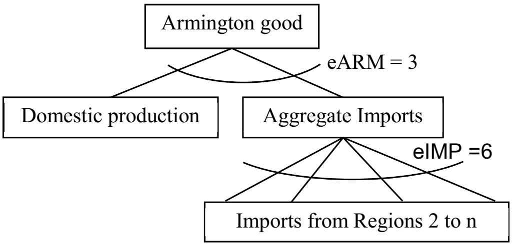


Figure B.5. Armington aggregate of bilateral imports. The parameters starting with small letter "*e*" indicate the elasticities of substitution at the level where they stay.

sectors: (a) refined oil ($e_{\text{ARM}} = 6$), (b) electricity ($e_{\text{ARM}} = 0.5$; $e_{\text{IMP}} = 0.3$), and (c) gas and coal ($e_{\text{IMP}} = 4$). With the trade of a good, the importing country pays a fixed unit cost to the international transport sector. The international transport is provided by a Cobb–Douglas composite of regional transport services.

Appendix C. List of the CMIP6 Models Used

Table C.1. List of CMIP6 models used.

ACCESS-CM2
ACCESS-ESM1-5
AWI-CM-1-1-MR
AWI-ESM-1-1-LR
BCC-CSM2-MR
BCC-ESM1
CAMS-CSM1-0
CanESM5
CAS-ESM2-0
CESM2-FV2
CESM2

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Table C.1. (*Continued*)

CESM2-WACCM-FV2
CESM2-WACCM
CIESM
CMCC-CM2-HR4
CMCC-CM2-SR5
CMCC-ESM2
E3SM-1-0
E3SM-1-1-ECA
E3SM-1-1
EC-Earth3-AerChem
EC-Earth3-CC
EC-Earth3
EC-Earth3-Veg-LR
EC-Earth3-Veg
FGOALS-f3-L
FGOALS-g3
FIO-ESM-2-0
GFDL-CM4
GFDL-ESM4
GISS-E2-1-G-CC
GISS-E2-1-G
GISS-E2-1-H
GISS-E2-2-H
IITM-ESM
INM-CM4-8
INM-CM5-0
IPSL-CM5A2-INCA
IPSL-CM6A-LR-INCA
IPSL-CM6A-LR
KACE-1-0-G
KIOST-ESM
MIROC6
MPI-ESM-1-2-HAM
MPI-ESM1-2-HR
MPI-ESM1-2-LR
MRI-ESM2-0
NESM3
NorCPM1
NorESM2-LM
NorESM2-MM
SAM0-UNICON
TaiESM1

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Online Appendix

The online appendix are available at https://www.worldscientific.com/doi/suppl/10.1142/S2010007824500052.

ORCID

Lin Ma https://orcid.org/0000-0001-8414-7744
Taoyuan Wei https://orcid.org/0000-0002-6007-148X
Kalle Nordling https://orcid.org/0000-0003-1824-9659

References

Aaheim, A, H Amundsen, T Dokken, T Ericson and T Wei (2012). Impacts and adaptation to climate change in European economies. *Global Environmental Change*, 22, 959–968.

Aaheim, A, A Orlov, T Wei and S Glomsrød (2018). GRACE model and applications. CICERO Report 2018/1. Centre for International Climate and Environmental Research, Oslo, Norway.

Aguiar, A, M Chepeliev, EL Corong, R McDougall and D van der Mensbrugghe (2019). The GTAP data base: Version 10. *Journal of Global Economic Analysis*, 4, 1–27.

Anser, MK, N Apergis and QR Syed (2021). Impact of economic policy uncertainty on CO_2 emissions: Evidence from top ten carbon emitter countries. *Environmental Science and Pollution Research*, 28, 29369–29378, doi: 10.1007/s11356-021-12782-4.

Berrebi, ZM and J Silber (1985). The Gini coefficient and negative income: A comment. *Oxford Economic Papers*, 37(3), 525–526, http://www.jstor.org/stable/2663310.

Bosello, F, E De Cian and R Roson (2007). Climate change, energy demand and market power in a general equilibrium model of the world economy. CMCC Research Paper No. 10, https://ssrn.com/abstract=1359084.

Bosello, F, F Eboli and R Pierfederici (2012). Assessing the Economic impacts of climate change. An updated CGE point of view. Working Papers No 2012.02, Fondazione Eni Enrico Mattei, https://EconPapers.repec.org/RePEc:fem:femwpa:2012.02.

Brockway, PE, S Sorrell, G Semieniuk, MK Heun and V Court (2021). Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable and Sustainable Energy Reviews*, 141, 110781, doi: 10.1016/j.rser.2021.110781.

Campagnolo, L and E De Cian (2022). Distributional consequences of climate change impacts on residential energy demand across Italian households. *Energy Economics*, 110, 106020, doi: 10.1016/j.eneco.2022.106020.

Carattini, S, S Kallbekken and A Orlov (2019). How to win public support for a global carbon tax. *Nature*, 565, 289–291.

Chen, C-N, T-W Tsaur and T-S Rhai (1982). The Gini coefficient and negative income. *Oxford Economic Papers*, 34(3), 473–478, http://www.jstor.org/stable/2662589.

Chen, X, F Yang, S Zhang, B Zakeri, X Chen, C Liu and F Hou (2021). Regional emission pathways, energy transition paths and cost analysis under various effort-sharing approaches for meeting Paris Agreement Goals. *Energy*, 232, 121024, doi: 10.1016/j.energy.2021.121024.

Dagdeviren, H, A Elangovan and R Parimalavalli (2021). Climate change, monsoon failures and inequality of impacts in South India. *Journal of Environmental Management*, 299, 113555.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Damgaard, C and J Weiner (2000). Describing inequality in plant size or fecundity. *Ecology*, 81(4), 1139–1142, doi: 10.2307/177185.

Davis, L, P Gertler, S Jarvis and C Wolfram (2021). Air conditioning and global inequality. *Global Environmental Change*, 69, 102299.

De Battisti, F, F Porro and A Vernizzi (2019). The Gini coefficient and the case of negative values. *Electronic Journal of Applied Statistical Analysis*, 12(1), 85–107, doi: 10.1285/i20705948v12n1p85. Available at SSRN: https://ssrn.com/abstract=3610829.

De Cian, E, E Lanzi and R Roson (2007). The impact of temperature change on energy demand: A dynamic panel analysis. FEEM Working Paper No. 46.07.

De Cian, E, E Lanzi and R Roson (2013). Seasonal temperature variations and energy demand: A panel cointegration analysis for climate change impact assessment. *Climatic Change*, 116, 805–825.

De Cian, E and I Sue Wing (2019). Global energy consumption in a warming climate. *Environmental and Resource Economics*, 72, 365–410.

Dixon, PM, J Weiner, T Mitchell-Olds and R Woodley (1988). Erratum to “Bootstrapping the Gini coefficient of inequality”. *Ecology*, 69, 1307.

Dowling, P (2013). The impact of climate change on the European energy system. *Energy Policy*, 60, 406–417, doi: 10.1016/j.enpol.2013.05.093.

Eboli, F, R Parrado and R Roson (2010). Climate-change feedback on economic growth: Explorations with a dynamic general equilibrium model. *Environment and Development Economics*, 15(5), 515–533, doi: 10.1017/S1355770X10000252.

Emenekwe, CC and NV Emodi (2022). Temperature and residential electricity demand for heating and cooling in G7 economies: A method of moments panel quantile regression approach. *Climate*, 10(10), 142, doi: 10.3390/cli10100142.

Eyring, V, S Bony, GA Meehl, CA Senior, B Stevens, RJ Stouffer and KE Taylor (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9, 1937–1958, doi: 10.5194/gmd-9-1937-2016.

Fan, J-L, J-W Hu and X Zhang (2019). Impacts of climate change on electricity demand in China: An empirical estimation based on panel data. *Energy*, 170, 880–888, doi: 10.1016/j.energy.2018.12.044.

Hasegawa, T, C Park, S Fujimori, K Takahashi, Y Hijioka and T Masui (2016). Quantifying the economic impact of changes in energy demand for space heating and cooling systems under varying climatic scenarios. *Palgrave Communications*, 2, 16013, doi: 10.1057/palcomms.2016.13.

Hsiang, SP, O Paulina and R Walke (2019). The distribution of environmental damages. *Review of Environmental Economics and Policy*, 13, 83–103.

Huang, W, J Miao and T Wei (2023). Rebound effects of energy efficiency improvement based on computable general equilibrium models: A systematic review. *Energy Efficiency*, 16(6), 65, doi: 10.1007/s12053-023-10148-y.

Isaac, M and DP Van Vuuren (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 37(2), 507–521.

Kilani, K (2022). The Gini coefficient and negative income: A probabilistic approach. HAL-03911502, https://hal.science/hal-03911502.

Mo, J, H Nie, W Wang and Y Liu (2023). Exploring pathway to achieving carbon neutrality in China under uncertainty. *Computers & Industrial Engineering*, 185, 109689, doi: 10.1016/j.cie.2023.109689.

Nie, H, R Kemp and Y Fan (2023). Investigating the adoption of energy-saving measures in residential sector: The contribution to carbon neutrality of China and Europe. *Resources, Conservation and Recycling*, 190, 106791, doi: 10.1016/j.resconrec.2022.106791.

Orlov, A, AS Daloz, J Sillmann, W Thiery, C Douzal, Q Lejeune and C Schleussner (2021). Global economic responses to heat stress impacts on worker productivity in crop production. *Economics of Disasters and Climate Change*, 5, 367–390, doi: 10.1007/s41885-021-00091-6.

Orlov, A, J Sillmann, K Aunan, T Kjellstrom and A Aaheim (2020). Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change*, 63, 102087.

Osobajo, OA, A Otitoju, MA Otitoju and A Oke (2020). The impact of energy consumption and economic growth on carbon dioxide emissions. *Sustainability* 12(19), 7965, doi: 10.3390/su12197965.

Pavanello, F, E De Cian, M Davide, M Mistry, T Cruz, P Bezerra, D Jagu, S Renner, R Schaeffer and AFP Lucena (2021). Air-conditioning and the adaptation cooling deficit in emerging economies. *Nature Communications*, 12(1), 6460.

Rosenthal, DH, HK Gruenspecht and EA Moran (1995). Effects of global warming on energy use for space heating and cooling in the United States. *The Energy Journal*, 16(2), 77–96.

Roson, R and M Sartori (2016). Estimation of climate change damage functions for 140 regions in the GTAP 9 database. *Journal of Global Economic Analysis*, 1(2), 78–115.

Sailor, DJ (2001). Relating residential and commercial sector electricity loads to climate — Evaluating state level sensitivities and vulnerabilities. *Energy*, 26(7), 645–657, doi: 10.1016/S0360-5442(01)00023-8.

Saunders, HD, J Roy, IML Azevedo, D Chakravarty, S Dasgupta, S de la Rue du Can, A Druckman, R Fouquet, M Grubb, B Lin, R Lowe, R Madlener, DM McCoy, L Mundaca, T Oreszczyn, S Sorrell, D Stern, K Tanaka and T Wei (2021). Energy efficiency: What has research delivered in the last 40 years? *Annual Review of Environment and Resources*, 46(1), 135–165, doi: 10.1146/annurev-environ-012320-084937.

Tol, RS (2013). The economic impact of climate change in the 20th and 21st centuries. *Climatic Change*, 117, 795–808.

Tol, RS, TE Downing, OJ Kuik and JB Smith (2004). Distributional aspects of climate change impacts. *Global Environmental Change*, 14(3), 259–272.

Tol, RS, S Petrick and K Rehdanz (2012). The impact of temperature changes on residential energy use. Working Paper Series 4412, Department of Economics, University of Sussex Business School.

United Nations (2023). Take action for the sustainable development goals, https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

Wei, T and A Aaheim (2023). Climate change adaptation based on computable general equilibrium models — A systematic review. *International Journal of Climate Change Strategies and Management*, 15(4), 561–576, doi: 10.1108/ijccsm-03-2022-0031.

Wei, T and Y Liu (2017). Estimation of global rebound effect caused by energy efficiency improvement. *Energy Economics*, 66, 27–34.

Wilbanks, T, V Bhatt, D Bilello, S Bull, J Ekmann, W Horak, Y Joe Huang, MD Levine, MJ Sale, D Schmalzer and MJ Scott (2008). *Effects of Climate Change on Energy Production and Use in the United States*. US Department of Energy Publications, No. 12. Washington, DC: U.S. Climate Change Science Program.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.

Zhang, T, K van der Wiel, T Wei, J Screen, X Yue, B Zheng, F Selten, R Bintanja, W Anderson, R Blackport, S Glomsrød, Y Liu, X Cui and X Yang (2022). Increased wheat price spikes and larger economic inequality with 2°C global warming. *One Earth*, 5, 907–916.

Zimm, C and N Nakicenovic (2020). What are the implications of the Paris Agreement for inequality? *Climate Policy*, 20(4), 458–467.

Clim. Change Econ. 2024.15. Downloaded from www.worldscientific.com
by 158.36.47.157 on 06/19/24. Re-use and distribution is strictly not permitted, except for Open Access articles.