

Open Research Online

The Open University's repository of research publications and other research outputs

Worldwide impacts of climate change on energy for heating and cooling

Journal Item

How to cite:

Labriet, Maryse; Joshi, Santosh R.; Vielle, Marc; Holden, Philip B.; Edwards, Neil R.; Kanudia, Amit; Loulou, Richard and Babonneau, Frédéric (2015). Worldwide impacts of climate change on energy for heating and cooling. *Mitigation and Adaptation Strategies for Global Change*, 20(7) pp. 1111–1136.

For guidance on citations see [FAQs](#).

© 2013 Springer Science+Business Media

Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1007/s11027-013-9522-7>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Worldwide impacts of climate change on energy for heating and cooling

Maryse Labriet¹, Santosh R. Joshi², Frédéric Babonneau³, Neil R. Edwards⁴,
Philip B. Holden⁵, Amit Kanudia⁶, Richard Loulou⁷, and Marc Vielle⁸

^{1,6,7}*Eneris Environment Energy Consultants, Madrid, Spain.*

^{2,3,8}*REME Laboratory, Swiss Federal Institute of Technology at Lausanne (EPFL), Switzerland.*

^{4,5}*Environment, Earth and Ecosystems, Open University, Milton Keynes, UK.*

³*ORDECSYS SARL, Switzerland*

⁶*KanORS-EMR, Noida, India.*

⁷*Kanlo, Lyon, France.*

Abstract

The energy sector is not only a major contributor to greenhouse gases, it is also vulnerable to climate change and will have to adapt to future climate conditions. The objective of this study is to analyze the impacts of changes in future temperatures on the heating and cooling services of buildings and the resulting energy and macro-economic effects at global and regional levels. For this purpose, the techno-economic TIAM-WORLD (TIMES Integrated Assessment Model) and the general equilibrium GEMINI-E3 (General Equilibrium Model of International-National Interactions between Economy, Energy and Environment) models are coupled with a climate model, PLASIM-ENTS (Planet-Simulator - Efficient Numerical Terrestrial Scheme). The key results are as follows. At the global level, the climate feedback induced by adaptation of the energy system to heating and cooling is found to be insignificant, partly because heating and cooling-induced changes compensate and partly because they represent a limited share of total final energy consumption. However, significant changes are observed at regional levels, more particularly in terms of additional power capacity required to satisfy additional cooling services, resulting in increases in electricity prices. In terms of macro-economic impacts, welfare gains and losses are associated more with changes in energy exports and imports than with changes in energy consumption for heating and cooling. The rebound effect appears to be non-negligible. To conclude, the coupling of models of different nature was successful and showed that the energy and economic impacts of climate change on heating and cooling remain small at the global level, but changes in energy needs will be visible at more local scale.

Keywords: Climate change, Heating, Cooling, Adaptation, Energy system, Bottom-up model, Computable general equilibrium model, Rebound effect

JEL codes: C6, O13, Q41, Q54

1 Introduction

Until recently, climate policies in the energy sector have focused on emission mitigation, given the contribution of energy to greenhouse gas emissions. However, awareness of the climate vulnerability and adaptation needs of the energy sector is increasing (Mideksa and Kallbekken, 2010; Ebinger and Vergara, 2011; Schaeffer et al., 2012). Several classes of possible impacts of climate change on energy demand and production have been noted: (i) changes in cooling efficiency of thermal and nuclear power generation, resulting in modified availability and efficiency of plants (Linnerud et al., 2011; Rübberke and Vögele, 2011); (ii) changes in seasonal river flows and in their variability, affecting hydropower potential and generation (Lehner et al., 2005; Hamududu and Killingtveit, 2012); (iii) changes in productivity of crops for bio-energy (Haberl et al., 2011); (iv) vulnerability of energy-related infrastructure to extreme events and sea level rise (Craig, 2011); (v) and finally, changes in space heating and cooling requirements, the focus of the current paper.

Several studies assess the impacts of climate change on heating and cooling at local or national level, often using engineering approaches. Amongst others, Wilbanks et al. (2007b) for the USA, Aebischer et al. (2007) for Switzerland and Europe, Dolinar et al. (2010) for Slovenia, Wang et al. (2010) for Australia, Ward (2008) for Yorkshire in the UK and Akpınar-Ferrand and Singh (2010) for India. Some of these studies assess the determinants of heating and cooling demands based on multi-country panel studies (Cian et al., 2007; Petrick et al., 2010). Very few studies analyze the impacts at global level. Amongst them, Isaac and van Vuuren (2009) assess energy use for future residential heating and air conditioning in the context of climate change. Mima and Criqui (2009) introduce temperature impacts in the partial equilibrium model POLES (Prospective Outlook for Long-term Energy Systems). Wilbanks et al. (2007a) emphasize the need to consider the different fuels used for heating and cooling since climate change may result in an increase in net annual electricity demand, driven by cooling, while demands for heating energy sources may decline. Such changes may lead to different energy and emission patterns, which may result in a feedback - or not - between the climate and the energy system, depending of the net balance in energy use and on the energy used for heating purposes and on the source of electricity for cooling. Wilbanks et al. (2007a) also note the possibility that new seasonal peaks in demand may occur, even where increases in cooling are balanced by decreases in heating in the annual average.

The general objective of this paper is to assess the impacts of variations in heating and

cooling of buildings due to future temperature changes, considering a multi-model approach allowing a consistent analysis of the linkage between climate, energy and macro-economic dynamics. A first specific objective concerns the analysis of energy and technology decisions resulting from these changes at global and regional levels, taking a systems perspective that accounts for impacts on the entire energy system and resulting substitution effects. This extends the analysis of [Isaac and van Vuuren \(2009\)](#), which focused on demands, ignoring substitution effects. A second specific objective is the assessment of possible feedbacks on the climate system of changes in emissions from the energy system. The increase of electricity generation for cooling, if not compensated by the decrease of energy use for heating, may be a source of additional greenhouse gases, which could accelerate climate change. Fuel details, needed to assess this feedback, were not analyzed in ([Mima and Criqui, 2009](#)). A third objective is to study both direct and indirect macro-economic impacts, including possible rebound effects resulting from a decrease of energy costs for households. There are only a few studies that investigate macro-economic effects of changes in energy demand due to climate change, particularly the rebound effect of prices. [Bosello et al. \(2007\)](#) rely on econometric estimation of the relationship between average temperature and long-run demand for energy goods. [Aaheim et al. \(2009\)](#) and [Eboli et al. \(2010\)](#) use the same approach to simulate changes in energy demand using dynamic CGE models.

Our approach relies on the coupling of an emulated version of the climate model PLASIM-ENTS (the Planet-Simulator coupled to the Efficient Numerical Terrestrial Scheme), with the TIAM-WORLD techno-economic model (TIMES Integrated Assessment Model) and the general equilibrium model GEMINI-E3 (General Equilibrium Model of International-National Interactions between Economy, Energy and Environment). The technologically detailed energy model TIAM-WORLD allows us to assess energy systems in a comprehensive way whilst the economy-wide model GEMINI-E3 examines the overall macroeconomic implications of such changes in heating and cooling energy demand due to climate change for services and residential purposes.

The paper is organized as follows: The next section presents the three models; Section 3 describes the baseline scenario; Section 4 presents the results, and Section 5 concludes.

2 Methodological Framework

The methodology involves the coupling of three models (Figure 1): the techno-economic TIAM-WORLD model provides greenhouse gas concentration to the emulator of the climate model PLASIM-ENTS, which sends back temperature increases to both TIAM-WORLD and to the economy-wide model GEMINI-E3. Information exchange between models is handled by a fully automated script that launches models, reads output of one and creates input for the next.

This can be done on a single computer or across a distributed network using the Community Integrated Assessment System tool (Warren et al., 2008). This section describes each model and their linkages. The next section describes the harmonization of TIAM-WORLD and GEMINI-E3.

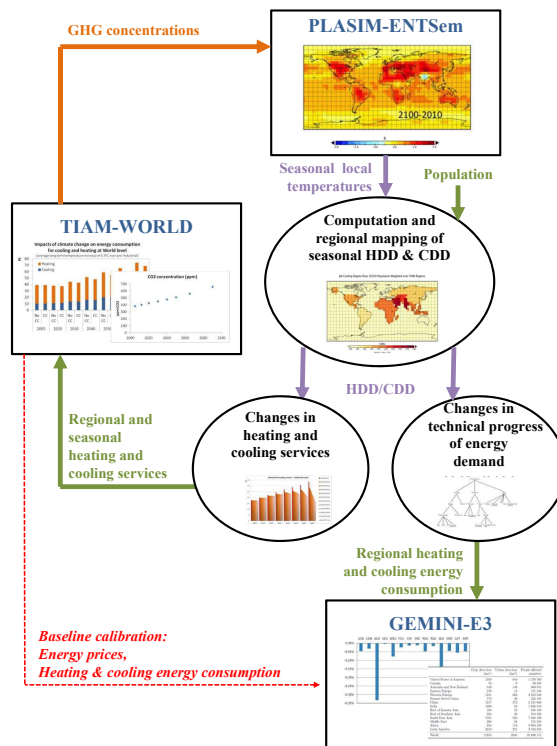


Figure 1: Integrated framework to model impacts of heating and cooling on energy and economic system

2.1 Climate model: PLASIM-ENTS

One of the principal obstacles to coupling complex climate models to the range of models needed to assess climate impacts in different sectors is the computational expense of the climate models. Replacing the climate model with an emulated version of its input-output response function circumvents this problem without compromising the possibility of including feedbacks and non-linear responses (Holden and Edwards, 2010).

The climate model emulator used here is PLASIM-ENTSem (Holden et al., 2013), an emulation of PLASIM-ENTS, Fraedrich et al. (2005) coupled to the ENTS vegetation and land surface model (Williamson et al., 2006), here run at T21 resolution (approximately 5 degree). PLASIM-ENTS has a 3D dynamic atmosphere, flux-corrected slab ocean and slab sea ice, and dynamic coupled vegetation. The validations of both PLASIM-ENTS and PLASIM-ENTSem

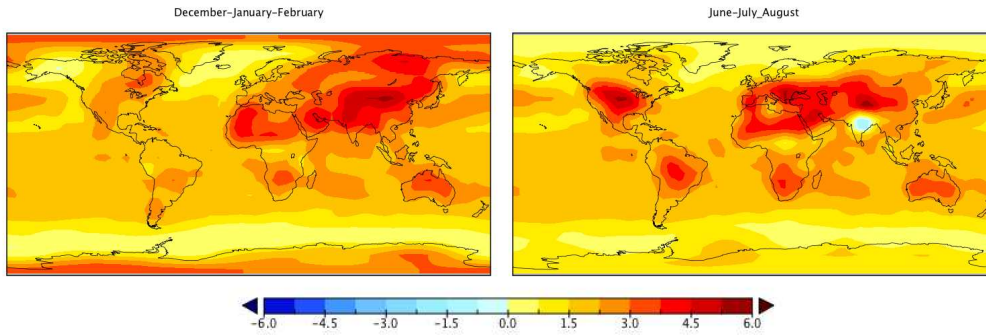


Figure 2: Spatial patterns of emulated warming over the next century (2100 - 2000 AD) in response to RCP6.0 forcing.

are described in detail in (Holden et al., 2013).

The slab sea ice was held fixed in the simulations used to build the version of the emulator used here, which predates the configuration described in (Holden et al., 2013). Warming patterns in response to RCP6.0 are illustrated in Figure 2. The emulator performs generally very well in capturing the spatial variability and magnitude of warming simulated by more complex models, but the neglect of the sea ice feedback in this configuration results in understated DJF (December-January-February) warming in the Arctic. Although caution will be required, this error dominantly affects temperatures in sparsely populated high-northern latitudes and so may not be problematic for large-scale human impact studies. Emulated south-east Asian JJA (June-July-August) temperatures suggest a cooling of up to 1.5K under RCP6.0. This arises due to a strengthening of the South-east Asian monsoon in PLASIM-ENTS that is associated with decreased incoming shortwave radiation (increased cloud cover) and increased evaporative cooling. Given the neglect of aerosol forcing in PLASIM-ENTS, this JJA cooling in south-east Asia should not be regarded as robust; aerosols are an important forcing of the south-east Asian monsoon through a range of likely competing effects (- see e.g. (Ganguly et al., 2012).

The climate data required for the assessment of heating and cooling changes due to climate changes can be summarized in terms of Heating Degree Days (HDDs) and Cooling Degree Days (CDDs). On a given day, the average temperature is calculated and subtracted from the baseline temperature; if the result is less than or equal to zero, then that day has zero HDDs (no heating requirements); if it is positive, then it represents the number of HDDs on that day. The sum of HDDs over a month provides an indication of the total heating requirements for that month. CDDs are directly analogous, but integrate the temperature excess relative to a baseline and provide a measure of the cooling demands for that month.

Although possible, calculating degree-days from the day-to-day temperature variability is restrictive as it cannot be transformed to a new baseline without repeating the underlying

simulations, which can be computationally prohibitive. Therefore, degree-days are not directly emulated by PLASIM-ENTSem. Instead they are derived from emulations of the seasonal average temperature and the variability of the daily temperature across the season, following the approach of [Schoenau and Kehrig \(1990\)](#). The critical assumption made is that daily temperatures are scattered about the monthly mean with a normal distribution. Seasonal HDDs and CDDs are computed at each of the $64 \times 32 = 2048$ PLASIM-ENTS grid cells from:

$$HDD = \frac{N}{\sigma\sqrt{2\Pi}} \int_{-\infty}^{B_H} (B_H - T)e^{[-(T-\mu)^2/2\sigma^2]} dT, \quad (1)$$

$$CDD = \frac{N}{\sigma\sqrt{2\Pi}} \int_{B_C}^{-\infty} (T - B_C)e^{[-(T-\mu)^2/2\sigma^2]} dT, \quad (2)$$

where N = number of days in the season, T = daily temperature, B_H = HDD baseline temperature ($^{\circ}\text{C}$), B_C = CDD baseline temperature ($^{\circ}\text{C}$), μ = average daily temperature across the season, σ = standard deviation of daily temperature across the season. For this analysis, $B_H = B_C = 18^{\circ}\text{C}$ is applied globally. In order to map the PLASIM-ENTS degree-day data onto TIAM-WORLD and GEMINI-E3 regions, we derive a population-weighted average over the grid cells that comprise a given region. We apply 2005 population data ([CIESIN and CIAT, 2005](#)) at a 0.25° resolution which we integrate up onto the PLASIM-ENTS grid. Moving to the lower resolution inevitably leads to approximations, most notably when highly populated coastal areas find themselves in grid cells which are assigned to be ocean in PLASIM-ENTS. We address this by assigning all grid cells that have a population greater than 500,000 to a TIAM-WORLD/GEMINI-E3 region, irrespective of whether or not that cell is assigned to be land or ocean in PLASIM-ENTS. This avoids the potential neglect of densely populated coastal regions, but comes at the expense of ascribing an oceanic climate to some populated regions, likely understating seasonal variability and future warming. The validation of seasonally and regionally resolved population-weighted degree-days is described in ([Holden et al., 2013](#)).

2.2 Techno-economic model: TIAM-WORLD

The TIMES Integrated Assessment Model (TIAM-WORLD) is a technology-rich model of the entire energy/emission system of the World split into 16 regions, providing a detailed representation of the procurement, transformation, trade, and consumption of a large number of energy forms ([Loulou, 2008](#); [Loulou and Labriet, 2008](#)). The description of the model is also available at: www.kanors.com. It computes an inter-temporal dynamic partial equilibrium on energy and emission markets based on the maximization of total surplus, defined as the sum of suppliers and consumers surpluses. In other words, the model finds optimal (cost-efficient) energy and technology mix to satisfy demands for energy services like lighting, cooking, heating, cooling of houses, kilometers driven by cars, trucks, tons of aluminium, cement to be produced,

etc. The model is set-up to explore the development of the World energy system until 2100. The model is calibrated to 2005 energy statistics of the International Energy Agency (IEA, 2013).

The model contains explicit detailed descriptions of more than 1500 technologies and several hundreds of energy, emission and demand flows in each region. Such technological detail provides a precise description of technology and fuel competition in entire energy system, where changes in one sector may have direct and indirect impacts on other sectors.

TIAM-WORLD integrates a climate module for the modeling of global changes related to greenhouse gas concentrations, radiative forcing and temperature increase.

2.3 General Equilibrium model: GEMINI-E3

GEMINI-E3 Bernard and Vielle (2008) is a multi-country, multi-sector, recursive computable general equilibrium model. All information about the model can be found at <http://gemini-e3.epfl.ch>. The model is based on the assumption of total flexibility in all markets, both macroeconomic markets such as the capital and the exchange markets (with the associated prices being the real rate of interest and the real exchange rate, which are determined endogenously), and microeconomic or sector markets (goods, factors of production). The GEMINI-E3 model is built on a comprehensive energy-economy dataset, the GTAP-8 database (Narayanan et al., 2012). This database incorporates a consistent representation of energy markets in physical units, social accounting matrices for each individual country/region, and a whole set of bilateral trade flows. Carbon emissions are computed on the basis of fossil fuel energy consumption in physical units. For the modeling of non-CO₂ greenhouse gases emissions (methane CH₄, nitrous oxide N₂O and fluorinated gases), we employ regional and sector-specific marginal abatement cost curves and emission projections.

2.4 The integrated framework

2.4.1 Linkages between emissions (TIAM-WORLD) and climate (PLASIM-ENTS)

The climate module of TIAM-WORLD does not compute the regional or seasonal temperature changes required for a relevant representation of the possible heating and cooling adjustments due to climate change. The coupling of TIAM-WORLD with an emulator of the climate model PLASIM-ENTS provides this additional information. Moreover, it adds realism in the way TIAM-WORLD simulates climate changes thanks to the more detailed representation of climate dynamics in PLASIM-ENTS. The global temperature increases obtained with PLASIM-ENTS tend to be slightly smaller than the temperature increase obtained with the endogenous climate module of TIAM-WORLD, reflecting a smaller equivalent temperature sensitivity of

PLASIM-ENTS than in TIAM-WORLD. Such differences are within the range of variation between state-of-the-art climate models.

In essence, there is an iterative exchange of data between the two models, whereby TIAM-WORLD sends to the climate emulator a time series of total greenhouse gas concentrations for the entire 21st century, computed in TIAM-WORLD, and the climate emulator sends to TIAM-WORLD the seasonal and regional temperatures, converted into seasonal heating and cooling degree-days for each of the regions of the model. These seasonal and regional degree-days are in turn used to compute new seasonal and regional heating and cooling demands in TIAM-WORLD.

2.4.2 Incorporating heating and cooling changes in TIAM-WORLD

In the Business As Usual (BAU) case, energy demands for heating and cooling do not consider any future temperature variations compared to the base year 2005. In this case, the drivers of future heating and cooling demands reflect changes in socio-economical characteristics of the regions, but consider the HDD and CDD as in the base year. Cooling deserves an additional comment. In practice, cooling demand depends not only on temperatures but also on socio-economic factors influencing the diffusion (purchase) of air-conditioning systems, this is usually described as an S-shaped curve function of the level of income: penetration of air conditioners has been found to climb steeply at a point when household income reaches US\$3300 per month (McNeil and Letschert, 2008). In other words, cooling energy services depend on the use of air-conditioning (directly linked to CDD), but also on the purchase of air-conditioning by new sectors of the community as they become more affluent (linked to CDD and socioeconomic drivers). McNeil and Letschert (2008) propose a saturation effect guided by the level of penetration of air-conditioners in the USA for a given CDD value. Following their methodology and numerical assumptions, the demands for cooling services of TIAM-WORLD have been adjusted given Gross Domestic Product (GDP), population assumptions and constant climate conditions as provided by PLASIM-ENTS for 2005. We observed that the climate factor influencing the purchase of air-conditioning already reaches its maximal value when considering CDD as observed for 2005 for all regions except Canada, Europe, Japan, Russia and South Korea. In these regions, future increases in CDD could, theoretically, increase the diffusion of air-conditioners to a larger proportion of the community. However, in this study we neglect this increased diffusion and consider only increased usage. The neglected impacts on energy would remain limited since the values of CDD for the relevant regions remains low.

Based on this analysis, the impacts on demands for heating and cooling services are calculated by adjusting these demands proportionally to the changes of HDDs and CDDs of each region with respect to the values of the base year. In other words, energy services for heating

with impact of climate change are given by:

$$EDH_{t,r}^{cc} = \frac{HDD_{t,r}}{HDD_{B,r}} \cdot EDH_{t,r} \quad (3)$$

where $EDH_{t,r}$ is the energy service for heating without climate change at time t and region r . B is the base year 2005.

Similarly, energy services for cooling with impact of climate change is given by

$$EDC_{t,r}^{cc} = \frac{CDD_{t,r}}{CDD_{B,r}} \cdot EDC_{t,r} \quad (4)$$

where $EDC_{t,r}$ is the energy service for cooling without climate change at time t and region r .

The new heating and cooling services result in the endogenous computation of a new supply-demand equilibrium.

2.4.3 Incorporating heating and cooling changes in GEMINI-E3

We incorporate heating and cooling changes in household and commercial activities. The households consumption is derived from a utility function based on nested Constant Elasticity of Substitution (CES) functions (see Figure 3). Figure 3 shows the nested CES structure used in GEMINI-E3 to describe the household consumption. Energy consumption is split in energy used for transportation purposes and for residential purposes. In each nest, energy can be substituted by a capital good represented by cars in the first case and by shelters in the second one. Since GEMINI-E3 describes only total energy consumption by household without representing the different purposes (heating, cooling, cooking, lighting, etc) the respective shares of energy consumption for heating and cooling are taken from the outputs of TIAM-WORLD for each period between 2010 and 2100 and for the baseline.

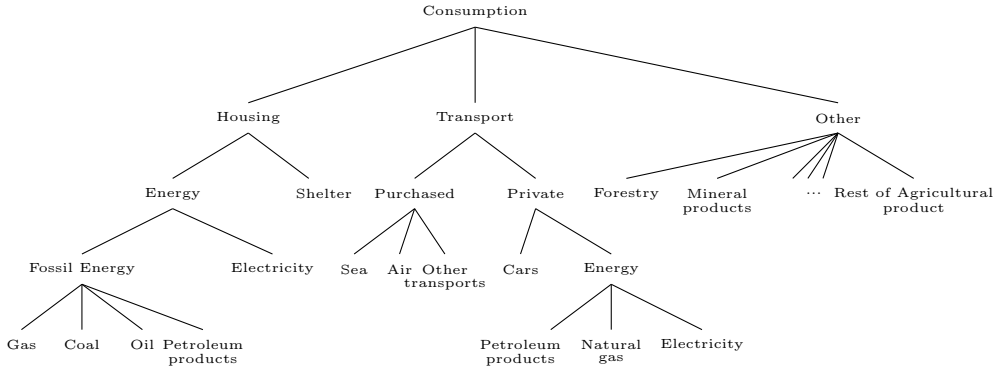


Figure 3: Nested CES structure of household consumption within GEMINI-E3

The next step is to introduce the variation of HDD and CDD in the GEMINI-E3 model by adjusting technical progress associated with fossil energy and electricity consumption for

residential purpose. This corresponds to the assumption that the changes in HDD/CDD are equivalent to as a decrease/increase of energy that is required to satisfy the same level of comfort of heating/cooling. The result will not only be a reallocation of demand as proposed by [Bosello et al. \(2007\)](#) and [Eboli et al. \(2010\)](#) but also a direct welfare impact emanating from a decrease/increase in energy needs. Concerning heating, the technical progress on fossil energy is increased taking into account the share of fossil energy that is used for heating computed from TIAM-WORLD and the change of HDD coming from PLASIM-ENTS. It is found from the results of the TIAM-WORLD that electricity is the main source of energy for cooling purpose while it represents only a small share of energy consumed for residential heating. With this information and for simplification, it is assumed that heating does not use electricity in our model simulation. For cooling, a similar protocol is assumed, the technical progress related to electricity is therefore decreased taking into account the share of electricity used for cooling and the change in CDD. The increase in electricity demand takes into account the different factors mentioned in section 2.4.2: the initial level of the CDDs (i.e. without climate change), the impact of climate change on the CDDs come from PLASIM-ENTS, while the diffusion of air conditioners is calibrated to the TIAM-WORLD model.

The same methodology as in household consumption is used for heating and cooling energy demand for commercial activities.

3 Harmonized baseline scenario

The baseline scenario of TIAM-WORLD and GEMINI-E3 was harmonized according to the following approach:

- A regional mapping is proposed, based on the lists of countries included in each region of the models (Table 1); in the rest of the paper, results will be presented according to the common region mapping; results for the original regions of each model are available upon request;
- The same assumptions on population and economic growth are used (section 3.1. below);
- Energy prices of fossil commodities (oil, natural gas and coal) used in GEMINI-E3 are calibrated to the prices endogenously computed by TIAM-WORLD in the reference case;
- In GEMINI-E3, the technical progress factors associated with energy consumption are adjusted in order to obtain similar energy consumption by type of energy and by region to TIAM-WORLD;
- The resulting GHG emissions obtained from both models are verified in order to guarantee that the resulting regional and seasonal temperature changes are the same so that energy

and economic results of both models can be jointly analyzed.

Table 1: A common regional classification between TIAM-WORLD and GEMINI-E3

| Common classification | TIAM-WORLD | GEMINI-E3 |
|--------------------------|--|--|
| Africa | Africa | Africa |
| Australia & New Zealand | Australia & New Zealand | Australia & New Zealand |
| Canada | Canada | Canada |
| China | China | China |
| Europe | Europe | Eastern and Western European Countries |
| Former Soviet Union | Russia, Other Eastern Europe | Former Soviet Union |
| India | India | India |
| Latin America | Mexico, Central and South America | Latin America |
| Middle East | Middle East | Middle East |
| Other Asia | Caucasus and central Asia, Japan, South Korea, Other Developing Asia | Rest of Eastern and Southern Asia, South East Asia |
| United States of America | United States of America | United States of America |

3.1 Demographic and economic assumptions

Regional population growth follows the median-fertility variant of the latest forecast given by the United Nations [United Nations and Social Affairs \(2011\)](#). The world population is projected to reach 9.2 billion in 2050 and 10 billion in 2100. Most of the additional 3.1 billion is estimated to come from Africa (+2.6), India (+0.3) and Middle East (+0.24). In contrast, the population in industrialized regions increases only slightly (USA +0.17) or declines (FSU -0.06 and Europe -0.01). China’s population is estimated to decrease by 0.4 billion over the century.

Global annual GDP growth decreases over the period from 3% in the short-term to 1.2% at the end of the century. Mid-term growth is driven by developing and emerging countries where economic growth reaches up to 7.5% and 6.5% in India and China, and slows down after mid-century. Short term estimates are based on Statistics/Outlook of the International Monetary Fund; long term estimates are based on data from European and international projects like PLANETS (“Probabilistic Long-term Assessment of New Energy Technology Scenarios”; <http://www.feem-project.net/planets>), REACCESS (“Risk of Energy Availability: Common Corridors for Europe Supply Security”; <http://reaccess.epu.ntua.gr/>), Energy Modelling Forum (<http://emf.stanford.edu>).

3.2 GHG emissions

GHG emissions computed by the models include CO₂ (from fossil energy combustion and land use), methane (CH₄) and nitrous oxide (N₂O). Figure 4 compares CO₂ emissions obtained with

GEMINI-E3 and TIAM-WORLD with those obtained with the representative concentration pathways (RCPs) (van Vuuren et al., 2011). CO₂ emissions profile obtained with GEMINI-E3 and TIAM-WORLD is in line with RCP 6.0 up to 2080. After this year, carbon emissions continue to grow in both models, where no climate constraint is imposed, contrary to RCP 6.0. Total radiative forcing corresponding to the emission trajectory of GEMINI-E3 and TIAM-WORLD reaches 6.3 W/m² at the end of the century, against 5.5 W/m² in RCP6.0 scenario. Global GHG emissions reach 18.4 GtC-eq in 2050 and 27.3 GtC-eq at the end of the century.

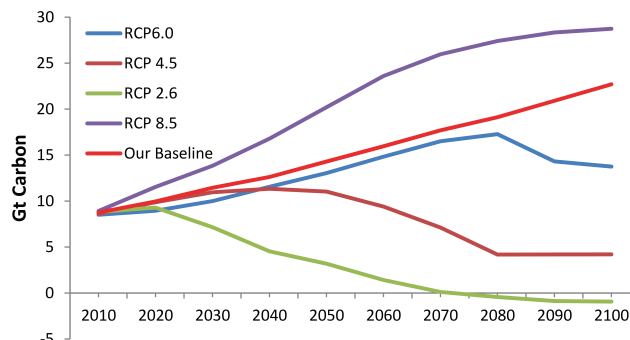


Figure 4: CO₂ emission profiles (Gt Carbon)- Harmonized baseline of GEMINI-E3 and TIAM-WORLD and RCPs

3.3 Cooling and heating services

Three groups of regions can be identified, based on the HDD and CDD dynamics computed by PLASIM-ENTS with the emissions of the harmonized baseline scenario (Figure 5):

- colder regions, characterized by high levels of HDD where the main expected impact of climate change is a reduction of heating services (FSU, Canada);
- warmer regions characterized by high levels of CDD where the main expected impact of climate change is an increase of cooling services (India, Middle East, Africa, Latin America, Australia & New Zealand, Other Asia);
- regions with intermediate climate where both heating and cooling appear to be important and the net impact of climate change may depend on each region (Europe, China, USA).

4 Results

4.1 Impacts on the energy system

Two complementary questions are at the heart of the proposed analysis. First, what are the impacts of future climate changes on heating and cooling services, and their possible

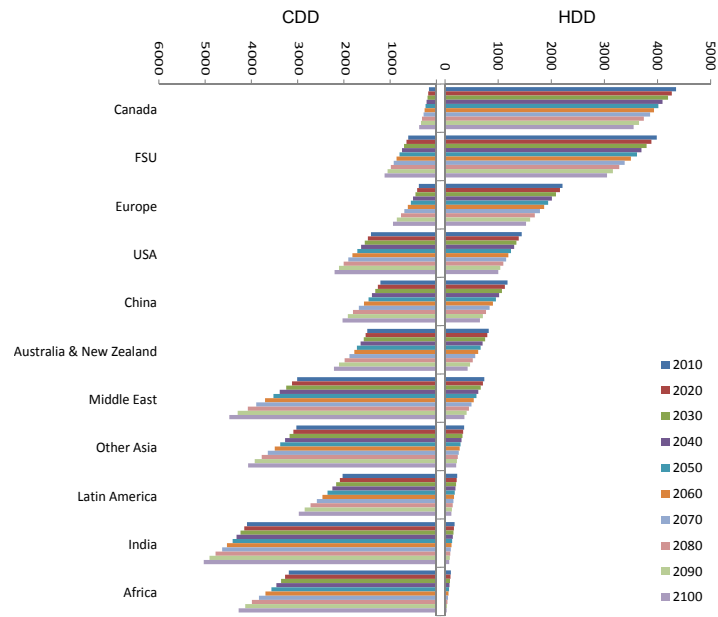


Figure 5: HDD and CDD corresponding to a long-term global average temperature increase of 3.3°C .

consequences on the entire energy system? Second, what are the possible feedbacks on the climate system of the changes observed in the energy system?

It is important to recall that no mitigation climate strategies are assessed in the current exercise and that the focus is on the adaptation of the energy system to the impacts of future climate change on heating and cooling. Such changes in heating and cooling behavior would represent spontaneous adaptation reactions by households and companies when facing variable local temperatures.

4.1.1 Different future temperature increases

A series of 12 scenarios were built and modeled, representing a range of long-term global mean temperature increase from 1.6 to 5.7°C , illustrating possible uncertainties in the contribution of radiative agents like aerosols, methane from oceans, as well as in climate sensitivity. The long term temperature increase of the Reference case is 3.3°C , corresponding to HDD and CDD as illustrated in Figure 5.

Notation: In all Figures, CCx.x corresponds to a scenarios with a long term mean temperature increase of x.x $^{\circ}\text{C}$ at the global level. Regional temperature increases may be different and are used to assess the changes in heating and cooling.

4.1.2 Global impacts: climate feedback and energy trends

Climate feedback

Climate results to be independent of the changes in heating and cooling due to future climate change at the global level, on the time horizon considered (2100) even in cases of higher changes in heating and cooling CO₂ concentration remains the same in the 12 cases (between 693 to 696 ppm). In other words, the feedback between the energy and climate systems due to changes in heating and cooling services at global level is negligible. However, this does not mean that the impacts of climate change on heating and cooling are negligible. It means that some changes compensate others, and that heating and cooling represent a relatively small contributor to total energy consumption.

Combined heating and cooling in the total energy balance

The share of combined heating and cooling energy consumption is small at the global level compared to the total energy consumption (less than 10%, Figure 6). The decrease of this share in the case where impacts of climate change are not considered reflects both socio-economic drivers in energy services (population, economic development) and technology dynamics (type and efficiency of technologies to provide the services). Other energy service increases more than heating and cooling services, and more efficient technologies penetrate the heating and cooling subsectors. More particularly, results show that coal/oil heating systems in place are progressively substituted by more efficient gas/electricity technologies. The difference between the shares obtained with and without climate change impacts illustrates the net (small) decrease of energy consumed for heating/cooling at the global level due to future climate change. More severe long term increase of temperature, such as 5.7°C instead of 3.3°C is not expected to affect the share of heating and cooling in total final energy consumption (Figure 6).

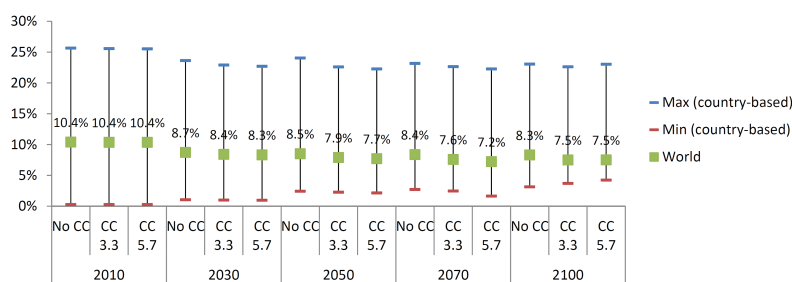


Figure 6: Share of heating and cooling in total final energy consumption for no climate change (No CC), 3.3°C (CC 3.3) and 5.7°C (CC 5.7) scenarios changes)

Respective contributions of heating and cooling adaptation

The overall decrease in energy consumption for heating and cooling following the adaptation to climate changes hides a higher decrease in energy for heating, compensated, to a certain extent,

by the increase in electricity for cooling (Figure 7). Observed changes (-35% for heating and +70% for cooling) are of the same magnitude as observed in [Mima and Criqui \(2009\)](#) (-31% for heating and +105% for cooling in 2100) and [Isaac and van Vuuren \(2009\)](#) (-34% and +72%) for temperature increases between 3.3 and 3.7°C. Inserted percentages must be used with precaution in order to avoid any misinterpretation since high percentages might represent very small absolute numbers. It is interesting to observe that a higher future global temperature (5.7°C instead of 3.3°C) translates into lower final energy consumption for heating and cooling only in the mid-term (Figure 7): in terms of final energy, changes in heating dominate over changes in cooling in the intermediate time horizon, while changes in cooling dominate over changes in heating in the longer term, or, in other words, when temperature reaches higher levels.

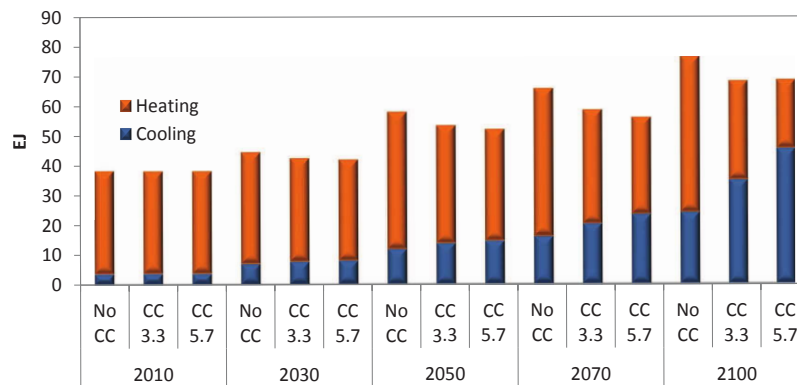


Figure 7: Global energy consumption for cooling and heating for no climate change (No CC), 3.3C (CC 3.3) and 5.7C (CC 5.7) scenarios

Fuel perspective

A major reduction in gas and coal for heating is observed (up to 70% compared to the case without climate change), while electricity increase (up to 66%) reflects how cooling consumption dominates heating consumption. It is interesting to note that the reduced needs for heating affects more gas and coal heating systems than biomass and electric heaters (both up to -45%), reflecting higher costs of natural gas in the longer term.

This additional demand for electricity is supplied mostly by coal and gas power plants, corresponding to an additional capacity of up to 1 GW in the worst temperature case (+0.4 GW in the Reference case with 3.3°C) versus the case without climate change impacts, followed by renewable (up to +0.5 GW in the worst temperature case, +0.3 GW in the Reference case with 3.3°C).

Emission perspective

Although global changes in heating and cooling are not expected to affect the climate system, it is interesting to observe the changes at the sector level, which could have consequences

on mitigation policies (Figure 8). Indeed, while emissions from buildings decrease (up to -1.2 GtCO₂ in 2100 in the highest temperature case) thanks to the reduction of heating, the increased demand for cooling translates into an increase of emissions in the power sector, given the additional installed capacities of coal and gas (up to +3.7 GtCO₂ in 2100 in the highest temperature case). The net balance is positive (+0.8 GtCO₂ in 2100 with a long-term temperature increase of 3.3°C, up to +2.5 GtCO₂ in 2100 in the highest temperature case). Isaac and van Vuuren (2009) estimate the additional emissions in the range of + 1.1 GtCO₂ for a long term temperature of 3.7°C. The climate system remains insensitive to these additional emissions given both their small magnitude and late timing.

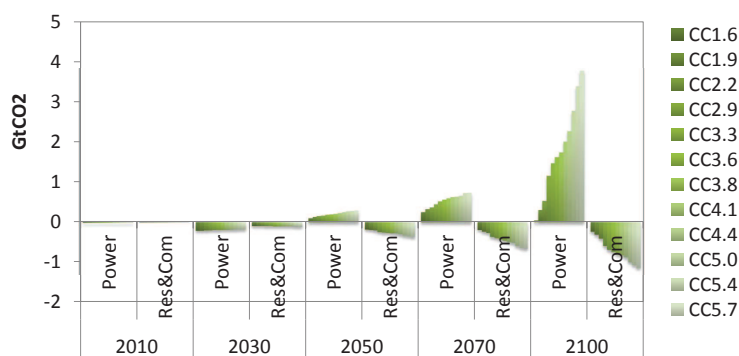


Figure 8: Variation of CO₂ emissions in power and residential/commercial sectors over the scenario without climate change impacts

4.1.3 Regional impacts

Impacts of heating and cooling adaptation to future climate change may have important consequences at regional levels, depending on the characteristics of the local energy systems and local climate changes. Such changes are illustrated in four contrasted cases: India, characterized by a warm climate and a low energy budget allocated to heating and cooling; FSU with a cold climate and a high energy budget allocated to heating and cooling; and Europe and China, characterized by intermediate climate and moderate to high energy budgets allocated to heating and cooling (Figure 5 and Table 2).

Table 2: Share of heating and cooling in total final energy consumption over 2005-2100 for long-term global temperature increase from 1.6 to 5.6°C

| | India | FSU | Europe | China |
|-------|-------|-----|--------|-------|
| CC1.6 | 0.4% | 14% | 15% | 4% |
| CC5.6 | 4% | 24% | 19% | 13% |

Adaptation of the heating and cooling services to future changes in temperature translates

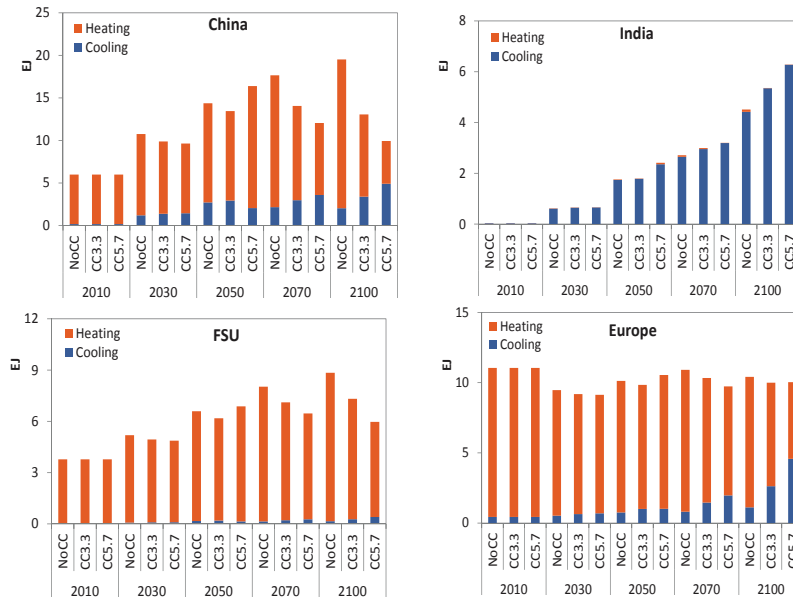


Figure 9: Total final energy consumed for heating and cooling with and without climate change impacts in China, India, FSU and Europe for no climate change (No CC), 3.3°C (CC 3.3) and 5.7°C (CC 5.7) scenarios

into an increase of energy for cooling in India (+250 TWh, or +21% with a long term temperature of 3.3°C, up to +42% in the highest temperature case compared to a situation without climate changes). In contrast a decrease of energy for heating is expected for FSU (up to -36%⁶) and for China (up to -47%⁶) while changes in heating and cooling almost compensate each other in Europe (up to -400 PJ in 2100), when considering total energy uses (Figure 9). A 21% increase in electricity due to cooling in India is estimated by [Akpınar-Ferrand and Singh \(2010\)](#). [Mima and Criqui \(2009\)](#) estimate that the heating increase will compensate for the cooling increase at EU level (-500 PJ in 2100).

As mentioned in the World analysis, adaptation to climate changes adds to the usual energy system dynamics. For example, the decrease in energy use observed in Europe between 2010 and 2030 is not climate related, but reflects the substitution of inefficient oil heaters by more efficient gas and biomass heaters. Impacts of climate change on specific energy commodities help to explain the magnitude of the positive (reducing) effects of climate change on the use of fossil fuels and biomass for heating purposes in the four regions except for India, where heating plays a negligible role in energy consumption (Figure 10). There is high demand for cooling from electricity generation in India, China as well as Europe. Not surprisingly, without any emission mitigation constraints, coal power plants appear to be the most cost-efficient option, resulting in moderate increases of CO₂ emissions for India and Europe, up to 10% in the highest temperature case (respectively +1.0 GtCO₂ and +0.6 GtCO₂). A slight decrease

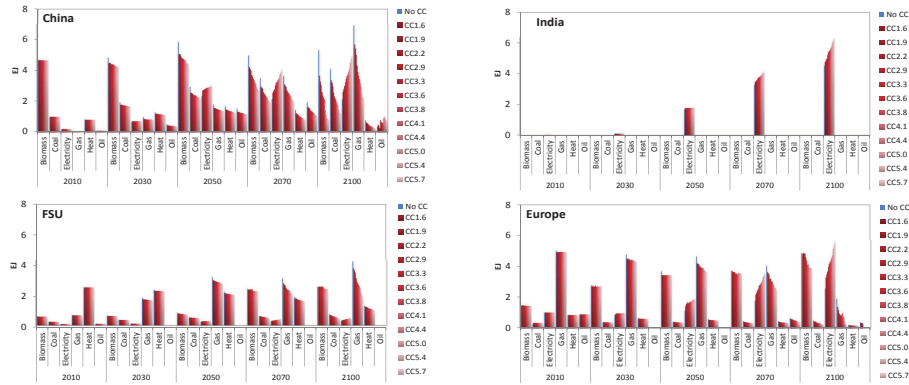


Figure 10: Specific energy commodities consumed for heating and cooling in China, India, FSU and Europe for 12 temperature scenarios

of emissions in FSU is observed (up to -0.14 GtCO_2 , equivalent to -3.5%). The substitution of renewable (wind power) by coal and gas power plants at the end of the horizon in Europe, in the case of high temperature increases, is guided by the reduction of fossil fuel consumption for heating purpose.

The seasonal impacts of climate change, more particularly on peak electricity generation, are reflected in changes in electricity prices. Electricity prices in Europe increases by up to 45% in summer days in the mid-term and 66% at the end of the horizon in Europe (up to 30 and 50% in the 3.3°C scenario). In India, the season with the highest increase (+55%) of electricity prices is the intermediate one (Fall and Spring), corresponding to the peak of temperature. The increase reaches 30% during summer days in China, while electricity prices remain unchanged in FSU.

4.2 Impacts on the macro-economic system

In this section, we analyse the economic impacts of climate change on energy demand from a macroeconomic perspective taking into account not only direct impacts on the energy system but also indirect impacts (rebound) coming from the general equilibrium effects. On one hand, the increase in technological progress associated with particular energy services is expected to result in a decrease in the price of the energy services, itself resulting in a possible increase of the consumption of those energy services; this is the direct rebound effect. On the other hand, the decrease in the energy bill may result in the increase in demand for other goods and services which in turn can increase the demand for energy services; this is the indirect rebound effect. A decrease in international energy prices in the case of a global decrease of energy consumption may also contribute to an increase in the demand for the energy services. Our general equilibrium rebound effect estimation differs from rebound effect estimated using

econometric methods because it also integrates indirect rebound effects in particular the fall of international energy prices that follows the decrease in worldwide fossil fuel energy consumption. This leakage effect is already identified in the case of climate policies (Paltsev, 2001) and explains for example the increase of fossil energy consumption by India. These rebound effects are well-documented in the economic literature (Dimitropoulos, 2007) explaining that when the cost of energy services falls (which is the case when we suppose that less energy is required to satisfy the same level of comfort) there is a tendency to increase the level of comfort (i.e. increase the temperature inside buildings) by using more energy which limits the fall in the initial calculation of change in energy demand. The general equilibrium rebound effects can be evaluated as a first approximation by comparing the initial calculation of change in energy demand introduced in GEMINI-E3 and the general equilibrium effect on energy demand computed by the model. Bosello et al. (2007) have found that the most important driving force behind the change in GDP is the change in the terms of trade induced by the change in the world demand for energy goods. The authors also have found that change in quantities demanded are in line with the initial shocks however *ex post* demand variation differs from the *ex ante* one because of the rebound effect of prices. Following this study, Aaheim et al. (2009); Eboli et al. (2010) use the same approach to simulate changes in energy demand using a dynamic CGE model. Eboli et al. (2010) have found that energy demand does not change much at a global level, however it is diverse across regions.

To better assess the magnitude of the macro-economic effects of decreasing consumption in heating and increasing demand in cooling, we run three scenarios (i) the decrease in heating energy consumption; (ii) the increase in cooling energy consumption; (iii) a combination of both effects. Similar to TIAM-WORLD, the long term temperature increase of the Reference case is 3.3°C. Results are focused on the direct and indirect macro-economic impacts. For each scenario, we present the results for the terminal year of the simulation, 2100.

4.2.1 Macro-economic impacts of the decrease in the heating energy consumption

As noted in section 4.1.2 the changes in the total energy balance are rather limited given the limited share of heating (and cooling) in total energy consumption. The most affected regions are Europe, China, USA, Canada and FSU, regions where the HDDs are above a certain threshold (around 1500) and/or regions that will face significant decrease of HDDs. The case of India clearly illustrates the rebound dynamic: the initial calculation shows there is no change in household fossil fuel energy consumption (this is due to negligible share of fossil fuel energy consumption for heating purpose) while general equilibrium effect shows the increase in fossil energy consumption which can be explained by a decrease in international energy price. Table 3 presents the changes in energy demand introduced in GEMINI-E3 as a result of climate

change, and the general equilibrium effect in household fossil energy consumption computed by GEMINI-E3 for the year 2100. By regressing energy use for space heating with HDD, [Duerinck et al \(2008\)](#) found an elasticity between heating energy demand and HDD of 0.55 on average for selected European Union member states. This corresponds to a rebound effect of 45%. The rebound effect computed by GEMINI-E3 at the European level, equal to 37.6%, 35.2% and 31.5% for long term temperature increase of 1.6°C, 3.3°C and 5.7°C respectively (Table 3). Simulation results show rebound effects are diverse across regions and are usually of larger percentage for low (1.6°C) temperature scenario than for high (5.7°C) temperature scenario. In Australia and New Zealand, rebound effect is least with 29.8% while Latin America sees highest rebound effect of 43.1% for 5.7°C temperature scenario. This difference in rebound effect in these regions mainly stems from variation of substitution and income effect arising from the change in price of energy ([Thomas and Azevedo, 2013](#)). In GEMINI-E3, household utility function uses nested constant elasticity of substitution that allows interactions between fossil fuel energy, electricity, shelter and other products. [Washida \(2004\)](#) showed positive correlation between rebound effect and value of elasticity of substitution.

Like other general equilibrium models, GEMINI-E3 assesses the welfare cost of policies through the measurement of the classical Dupuit's surplus, i.e. in its modern formulation, the Compensating Variation of Income (CVI). Decomposition of the welfare cost into components is a complex issue that has been addressed in the literature by ([Harrison et al., 2000](#)). In the current application, the aim is the decomposition between welfare gains derived from the decrease of energy needs for heating and welfare gain/cost related to the changes in imports/exports of fossil fuel energy (called Gains from Terms of Trade (GTT)), in order to obtain a general idea of their relative importance.

The difference between the welfare gain/cost and the GTT represents the domestic gain/cost that would occur in a closed economy, i.e. without international trade. Figure 11 gives these 3 components of welfare. The decrease of the energy needs for heating creates domestic gains which are of course correlated to the decrease of the energy consumption and to the share of these energy expenditures in the GDP. China, Europe and FSU benefit in terms of welfare gain from the decrease of HDDs corresponding to a decrease of heating needs. In the case of energy exporting regions, the welfare gain is reduced by losses of revenue coming from less energy exports. This is found in our simulation results for Middle East, Former Soviet Union, Africa and Canada. Moreover, the aggregated impacts are negative for Middle East and Africa, as the domestic gains coming from the decrease of heating consumption are very limited. China and Europe experience positive welfare, for the other regions the positive change of welfare is less than 0.2% of household consumption in the reference case temperature profile. Simulation results show that welfare gains are highest for China; ranging from small percentage change

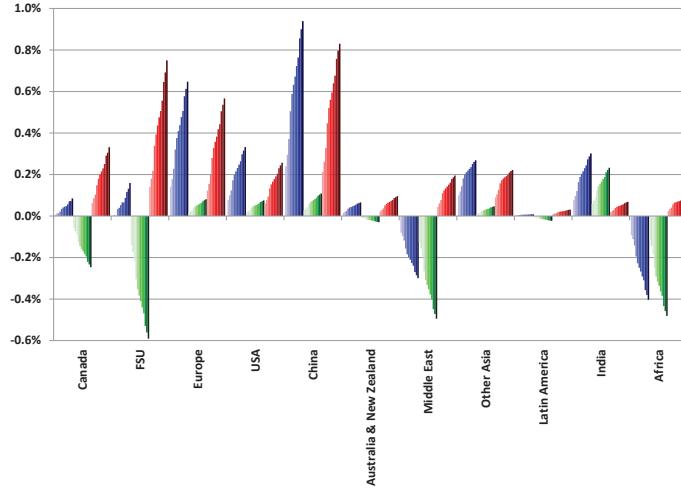


Figure 11: Welfare change in 2100, as a % of household consumption, for heating energy demand (each column represent 12 temperature scenarios for welfare (blue), GTT (green), domestic gain/cost(red))

of 0.24% to significant percentage change of 0.94% of household consumption for 1.6°C and 5.7°C temperature profile scenarios respectively.

Table 3: Initial calculation, general equilibrium and rebound effect in Household fossil energy consumption in 2100 for long-term temperature of 1.6°C, 3.3°C and 5.7°C

| | 1.6°C Scenario | | | 3.3°C Scenario | | | 5.7°C Scenario | | |
|--------------------------|----------------|-------|-------|----------------|--------|-------|----------------|--------|-------|
| | I.C. | G.E. | R.E | I.C. | G.E. | R.E | I.C. | G.E. | R.E |
| Africa | -2.3% | -1.4% | 39.1% | -5.8% | -3.6% | 37.7% | -7.7% | -4.8% | 37.7% |
| Australia & New Zealand | -4.3% | -3.0% | 30.2% | -10.8% | -7.5% | 30.5% | -17.1% | -12.0% | 29.8% |
| Canada | -5.1% | -3.0% | 41.2% | -14.3% | -8.6% | 39.7% | -25.8% | -16.3% | 36.8% |
| China | -7.7% | -4.8% | 37.7% | -18.3% | -11.7% | 36.0% | -28.9% | -19.1% | 33.9% |
| Europe | -9.3% | -5.8% | 37.6% | -24.2% | -15.7% | 35.2% | -41.0% | -28.1% | 31.5% |
| Former Soviet Union | -3.0% | -2.0% | 33.3% | -8.2% | -5.5% | 33.3% | -15.2% | -10.2% | 32.9% |
| India | 0.0% | 0.3% | - | 0.0% | 0.6% | - | 0.0% | 1.0% | - |
| Latin America | -1.5% | -0.9% | 40.0% | -3.4% | -1.9% | 42.5% | -5.1% | -2.9% | 43.1% |
| Middle East | -2.3% | -1.4% | 39.1% | -6.0% | -3.8% | 37.2% | -9.5% | -6.0% | 36.8% |
| Other Asia | -5.9% | -3.7% | 37.3% | -11.5% | -7.3% | 36.6% | -15.1% | -9.6% | 36.4% |
| United States of America | -8.7% | -5.5% | 36.8% | -21.8% | -14.4% | 34.0% | -36.3% | -25.1% | 30.9% |
| World | -4.7% | -2.9% | 38.3% | -11.5% | -7.3% | 36.7% | -18.7% | -12.3% | 34.2% |

Note: I.C. is initial calculation, G.E. is general equilibrium and R.E. is rebound effect (defined as $1 - \frac{G.E.}{I.C.}$)

4.2.2 Macro-economic impacts of the increase in the cooling energy consumption

According to the level of impact on electricity consumption, three groups of regions emerge. The regions that are the most affected are Europe, USA, Canada and Middle East (Figure 12). Similar to the general equilibrium rebound effect in heating energy consumption, the general equilibrium effect of the increase in electricity consumption is lower than the computed

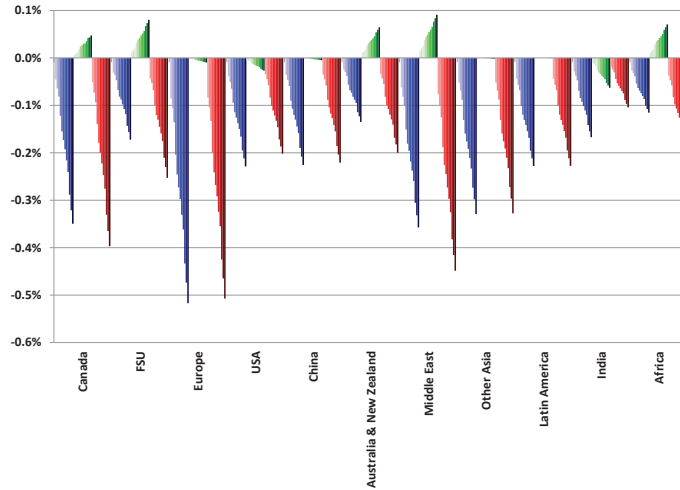


Figure 12: Welfare change in 2100, as a % of household consumption, for cooling energy demand (each column represent 12 temperature scenarios for welfare (blue), GTT (green), domestic gain/cost(red))

electricity consumption implemented in GEMINI-E3. At the global level, the rebound effect is equal to 37.5%, 40.9% and 42.4% for long term temperature increase of 1.6°C, 3.3°C and 5.7°C (Table 4). Rebound effects are diverse across regions with highest (63.5% for 5.7°C temperature scenario) in Canada and least (31.1% for 5.7°C temperature scenario) in India. This shows that the variations in rebound effects rely on the differences in economic structure of respective regions.

Table 4: Initial calculation, general equilibrium and rebound effect in electricity consumption in 2100 for 1.6°C, 3.3°C and 5.7°C scenario

| | 1.6°C Scenario | | | 3.3°C Scenario | | | 5.7°C Scenario | | |
|--------------------------|----------------|------|-------|----------------|------|-------|----------------|-------|-------|
| | I.C. | G.E. | R.E. | I.C. | G.E. | R.E. | I.C. | G.E. | R.E. |
| Africa | 4.7% | 3.2% | 31.9% | 12.3% | 8.2% | 33.0% | 23.9% | 15.7% | 34.3% |
| Australia & New Zealand | 3.4% | 1.8% | 47.1% | 9.9% | 5.0% | 49.5% | 20.3% | 10.0% | 50.7% |
| Canada | 1.4% | 0.7% | 50.0% | 5.0% | 1.6% | 67.4% | 11.5% | 4.2% | 63.5% |
| China | 1.2% | 0.8% | 33.3% | 3.6% | 2.3% | 35.9% | 7.7% | 4.9% | 36.4% |
| Europe | 4.8% | 3.0% | 37.5% | 14.4% | 8.3% | 42.4% | 26.6% | 17.4% | 34.6% |
| Former Soviet Union | 1.0% | 0.7% | 30.0% | 2.8% | 1.8% | 36.2% | 5.9% | 3.8% | 35.6% |
| India | 0.8% | 0.6% | 25.0% | 2.3% | 1.6% | 31.2% | 4.5% | 3.1% | 31.1% |
| Latin America | 5.1% | 3.1% | 39.2% | 13.9% | 8.2% | 40.9% | 27.0% | 15.5% | 42.6% |
| Middle East | 3.8% | 2.6% | 31.6% | 11.4% | 7.4% | 34.9% | 23.0% | 14.6% | 36.5% |
| Other Asia | 2.2% | 1.3% | 40.9% | 6.6% | 3.6% | 44.9% | 13.8% | 7.4% | 46.4% |
| United States of America | 1.3% | 0.7% | 46.2% | 3.8% | 1.9% | 51.3% | 7.7% | 3.6% | 53.2% |
| World | 2.4% | 1.5% | 37.5% | 6.9% | 4.1% | 40.9% | 14.4% | 8.3% | 42.4% |

The welfare cost associated with the increase of CDDs is directly correlated to the change in electricity consumption. The gain/cost derived from terms of trade remains modest in comparison to the domestic cost because electricity is mainly generated from energy sources

that are produced domestically (coal, renewable and uranium) except for power plants using natural gas. For Europe, the most affected region, welfare loss is estimated to be 0.09%, 0.25% and 0.52% for long term increases in temperature of 1.6°C, 3.3°C and 5.7°C respectively.

4.2.3 Macro-economic impact of changes in both heating and cooling

In this scenario, we simulate the decrease of energy for space heating needs and the increase of electricity for cooling buildings simultaneously. Since the interactions between heating and cooling demand are limited (fossil fuels on one side, electricity on the other one), the results are approximately equivalent to the sum of the two effects presented above (Figure 13). At the global level, the macroeconomic impact is limited as the energy expenditure for heating and cooling represents only a small share of total energy consumption and a fortiori in respect to macroeconomic aggregates like GDP or household consumption. Moreover, welfare gains due to savings from a decrease in fossil fuel consumption is compensated by the increases in expenditure of electricity consumption. Results are however quite diverse impacts at regional level (Figure 14): the macroeconomic impact of climate change on energy demand is negative for Canada, FSU, Middle East and Africa, these regions suffer from losses due to terms of trade. In the case of FSU, the decrease of energy expenditure for heating cannot compensate the loss of revenue due to a decrease in energy exports. Europe, China, USA and Other Asia benefit from a decrease in heating energy consumption that overcompensates the energy expenditure for cooling. China benefits the most in terms of welfare; ranging from 0.21% (at 1.6°C) to 0.71% (at 5.7°C). In contrast to Latin America, Australia and New Zealand are regions where the increasing expenditure for cooling buildings induces welfare costs. In India and Other Asia regions welfare is positive being mainly related to gains from terms of trade.

4.3 Synthesis and limitations

Table 5 presents a synthesis of the main results. Several limitations and uncertainties deserve some discussion and suggest further research. One weakness in the version of PLASIM-ENTS used here is the assumption of fixed sea ice, which leads to the underestimate of emulated high latitude warming. Moreover, its resolution (approximately 5 degree) is relatively coarse. The analysis of several future temperature scenarios helped compensate for uncertainties on future temperatures. Further analysis may use the recently developed PLASIM-ENTS model with dynamic arctic sea ice. TIAM-WORLD is data-intensive and long-term characteristics of technologies are uncertain and may affect preferred fuels and technologies. Population and economic growth may also deeply affect future energy service demands, amongst them, heating and cooling. Finally, detailed energy statistics for heating and cooling remain spare in some regions. In GEMINI-E3, the key parameters are the elasticities and in particular those related

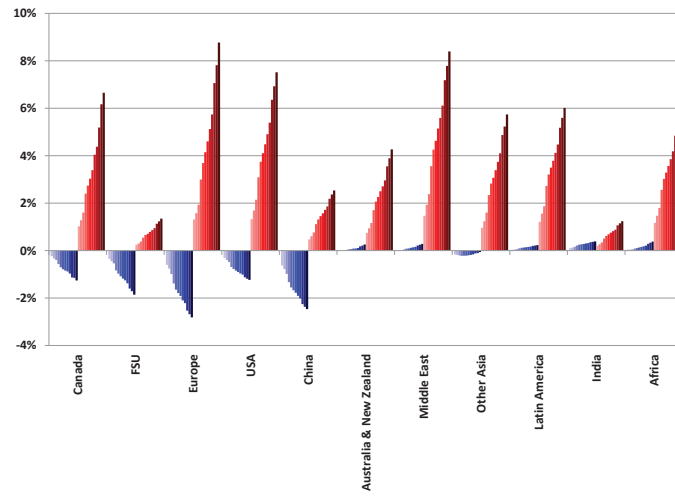


Figure 13: Percentage change in 2100 over the case without climate change, in fossil energy and electricity consumption, for both heating and cooling energy demand (each column represent 12 temperature scenarios for fossil energy (blue) and electricity(red))

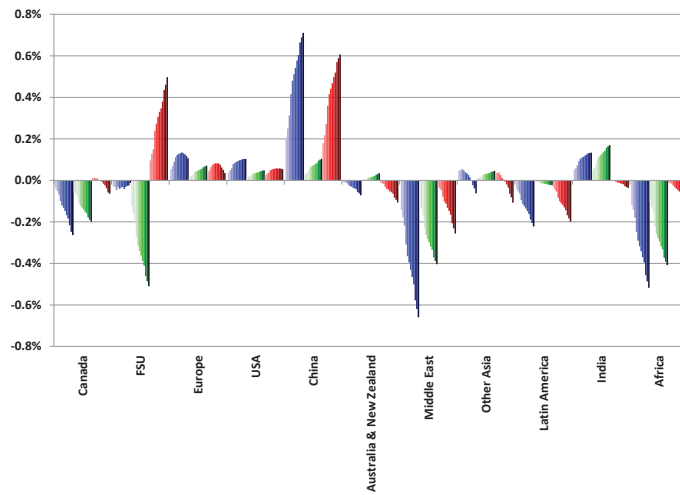


Figure 14: Welfare change in 2100, as a % of household consumption, for both heating and cooling energy demand (each column represent 12 temperature scenarios for welfare (blue), GTT (green), domestic gain/cost(red))

to energy consumption. Like other CGE models they are based on literature review. The uncertainty surrounding these parameters and the impact on the results could be analysis by performing stochastic analysis, as for example in Babonneau et al. (2012) and Labriet et al. (2012). As regards future changes in cooling and heating, their estimation is based on a fixed threshold temperature (18°C), reflecting the temperature usually used for HDD and CDD computation. The choice of spatially variable threshold temperatures may better reflect real heating and cooling behaviors. Changes in future population density may also affect total HDD and CDD and is not considered in the study.

Table 5: Main insights

| Research question | Insights (qualitative focus) |
|---|---|
| What are the impacts of future climate changes on the energy system? | <i>Global level</i> |
| | – Changes in heating dominate over changes in cooling in the intermediate horizon. Changes in cooling dominate over changes in heating when temperature reaches higher levels. |
| | – Major reduction in gas and coal for heating, net increase in electricity. |
| What is the feedback on the climate system induced by changes in heating and cooling? | <i>Regional level</i> |
| | – Large variations depending on both climatic and energy system characteristics. |
| | – Increase of electricity price in warm seasons. |
| What are the macro-economic impacts of changes in heating and cooling? | – Fuel substitution observed in other sectors (system effect) |
| | Feedback is negligible, because heating and cooling changes compensate each other at the global level, and heating and cooling represent a reduced share of total energy consumption. |
| | <i>Global level</i> |
| – Limited macroeconomic impacts in terms of welfare change. | <i>Global level</i> |
| | – Important rebound effect that moderate the impact of climate change. |
| | <i>Regional level</i> |
| – Regional welfare impacts are diverse with negative effect coming from loss of terms of trade and positive welfare impacts comes mainly through decrease in expenses for heating | |

5 Conclusion

The research has two types of outputs. The first relates to the energy and macro-economic impacts of climate-induced changes in heating and cooling. Globally, an absence of climate feedback induced by the adaptation of the energy system to future heating and cooling needs was found, in contrast with significant changes at regional levels, most particularly in terms of additional power capacity, resulting in increases in electricity prices. The macroeconomic impact of climate change on heating and cooling energy demand is also limited at global level

but diverse across regions. Negative (or positive) welfare impact was identified as mainly due to loss (or gain) from terms of trade. Macro-economic impacts show also quite high rebound effects for both heating and cooling energy consumption.

On top of these applied results, the development of the coupling methodology represents an important output of the research, making possible the complementary use of different models in an integrated and user-friendly framework.

Further research may include the use of a more complete climate system model with more realistic representation of sea ice, ocean and ecosystem responses; the refinement of the computation of heating and cooling, for example with variable threshold temperatures; the addition of other impacts of climate change, for example on hydropower plants and thermal power plants, and more details of the resulting interactions with socio-economic dynamics, for example effects on population density reflecting climate-related migrations.

Acknowledgements

The research leading to these results has received funding from the EU Seventh Framework Programme (ERMITAGE FP7/2007-2013) under Grant Agreement n°265170. We would like to thank Dr. Philomena Bacon for her comments and suggestions. We would also like to thank the participants of Swiss Society of Economics and Statistics (SSES) Annual Congress 2013, Neuchatel, Switzerland and of the International Energy Workshop 2013, Paris, France for their comments and suggestions.

References

- Aaheim A, Amundsen H, Dokken T, Ericson T, Wei T (2009) A macroeconomic assessment of impacts and adaptation to climate change in Europe. CICERO Report 2009:06 [3](#), [19](#)
- Aebischer, B., Henderson, G., Jakob M, Catenazzi, G (2007) Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. ECEEE Summer Study, Panel 5, Energy efficient buildings, pp 859–870 [2](#)
- Akpinar-Ferrand E, Singh A (2010) Modeling increased demand of energy for air conditioners and consequent CO₂ emissions to minimize health risks due to climate change in India. *Environmental Science & Policy*, 13(8):702–712 [2](#), [17](#)
- Babonneau F, Vielle M, Haurie A, Loulou R (2012) Combining Stochastic Optimization and Monte-Carlo Simulation to Deal with Uncertainties in Climate Policy Assessment. *Environmental Modeling and Assessment*, 17(1):51–76 [25](#)

- Bernard A, Vielle M (2008) GEMINI-E3, A General Equilibrium Model of International National Interactions between Economy, Energy and the Environment. *Computational Management Science*, 5(3):173–206 [7](#)
- Bosello R, Cian E, Roson R (2007) Climate Change, Energy Demand and Market Power in a Computable General Equilibrium Model of the World Economy. Working paper 71.07, Fondazione Eni Enrico Mattei (FEEM) [3](#), [10](#), [19](#)
- Cian E, Lanzi E, Roson R (2007) The Impact of Temperature Change on Energy Demand: A Dynamic Panel Analysis. Fondazione Eni Enrico Mattei (FEEM), Working paper 46.07 [2](#)
- CIESIN and CIAT (2005) Gridded population of the world, version 3 (GPWv3). Technical report, Center for International Earth Information Network (CIESIN) and Centro Internacional de Agricultura Tropical (CIAT). Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University [6](#)
- Craig R (2011) Energy system impact. Technical report, FSU College of Law, Public Law Research Paper No. 503 [2](#)
- Department of Economic United Nations and Population Division Social Affairs (2011) World Population Prospects: The 2010 Revision. Technical report [11](#)
- Dimitropoulos J (2007) Energy productivity improvements and the rebound effect: An overview of the state of knowledge. *Energy Policy*, 35(12):6354–6363 [19](#)
- Dolarin M, Vidrih B, Kajfež-Bogataj L, Medved S (2010) Predicted changes in energy demands for heating and cooling due to climate change. *Physics and Chemistry of the Earth, Parts A/B/C*, 35(12):100–106 [2](#)
- Duerinck J, Renders N, Schoeters K (2008) Assessment and improvement of methodologies used for Greenhouse Gas projection. Vlaamse Instelling voor Technologisch Onderzoek [20](#)
- Ebinger J, Vergara W (2011) Climate Impacts on Energy Systems - Key Issues for Energy Sector Adaptation. The International Bank for Reconstruction and Development/The World Bank [2](#)
- Eboli F, Parrado R, Roson R (2010) Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, 5(15):515–533 [3](#), [10](#), [19](#)
- Eskeland G, Mideksa T (2010) Electricity demand in a changing climate. *Mitigation Adaptation Strategies for Global Change*, 5(15):877–897

- Fraedrich K, Jansen H, Kirk E, Luksch U, Lunkeit F (2005) The planet simulator: Towards a user friendly model. *Meteorologische Zeitschrift*, 14(3):299–304 [4](#)
- Ganguly D, Rasch P, Wang H, Yoon J (2012) Climate response of the South Asian monsoon system to anthropogenic aerosols. *Journal of Geophysical Research*, 117 [5](#)
- Haberl H, Erb K, Krausmann F, Bondeau A, Lauk C, Mller C, Plutzar C, Steinberger J (2011) Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, 35(12):4753–4769 [2](#)
- Hamududu B, Killingtveit A (2012) Assessing climate change impacts on global hydropower. *Energies*, 5:305–322 [2](#)
- Harrison J, Horridge M, Pearson K (2000) Decomposing Simulation Results with Respect to Exogenous Shocks. *Computational Economics*, 15:227–249 [20](#)
- Holden PB, Edwards NR (2010) Dimensionally reduced emulation of an aogcm for application to integrated assessment modelling. *Geophysical Research Letters*, 37(21): n/a–n/a [4](#)
- Holden PB, Edwards NR, Garthwaite PH, Fraedrich K, Lunkeit F, Kirk E, Labriet M, Kanudia A, Babonneau F (2013) PLASIM-ENTSem: a spatiotemporal emulator of future climate for impacts assessment. *Geoscientific Model Development Discussions*, 6:3349–3380 [4](#), [5](#), [6](#)
- IEA (2013) Energy Statistics for OECD and Non-OECD countries. Available via <http://data.iea.org>. [7](#)
- Isaac M, van Vuuren D (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 37(2):507–521 [2](#), [3](#), [15](#), [16](#)
- Labriet M, Kanudia A, Loulou R (2012) Climate mitigation under an uncertain technology future: A TIAM-World analysis. *Energy Economics*, 34, Supplement 3(0):S366–S377 [25](#)
- Lehner B, Czisch G, Vassolo S (2005) The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energy Policy*, 33(7):839–855 [2](#)
- Linnerud K, Mideksa T, Eskeland G (2011) The impact of climate change on nuclear power supply. *The Energy Journal*, 32:149–168 [2](#)
- Loulou R (2008) ETSAP-TIAM: the TIMES integrated assessment model Part II: mathematical formulation. *Computational Management Science*, 5:7–40 [6](#)
- Loulou R, Labriet M (2008) ETSAP-TIAM: the TIMES integrated assessment model Part I: Model Structure. *Computational Management Science*, 5:41–66 [6](#)

- McNeil M, Letschert V (2008) Future air conditioning energy consumption in developing countries and what can be done about it: The potential of efficiency in the residential sector. Technical report, Lawrence Berkeley National Laboratory [8](#)
- Mideksa T, Kallbekken S (2010) The impact of climate change on the electricity market: A review. *Energy Policy*, 38(7):3579–3585 [2](#)
- Mima S, Criqui P (2009) Assessment of the impacts under future climate change on the energy systems with the poles model. In: International Energy Workshop 17-19 June, 2009, Fondazione Giorgio Cini, Italy [2](#), [3](#), [15](#), [17](#)
- Narayanan B, Aguiar A, McDougall R (2012) Global Trade, Assistance, and Production: The GTAP 8 Data Base. Center for Global Trade Analysis, Purdue University, 2012. [7](#)
- Paltsev S (2001) The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage. *The Energy Journal*, 22(4):53–79 [19](#)
- Petrick S, Rehdanz K, Tol RSJ (2010) The impact of temperature changes on residential energy consumption. Kiel Working Paper No. 1618, Kiel Institute for the World Economy [2](#)
- Rübelke D, Vögele S (2011) Impacts of climate change on european critical infrastructures: The case of the power sector. *Environmental Science & Policy*, 14(1):53–63 [2](#)
- Schaeffer R, Szklo A, de Lucena A, Borba B, Nogueira L, Fleming F, Troccoli A, Harrison M, Boulahya M (2012) Energy sector vulnerability to climate change: A review. *Energy*, 38(1):1–12 [2](#)
- Schoenau G, Kehrig R (1990) Method for calculating degree-days to any base temperature. *Energy and Buildings*, 14(4):299–302 [6](#)
- Thomas B, Azevedo I (2013) Estimating direct and indirect rebound effects for U.S. households with input-output analysis Part 1: Theoretical framework. *Ecological Economics*, 86:199–210 [20](#)
- van Vuuren D, Edmonds D, Kainuma M, Riahi K, Thomson A, Hibbard D, Hurtt G, Kram T, Krey V, Lamarque J, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose S (2011) The representative concentration pathways: an overview. *Climatic Change*, 109:5–31 [12](#)
- van Vuuren D, Bayer L, Chuwah C, Ganzeveld L, Hazeleger W, Hurk B (2012) A comprehensive view on climate change: Coupling of earth system and integrated assessment models. *Environmental Research Letters*, 7(2):024012

- Wang X, Chen D, Ren Z (2010) Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment*, 45(7):1663–1682 [2](#)
- Ward I (2008) Will global warming reduce the carbon emissions of the Yorkshire Humber Region’s domestic building stock A scoping study. *Energy and Buildings*, 40(6):998–1003 [2](#)
- Warren R, de la Nava Santos S, Arnell NW, Bane M, Barker T, Barton C, Ford R, Fssel H-M, Hanking Robin KS, Klein R , Linstead C, Kohler J, Mitchell TD, Osborn TJ, Pan H, Raper SCB, Riley G, Schellnhber HJ, Winne S, Anderson D (2008) Development and illustrative outputs of the Community Integrated Assessment System (CIAS), a multi-institutional modular integrated assessment approach for modelling climate change. *Environmental Modelling & Software* 23(5):592-610
- Washida T (2004) Economy-wide model of rebound effect for environmental efficiency. In: *International Workshop on Sustainable Consumption*, University of Leeds [20](#)
- Wilbanks, TJ, Romero Lankao P, Bao M, Berkhout F, Cairncross S, Ceron J-P, Kapshe M, Muir-Wood R, Zapata-Marti R (2007a) Industry, settlement and society. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp 357–390. Cambridge University Press, Cambridge, UK [2](#)
- Wilbanks TJ, Bhatt V, Bilello DE, Bull SR, Ekmann J, Horak WC, Huang YJ, Levine MD, Sale MJ, Schmalzer DK, Scott MJ (2007b) *Effects of Climate Change on Energy Production and Use in the United States*. Department of Energy, Office of Biological & Environmental Research, Washington, DC., USA, 160 pp. [2](#)
- Williamson M, Lenton T, Shepherd J, Edwards NR (2006) An efficient numerical terrestrial scheme (ENTS) for earth system modelling. *Ecological Modelling*, 198(34):362–374 [4](#)