Impacts of climate change on heating and cooling: a worldwide estimate from energy and macro-economic perspectives

Maryse Labriet1, Santosh R. Joshi2, Amit Kanadia3, Neil R. Edwards4, and Philip B. Holden4

1Eneris Environment Energy Consultants, Madrid, Spain.
2REME, École Polytechnique Fédérale de Lausanne, Switzerland.
3KanORS-EMR, Noida, India.
4Environment, Earth and Ecosystems, Open University, Milton Keynes, UK.

Abstract

The energy sector is not only a major driving force of climate change, it is also vulnerable to future climate change. In this paper, we analyze the impacts of changes in future temperature on the heating and cooling services both in terms of global and regional energy impacts and macro-economic effects. For this purpose, the technico-economic TIMES-WORLD and the general equilibrium GEMINI-E3 model are coupled with a climate model, PLASIM-ENTS, to assess the regional and seasonal temperature changes and their consequences on the energy and economic systems. One of the main insight of the analysis is the absence of climate feedback induced by the adaptation of the energy system to future heating and cooling needs, since the latter represent a limited share of total final energy consumption and emissions, and the heating and cooling changes tend to compensate each other, at the global level. However, significant changes may be observed at regional levels, more particularly in terms of additional power capacity required to satisfy the new cooling demands. In terms of macro-economic impacts, welfare gains comes from the decrease of energy for heating and to welfare loss due to an increase of electricity for space cooling. For energy exporting countries welfare gain is

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reduced (or lost) due to losses of revenue coming from less energy export while for non-energy exporting countries welfare gains is linked to the decrease of energy needs for heating overcompensate the cost coming from the increase of electricity consumption.

**Keywords:** Climate change, Heating, Cooling, Adaptation, Energy system, Bottom-up model, Top-down model.

## 1 Introduction

Energy sector is not only a driver of climate change, given the large contribution of the sector to greenhouse gas emissions, it is also vulnerable to the effects of climate change. While the focus of interest until recently has mainly been on the emission mitigation of the energy sector rather than on the climate vulnerability and resilience of the sector, awareness of the implications of impacts and adaptation for energy is increasing (Ebinger and Vergara, 2011; CCSP, 2007; Schaeffer et al., 2012; Mideksa and Kallbekken, 2010). There are several possible impacts of climate change on the energy demand and production (i) changes in cooling efficiency of thermal and nuclear power generation, resulting in modified availability and efficiency of the plants (Linnerud et al., 2011; Rübbelke and Vögele, 2011); (ii) changes in the seasonal river flows and in their variability, affected hydropower potential and generation (Lehner et al., 2005; Hamududu and Killingtveit, 2010; Iimi, 2007); (iii) changes in productivity of crops for bio-energy (Haberl et al., 2011); (iv) changes in space heating and cooling requirements for buildings (Isaac and van Vuuren, 2009; Mima and Criqui, 2009); (v) vulnerability of energy-related infrastructure to extreme events and sea level rise (Craig, 2011).

Without surprise, several studies have shown the potential increase of cooling demands and decrease of heating demands given future climate change, although the range of changes will depend on the regional and seasonal temperatures (Dolinar et al., 2010; Frank, 2005; Christenson et al., 2006; Wang et al., 2010; Ward, 2008). Such changes may lead to different energy and emission patterns, which may result in a feedback between the climate and the energy system. Since two opposite effects may happen (decrease of heating and increase of cooling), the net balance in energy use might be positive or negative depending on regional climatic conditions (Isaac and van Vuuren, 2009). However, since these changes usually occurring at different seasons, an annual compensation of the increase of cooling by a decrease of heating will not avoid the possibility of new peaks of demands during the warm seasons. In terms of emission balance, the net im-
The energy and economic implications of changes in heating and cooling dynamics in the context of climate change using an emulated version of the climate model PLASIM-ENTS, coupled with the TIAM-WORLD techno-economic model TIAM-WORLD and the general equilibrium model GEMINI-E3. Next section presents the three models used in the exercise, as well as how energy demands for heating and cooling are estimated, taking into account future climate changes.

2 Methodological Framework

2.1 Climate model: PLASIM-ENTS

One of the principal obstacles to coupling complex climate models to impacts models is their high computational expense. 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 used in this application is PLASIM-ENTS, the Planet Simulator (Fraedrich et al., 2005) coupled to the ENTS land surface model (Williamson et al., 2006). The resulting model has a 3D dynamic atmosphere, flux-corrected slab ocean and slab sea ice, and dynamic coupled vegetation. The slab sea ice is held fixed in these simulations. The model is run at T21 resolution (around 5°).

The PLASIM-ENTS simulations as well as its emulations generally compare favourably with the AR4 predictions (Figure 1). One significant shortcoming is the understated DJF warming in the Arctic, a consequence of the neglect of the sea-ice feedback in these PLASIM-ENTS simulations. Although caution will be required, the error dominantly affects temperatures in sparsely-populated high-northern latitudes and so may not be problematic for large-scale human impact studies. Sea-ice feedback will be introduced into the ensemble for the next generation emulator. The emulator clearly performs very well in capturing the spatial variability and magnitude of the warming. These comparisons illustrate that any errors introduced by the emulation of temperature are unlikely to be significant compared to the errors in the simulator itself.
The climate data required for the assessment of heating and cooling changes due to climate changes are Heating Degree Days (HDDs) and Cooling Degree Days. HDDs provide a measure that reflects heating energy demands, calculated relative to some baseline temperature: on a given day, the average temperature is calculated and subtracted from the baseline temperature; if the value is less than or equal to zero, then that day has zero HDDs (no heating requirements); if the value is positive, then that number 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 a climate model can output degree-days explicitly, calculated from the day-to-day temperature variability, such an approach 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 but instead derived from emulations of average temperature and daily variability, as defined by the standard deviation of the daily temperature across the season, following the approach of Schoenau and Kehrig (1990). The assumption made is that daily temperatures are scattered about the monthly mean with a normal distribution.

Seasonal HDDs and CDDs are computed at each PLASIM-ENTS cell from:

\[
\text{HDD} = \frac{N}{\sigma \sqrt{2\pi}} \int_{-\infty}^{B_H} (B_H - T) e^{-\frac{(T-\mu)^2}{2\sigma^2}} dT
\]

\[
\text{CDD} = \frac{N}{\sigma \sqrt{2\pi}} \int_{B_C}^{\infty} (T - B_C) e^{-\frac{(T-\mu)^2}{2\sigma^2}} dT
\]

where, \( N \) = number of days in the season, \( T \) = daily temperature, \( B_H \) = HDD baseline temperature, \( B_C \) = CDD baseline temperature, \( \mu \) = average daily temperature across the season, \( \sigma \) = standard deviation of daily temperature across the season. For the current analysis, \( B_H = B_C = 18^\circ C \) is applied globally.

HDDs and CDDs are calculated at each of the 64x32=2048 GENIE gridcells. In order to convert these onto TIAM 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. We note that moving to the lower resolution inevitably leads to approximations, most notably when highly populated regions near ocean find themselves in grid cells which are assigned to be ocean in PLASIM-ENTS, so that the coastal grid cells are likely to be under-represented in the population weighted average.
2.2 Cooling and heating services

In the case without considering future climate change, 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 countries, but consider the same temperature (HDD and CDD) as in the base year. Cooling deserves an additional comment. Indeed, cooling demands depend on CDD but also on socio-economic factors influencing the diffusion (purchase) of air-conditioning systems, which is usually described as an S-shaped curve function of the level of income: penetration of air conditioners used to start climbing steeply at a mensual income per household of about US$3300 (McNeil and Letschert, 2008). Following the methodology and numerical assumptions proposed by the authors, including a saturation effect guided by the level of penetration of air-conditioners in the USA for a given CDD value, the demands for cooling services of TIAM-WORLD were adjusted, given the GDP and POP assumptions and constant climate conditions as provided by PLASIM-ENTS in 2005. The availability rate, defined as the share of population equipped with air-conditioning compared to the population who need air-conditioning, reaches it maximum in all regions by 2050, except in Africa, Central Asia and Caucase, Other Easter Europe and Indonesia, given GDP assumptions. More important, the climate factor influencing the purchase of air-conditioning (without considering socio-economic constraints) already reaches its maximal value when considering CDD as observed 2005 for all countries but Canada, Europe, Japan, Other Eastern Europe, Russia and South Korea. The consequence is that future increase of CDD would possibly raise the purchase of air-conditioners only in the countries above (which are also the coldest countries), not in the others (which are the warmest ones), where the dominating factor of air-conditioner purchase is the level of income. In other words, future increase of CDD could accelerate the purchase of air-conditioners only in the coldest countries; this effect is not considered in this study, the impacts on energy would remain limited since CDD remain low. At the opposite, in the warmest countries, future increase of CDD would have an impact on the use of air-conditioners, not on the purchase dynamics.

This analysis supports the approach to compute the changes in heating and cooling demands in the case with climate change: 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 is given by:

\[ EDH_{t,r}^{cc} = \frac{HDD_{t,r}}{HDD_B} \cdot EDH_{t,r} \]  

(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 2000 for GEMINI-E3 and 2005 for TIAM-WORLD.

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

\[ EDC_{t,r}^{cc} = \frac{CDD_{t,r}}{CDD_B} \cdot EDC_{t,r} \]  

(4)

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

The analysis of the possible feedback between the energy and the climate systems shows that such a retroaction can be neglected in the case of the impacts of heating and cooling changes. In other words, the changes of heating and cooling won’t contribute to additional changes in the future climate, and the one-time adjustment of the demands as proposed above reflects in a relevant manner the future changes of heating and cooling.

Three groups of regions can be identified, based on the HDD and CDD dynamics (Figures 1 and 2):

- colder regions, characterized by high levels of HDD and where the main expected impact of climate change is a reduction of HDD (Russia, Canada);
- warmer countries characterized by high levels of CDD and where the main expected impact of climate change is an increase of CDD (India, Other Developing India, Middle East, Africa, Central and South America, Mexico, Australia);
- 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, Japan, USA, Caucasus and Central Asia).

Sections 3 and 4 provide more details on how heating and cooling services are modified in each model.

### 2.3 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). It computes
Figure 1: Spatial patterns of warming over the next century. Left hand panels are DJF (December-January-February) and the right hand panels are JJA (June-July-August). Three ensembles are compared: top) AR4 multi-model ensemble with SRES A1B forcing, centre) PLASIM-ENTS simulated ensemble with RCP4.5 forcing and bottom) PLASIM-ENTS emulated ensemble with RCP4.5 forcing.
Figure 2: HDD and CDD corresponding to a long-term global average temperature increase of 3.3°C - For each region, each column represents HDD and CDD for 2010, 2020, 2030, ... until 2100.
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. The model is set-up to explore the development of the World energy system until 2100.

The model contains explicit detailed descriptions of more than 1500 technologies and several hundreds of energy, emission and demand flows in each region, logically interconnected to form a Reference Energy System. Such technological detail allows precise tracking of optimal capital turnover and provides a precise description of technology and fuel competition.

TIAM-World is driven by demands for energy services in each sector of the economy, which are specified by the user for the Reference scenario, and have each an own price elasticity. Each demand may vary endogenously in alternate scenarios, in response to endogenous price changes. Although the model does not include macroeconomic variables beyond the energy sector, there is evidence that accounting for price elasticity of demands captures a preponderant part of feedback effects from the economy to the energy system (Bataille, 2005; Labriet et al., 2012).

TIAM-World integrates a climate module permitting the computation and modeling of global changes related to greenhouse gas concentrations, radiative forcing and temperature increase, resulting from the greenhouse gas emissions endogenously computed (Loulou et al., 2009).

In the recent years, TIAM-WORLD has been used to assess the assessment of future climate and energy strategies at global and region levels in full or partial climate agreements and uncertain contexts (Loulou et al., 2009; Labriet and Loulou, 2008; Loulou et al., 2012).

Although TIAM-WORLD, as any integrated assessment model, can be run in a standalone manner with global climate constraints (temperature, radiative forcing, greenhouse gas concentration), the climate module of TIAM-WORLD does not compute the regional nor seasonal temperature changes as needed 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 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 tends 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 usual in climate modeling.

In essence, there is an iterative exchange of data between the two models, whereby TIAM-WORLD sends to the climate emulator a set 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 in seasonal heating and cooling degree-days for each of the regions of the model. These seasonal and regional degree-days are used to compute new seasonal and regional heating and cooling demands in TIAM-WORLD.

2.4 General Equilibrium model: GEMINI-E3

GEMINI-E3 (Bernard and Vielle, 2008)\(^1\) is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the other CGE models (EPPA, ENV-Linkage, etc) built and implemented by other modeling teams and institutions, and sharing the same long experience in the design of this class of economic models. The standard 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 then endogenous), 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 (Badri Narayanan et al., 2012). This database incorporates a consistent representation of energy markets in physical units, social accounting matrices for each individualized country/region, and the whole set of bilateral trade flows. Additional statistical information accrues from OECD national accounts, IEA energy balances and energy prices/taxes and IMF Statistics (Government budget for non OECD countries). Carbon emissions are computed on the basis of fossil fuel energy consumption in physical units. For the modeling of non-CO\(_2\) greenhouse gases emissions (CH\(_4\), N\(_2\)O and F-gases), we employ region- and sector-specific marginal abatement cost curves and emission projections provided by the US-EPA (U.S. Environmental Protection Agency, 2011, 2012). GEMINI-E3 describes now 24 sectors. Table 1 gives the definition of the classifications used.

\(^{1}\)All information about the model can be found at \url{http://gemini-e3.epfl.ch}, including its complete description.
Table 1: Dimensions of the GEMINI-E3 model

<table>
<thead>
<tr>
<th>Regions</th>
<th>Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States of America</td>
<td>USA 01 Coal</td>
</tr>
<tr>
<td>Canada</td>
<td>CAN 02 Crude Oil</td>
</tr>
<tr>
<td>Australia &amp; New Zealand*</td>
<td>AUZ 03 Natural Gas</td>
</tr>
<tr>
<td>Eastern European Countries</td>
<td>EEU 04 Refined Petroleum</td>
</tr>
<tr>
<td>Western European Countries</td>
<td>WEU 05 Electricity</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>FSU Non-Energy</td>
</tr>
<tr>
<td>China</td>
<td>CHI 06 Forestry</td>
</tr>
<tr>
<td>India</td>
<td>IND 07 Mineral Products</td>
</tr>
<tr>
<td>Rest of Eastern Asia</td>
<td>REA 08 Chemical, rubber, Plastic</td>
</tr>
<tr>
<td>Rest of Southern Asia</td>
<td>RSA 09 Metal and Metal products</td>
</tr>
<tr>
<td>South East Asia</td>
<td>SEA 10 Paper products publishing</td>
</tr>
<tr>
<td>Middle East</td>
<td>MID 11 Transport nec</td>
</tr>
<tr>
<td>Latin America</td>
<td>LAT 12 Sea Transport</td>
</tr>
<tr>
<td>Africa</td>
<td>AFR 13 Air Transport</td>
</tr>
<tr>
<td>Primary Factors</td>
<td>15 Machinery and Equipment goods</td>
</tr>
<tr>
<td>Labor</td>
<td>16 Services</td>
</tr>
<tr>
<td>Capital</td>
<td>17 Dwellings</td>
</tr>
<tr>
<td>Energy resource (sectors 01-03)</td>
<td>18 Construction</td>
</tr>
<tr>
<td>Land (sectors 20-24)</td>
<td>19 Water</td>
</tr>
<tr>
<td>Other inputs</td>
<td>20 Paddy rice</td>
</tr>
<tr>
<td></td>
<td>21 Wheat</td>
</tr>
<tr>
<td></td>
<td>22 Cereals</td>
</tr>
<tr>
<td></td>
<td>23 Oilseeds</td>
</tr>
<tr>
<td></td>
<td>24 Rest of agriculture sectors</td>
</tr>
</tbody>
</table>

* The region Australia and New Zealand also includes Oceanic countries.

2.4.1 Household energy demand

In the standard version of GEMINI-E3 (Bernard and Vielle, 2008) the households consumption is derived from an utility function based on a Stone-Geary (Stone, 1983) (called also a Linear Expenditure System (LES)). We have replaced this functional form by a nested CES utility function, that allows us to describe more precisely the household energy consumption. Figure 3 shows the nested CES structure now used in GEMINI-E3.

We have split energy consumption in two parts:

- those used for transportation purposes,
- and the other consumed for residential purposes (heating, cooling, cooking, lighting,...).

In each nest, energy can be substituted by a capital good representing in the first case cars and in the second one shelters.

2.4.2 Baseline scenario

Baseline scenarios in GEMINI-E3 models are built from i) forecasts or assumptions on population and economic growth in the various countries/regions, ii) prices of energy in world markets, in particular the oil price and iii) national (energy) policies. We have
used UN median variant to forecast population, the data from International Energy Outlook 2011 (Energy Information Administration, 2011) and TIAM-WORLD is used to forecast GDP growth, and prices of energy\(^2\) are taken from TIAM-WORLD. We build a reference baseline for the period 2007-2100 with yearly time-steps. Our reference baseline is closely related to RCP 6 and baseline climate year is 2000.

Figure 4 summarizes the methodology used to analyse the impacts on the energy sector.

3 Impacts on the energy system

3.1 Assumptions related to future temperature increases

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

\(^2\)Supply prices on oil, coal and natural gas.
system? Second, what are the possible feedbacks on the climate system of the changes observed in the energy system?

Given the endogenous detailed representation of the energy system, including heating and cooling in both residential and commercial sectors of TIAM-WORLD, the modeling of several future temperature trajectories contributes to the better understanding of the changes in both total and specific energy consumed for heating and cooling, endogenously assessed by the model, as well as the possible consequences on other sectors such as power generation, expected to increase to satisfy electricity demands for cooling.

For this purpose, a series of 14 scenarios was built and modeled, representing a range of long-term global mean temperature increase from 1.6 to 5.6°C (Figure 5). The long term temperature increase of the Reference case of TIAM-WORLD is 3.3°C, corresponding to HDD and CDD as illustrated in figure 2.

It is important to remind that no mitigation climate strategies are assessed in the current exercise and 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 changes would represent spontaneous adaptation reactions by households and companies when facing variable local temperatures.
Figure 5: Range of global mean temperature increase over pre-industrial period used to assess the impacts of climate change on heating/cooling.

Notation: In all figures, CCx.x corresponds to a scenarios with a long term mean temperature increase of x.x °C at the global level. Regional temperature increases may be different and are computed by PLASIM-ENTs and used to assess the changes in regional heating and cooling.

3.2 Global impacts and climate feedback

3.2.1 Climate feedback

The main result is that climate appears to be independent from 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 temperature increase (Figure 6. 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, neither at the global level nor at regional levels (next section). The characteristics of the global energy system and its changes under heating and cooling adaptation to climate change explain this result.
3.2.2 Heating and cooling in the total energy balance

First, the share of heating and cooling energy consumption is small at the global level compared to the total energy consumption of the system (less than 12%, Figure 7). The decrease of this share in the case where impacts of climate change are not considered reflects both the socio-economic drivers of the demands for energy services and the technology choices: demands for other energy services (other residential and commercial uses and other sectors) increase more than heating and cooling services, and more efficient technologies penetrate in the heating and cooling subsectors; more particularly, coal/oil heating systems are substituted by more efficient gas/electricity technologies. The difference with the shares observed in the case where impacts of climate change are considered illustrates the net decrease of energy consumed for heating/cooling at the global level due to future climate change. More severe long term increase of temperature does not affect the shares of heating and cooling in total final energy consumption (Figure 7).

3.2.3 Respective contributions of heating and cooling adaptation

Additional to the low share of heating and cooling in total energy consumption, changes in global energy consumption remain at levels of less than 1% (Figure 8) because the
It is interesting to notice that increased future global temperature translates in lower energy consumption for heating and cooling only in the mid-term (Figure 9): when aggregated in total final energy consumption, changes due to decreased heating dominates over the increased cooling in the intermediate time horizon. In the longer term, the increase of cooling dominates over the decrease of heating, resulting in total energy for heating and cooling very close to the case with a lower future temperature increase.

### 3.2.4 Fuel perspective

Figures 10, 11 and 12 illustrate the impacts of climate change on the different energy commodities consumed for heating (various energy commodities) and cooling (electricity) purpose. While the consumption of all energy commodities is reduced given the decrease of heating needs (with gas dominating the fuels consumed for heating purposes), electricity consumption is strongly dominated by the increase in cooling needs.

This additional demand for electricity is supplied mostly by coal and gas power plants (Figure 13), 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).
Figure 8: Total final energy with and without climate change impacts

Figure 9: Global energy consumption for cooling and heating with and without climate change impacts
case, +0.3 GW in the Reference case with 3.3°C).

![Final Energy Consumption - Heating](image)

**Figure 10:** Impacts of climate change on fuels used for heating at World level

### 3.2.5 Emission perspective

Although the changes in heating and cooling don’t affect the climate, it is interesting to observe the changes at the sector level, which could have consequences on mitigation policies. Indeed, while emissions from buildings decrease (up to -1.2 GtCO₂ in 2100 the worst temperature case) thanks to the reduction of heating, the increased demand for cooling translates in an increase of emissions of up to in the power sector, given the additional coal and gas installed capacities (up to +3.7 GtCO₂ in 2100 in the worst temperature case). The net balance is positive (up to +2.5 GtCO₂ in 2100). The climate system remains insensitive to these additional emissions, as mentioned above, given both their small magnitude and late occurrence.
Figure 11: Impacts of climate change on fuels used for cooling at World level

Figure 12: Impacts of climate change on fuels used for heating at World level
Figure 13: Impacts of climate change on electricity production at World level

Figure 14: Impacts of climate change on sector CO₂ emissions by sector at World level
Figure 15: Variation of CO₂ emissions in power and residential/commercial sectors over the scenario without climate change impacts

3.3 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, Russia with a cold climate and a high energy budget allocated to heating and cooling, and Europe and China, characterized by an intermediate climate and moderate to high energy budget allocated to heating and cooling (Figure 2, Table 2).

Table 2: Share of heating and cooling in total final energy consumption

<table>
<thead>
<tr>
<th>Range over 2005-2100 for long-term temperature increase from 1.6 to 5.6°C</th>
<th>0.4% to 4%</th>
<th>14% to 24%</th>
<th>15% to 19%</th>
<th>4% to 13%</th>
</tr>
</thead>
</table>

Adaptation of the heating and cooling services to future changes in temperature translates in dominating increase of energy for cooling in India, dominating decrease of energy for heating in Russia but also in China, where energy changes in heating are stronger than in cooling, while changes in heating and cooling result as compensating each other in Europe, when considering total energy uses (Figure 16). Of course, usual energy system dynamics also occur, on top of the climate effects. For example, the decrease of energy use observed in Europe between 2005 and 2020 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 understanding the magnitude of the positive effects of climate change on the use of fossil fuels and biomass for heating purpose in the four countries but India, where heating plays a negligible role in energy consumption, and at the contrary, the possible pressure of cooling on electricity generation in India, China as well as Europe (Figures 17 and 18). Not surprisingly, without any emission mitigation constraints, coal power plants appear to be the most cost-efficient option, resulting in moderate increase of CO$_2$ emissions of India and Europe in the 3.3°C temperature case (up to 4% - but up to 10% in the worst temperature case). At the opposite, a slight decrease of emissions in Russia may be observed (up to -3.5%).

Figure 16: Total final energy consumed for heating and cooling with and without climate change impacts in India, Russia, Europe and China

The seasonal impacts of climate change, more particularly on the generation, peak management and price of electricity (and possible gas) deserves more analyses. The results and main insights will be added in the coming updated version of the manuscript, taking into account also the impacts of temperature increase on the efficiency and availability of thermal power plants.
Figure 17: Impacts of climate change on specific energy commodities consumed for heating and cooling in India, Russia, Europe and China
Figure 18: Impacts of climate change on electricity supply in India, Russia, Europe and China
4 Macroeconomic impacts

4.1 Incorporating energy demand changes in general equilibrium model

In GEMINI-E3, for households we describe only total energy consumption without describing the different purposes (heating, cooling, cooking, lighting, etc. see section 2.4.1), following the nested CES functions represented in Figure 3. Total energy consumption for residential needs ($HCRES_{r}$) is given by:

$$ HCRES_{r} = HCRES_{r} \cdot \lambda_{r}^{hres} \cdot \alpha_{r}^{hres} \cdot \left[ \frac{PHCRES_{r}}{PHCRESE_{r} \cdot \lambda_{r}^{hres}} \right]^{\sigma_{r}^{hres}}, \quad (5) $$

where $HCRES_{r}$ represents household consumption for residential purposes (i.e. expenses related to the shelter and the energy), $PHCRES_{r}$ and $PHCRESE_{r}$ are respectively the price of residential consumption and the aggregated energy price used for residential purposes (heating, cooling, cooking,...). $\sigma_{r}^{hres}$, $\alpha_{r}^{hres}$ and $\lambda_{r}^{hres}$ represent the CES parameters, respectively the elasticity of substitution, the share parameter and the technology shifter. Total energy is split between coal, refined oil, natural gas and electricity distinguished by GEMINI-E3 with the following CES functions:

$$ HCRES_{r} = HCRES_{r} \cdot \lambda_{r}^{hres} \cdot \alpha_{r}^{hres} \cdot \left[ \frac{PHCRES_{r}}{PHCRESE_{r} \cdot \lambda_{r}^{hres}} \right]^{\sigma_{r}^{hres}}, \quad (5) $$

where $HCRES_{r}$ represents household consumption for residential purposes (i.e. expenses related to the shelter and the energy), $PHCRES_{r}$ and $PHCRESE_{r}$ are respectively the price of residential consumption and the aggregated energy price used for residential purposes (heating, cooling, cooking,...). $\sigma_{r}^{hres}$, $\alpha_{r}^{hres}$ and $\lambda_{r}^{hres}$ represent the CES parameters, respectively the elasticity of substitution, the share parameter and the technology shifter. Total energy is split between coal, refined oil, natural gas and electricity distinguished by GEMINI-E3 with the following CES functions:

$$ HCRESF_{r} = HCRES_{r} \cdot \lambda_{r}^{hres} \cdot \alpha_{r}^{hres} \cdot \left[ \frac{PHCRES_{r}}{PHCRESE_{r} \cdot \lambda_{r}^{hres}} \right]^{\sigma_{r}^{hres}}, \quad (5) $$

Where $HCRESF_{r}$ represents total fossil energy consumption for residential purpose, $PHCRESEF_{r}$ the price of this energy and $\theta_{r}^{hres}$ a technical progress associated to this fossil energy. Electricity consumption by households is given by:

$$ H_{05,r} \cdot \lambda_{r}^{hres} \cdot \alpha_{r}^{hres} \cdot \left[ \frac{PHCRES_{r}}{PHCRESE_{r} \cdot \lambda_{r}^{hres} \cdot \lambda_{r}^{hres} \cdot \lambda_{r}^{hres} \cdot \lambda_{r}^{hres}} \right]^{\sigma_{r}^{hres}}, \quad (5) $$

and fossil energies (where $i=01,02,03,04$) consumed for residential purpose are computed by the following equation:

$$ H_{i,r} = HCRESF_{r} \cdot \lambda_{r}^{hres} \cdot \alpha_{i,r}^{hres} \cdot \left[ \frac{PHCRESF_{r}}{PHCRESEF_{r} \cdot \lambda_{r}^{hres} \cdot \lambda_{r}^{hres}} \right]^{\sigma_{i,r}^{hres}}, \quad (5) $$

The impacts of climate change on heating and cooling demands are computed through the HDD and CDD indicators. They are used to modify the parameters $\theta_{05,r}$ and $\theta_{r}^{hres}$. We assume that the decrease of energy needs for heating coming from the decrease of
HDDs can be considered as an increase of the technical progress associated to this consumption. The same hypothesis is applied for cooling but in this case we decrease the technical progress. As GEMINI-E3 does not distinguish within the energy consumption for residential between the different uses, we consider the budget shares (in monetary unit) of heating and cooling coming from the TIAM-WORLD model for each period and for the baseline. In the scenarios, we modify the technical progress by using the following equations:

\[
\theta_{05,r}^t = \frac{\theta_{05,r}}{1 + \beta_{heating}^{05,t,r} \left( \frac{HDD_t,r}{HDD_{2000},r} - 1 \right) + \beta_{cooling}^{05,t,r} \left( \frac{CDD_t,r}{CDD_{2000},r} - 1 \right)}
\]

\[
\theta_{hresef,r}^t = \frac{\theta_{hresef,r}}{1 + \beta_{heating}^{hresef,t,r} \left( \frac{HDD_t,r}{HDD_{2000},r} - 1 \right) + \beta_{cooling}^{hresef,t,r} \left( \frac{CDD_t,r}{CDD_{2000},r} - 1 \right)}
\]

Where \(\beta_{heating}^{05,t,r}\) (\(\beta_{cooling}^{05,t,r}\)) represent the share of electricity used for heating (for cooling) in the total electricity consumption for household, and \(\beta_{heating}^{hresef,t,r}\) (\(\beta_{cooling}^{hresef,t,r}\)) represent the share of fossil energy used for heating (for cooling) in the total fossil energy consumption for household. \(\theta_{hresef,r}\) and \(\theta_{05,r}\) are the technical progresses used in the reference case. These budget shares are presented in Figures 19 and 20. The budget shares are computed in value from TIAM-WORLD figures and are equal to expenses in energy heating (i.e. quantity \(\times\) price) divided by total expenses of households in energy including residential and transportation purposes. The final impact of climate change on energy consumption will depend of course of the respective shares on heating and cooling coming from TIAM-WORLD and the changes in the HDDs and CDDs.

We apply a same methodology for heating and cooling in commercial activities. In this case we modify the technical progress associated with the services sector represented in GEMINI-E3.

### 4.2 Results and Analysis

We run 3 scenarios related to the impacts of climate change on the energy demands:

- in the first one, we analyse the decrease in the heating energy consumption,
- in the second one, we study the increase of cooling energy consumption,
- in the final one, we simulate the both effects.

For each simulation we present the results for the year 2100.
Figure 19: Budget share of heating energy consumption on total energy consumption in percentage (left axis) and HDD (right axis) in 2010

Figure 20: Budget share of cooling electricity consumption on total electricity consumption in percentage (left axis) and CDD (right axis) in 2010
4.2.1 Decrease in the heating energy consumption

Figure 21 shows the changes of the HDDs in 2100 and the variations of household total fossil energy consumption. The regions with the highest space heating energy demands (refer to the budget shares represented in Figure 19) are European countries, Former Soviet Union, China and north American countries. For these regions, energy demand for space heating declines within a range of 10% to 30% in 2100, resulting in significant energy savings. Nevertheless even if the decreases of energy consumption for space heating are significant, the impacts on fossil energy consumption of households (including energy used for private transportation) are rather limited and never higher than 5.5% (see China). At the global level, the decrease of consumption in fossil energy by households is equal to 2.6%. Analyses done with TIAM-WORLD coupled with PLASIM-ENTS reaches similar conclusions in longer terms, and even in cases where the future climate changes are increased.

It is also interesting to note that the ex-post decrease of heating energy computed by GEMINI-E3 is always less important than the ex-ante change introduced in the model. For example, for the USA we implement an ex-ante change of fossil energy equal to 8.2\%\footnote{the ex-ante change is equal with our notation to: $1 - \frac{1}{1 + \beta_{h,ref,usa} \left( \frac{HDD_{usa,2000}}{HDD_{usa,2000} - 1} \right)}$, but the ex-post variation computed by GEMINI-E3 is about 5.3%. This difference stems from a rebound effect, which is well-documented in the economic literature (Dimitropoulos, 2007) explaining that when the cost of energy services is decreasing (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 ex-ante fall.}

Of course the impact is much less important on energy consumption at the national level even if we take into account the decrease of heating by the commercial activities. Figure 22 shows that the most affected regions are the Eastern European countries where the decrease of heating demand induces a fall of total energy consumption by 2.1%.

The decrease of the energy needs for heating creates of welfare gain which are of course correlated to decrease of the energy consumption (see Figure 22). For regions that are energy exporting countries this welfare gain is reduced by losses of revenue coming from less energy exports. This is the case of Middle East countries, Former Soviet Union, Africa and Canada. Two regions experience a welfare loss, Middle East and Africa. In these regions the need of space heating is rather limited and therefore the benefit from a reduced demand of space heating can not offset the loss of energy
Figure 21: Variation in household fossil energy in % (left axis) and HDDs change in % (right axis) in 2100 - Scenario: impact of CC on heating demand

exports, in contrary for example to other energy exporting regions like Former Soviet Union.

4.2.2 Increase in the cooling energy consumption

In this scenario we increase the energy demand for space cooling by changing the technical progress associated to electricity consumption for household consumption and the services sector. Figure 23 gives the impacts of the climate change on total electricity consumption and the changes in CDDs. For regions where the level of CDDs is significant (i.e. India, South Asia, Middle East, Latin America and Africa), the need for space cooling increases within a range of 10% to 30% in 2100. The final impact on electricity consumption is explained by three factors:

- the initial level of the CDDs (i.e. without climate change),
- the diffusion and use of coolers linked to socio-economic factors (McNeil and Letschert, 2008),
- the impact of the climate change on the CDDs.

The two first factors are represented in GEMINI-E3 by the parameter $\beta^{cooling}_{05.1r}$ which is calibrated from the TIAM-WORLD Model. The last one is computed from PLASIM-
The increase of total electricity consumption remains moderate, at the global level. Total electricity (of all sectors) demand increases by 1.2% in 2100, the highest increase is equal to 2.7% in USA.

The increase in electricity consumption for cooling purpose has detrimental effects on the economy but at seemingly low levels. The welfare impact expressed in percentage of household consumption is always below 0.08%. Figure 24 shows these regional welfare costs.

4.2.3 Impact of climate change on energy consumption

We combine in this scenario the decrease of energy for space heating needs and the increase of electricity for cooling buildings. Figure 25 presents the impacts on fossil energy consumption, electricity consumption and CO$_2$ emissions. This figure shows that although the variation in percentage of electricity is generally greater than the percentage change in the consumption of fossil fuels, the final impact is a reduction in CO$_2$ emissions, except for Latin America and India, where the increase of electricity induces an increase in CO$_2$ emissions by the electricity sector. However the impact on CO$_2$ emissions is low, and never higher than a decrease of 2.0%, at the global level CO$_2$
Figure 23: Variation in electricity consumption of all sectors in % (left axis) and CDDs change in % (right axis) in 2100 - Scenario: impact of CC on cooling demand

Figure 24: Welfare changes in % of household consumption in 2100 - Scenario: impact of CC on cooling demand
emissions decreases by 0.6% in 2100. Analysis done with TIAM-WORLD coupled with PLASIM-ENTS confirms that the global feedback between the energy and the climate systems due to changes in heating and cooling remains very small even in 2100 (less than 1% increase of global emissions), even if changes at national levels are not small in some cases.

The welfare impacts are presented in Figure 26. They are equal to the sum of the welfare gains coming from the decrease of energy for heating (except for energy exporting countries which experiences loss of exports revenue see section 4.2.1) and to the welfare losses due to an increase of electricity for space cooling. For non energy exporting countries, the welfare gains linked to the decrease of energy needs for heating overcompensate the cost coming from the increase of electricity consumption.

![Figure 25: Variation in fossil energy consumption, electricity consumption and CO2 emissions in %- Scenario: impact of CC on heating and cooling combined](image)

5 Conclusion

Adaptation to future climate change includes changes in heating and cooling, being on an autonomous or planned basis. The analysis, based on the coupling of a climate model with a techno-economic energy model and a general equilibrium model, confirms that the impacts on the energy system may be large at the regional levels, with decrease of energy uses (mostly fossil fuels and biomass) for heating, and increase of electricity for
cooling depending of course on the regions. The impacts on electricity generation may reach up to several GW in some regions, often supplied by coal, resulting in additional greenhouse emissions. However, the climate feedback is negligible, given the small share of heating and cooling in total final energy use and also the balancing, at the global level, of the increased emissions from the additional electricity supply by the decrease of emissions by associated to space heating. (Range of % of changes in energy uses for heating and cooling should be used carefully, and therefore are not provided as main insights; they could indeed give wrong signals, since they may hide may small absolute numbers and therefore not be significant).

At the macro-economic level, welfare gains and losses are observed, associated to changes in energy consumption as well as in energy trade dynamics. They remain however small.

Several other impacts of climate change on the energy system are being implemented in the models, to be combined with the heating and cooling effects: the impacts of temperature increase on the efficiency and availability of thermal plants, on the bioenergy availability and price and on the hydroelectricity potentials. The impacts on electricity prices and peak management will deserve more attention once the different possible effects of climate change will be combined in the models. Extreme events and vulnerability of other energy resources are be covered by this study.
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