Modeling the Impacts of Climate Change on the Energy Sector: a Swiss perspective[*]

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Abstract

When speaking of energy production and consumption in the context of climate change, the interest usually lies in mitigation policies and measures, i.e. the energy system is seen as an emitter of greenhouse gases. This paper takes a different approach and analyzes the impacts of climate change on the Swiss energy system. We study the impacts of a changing climate on both the energy demand and supply. For the former impacts, it is predicted that higher temperatures will modify future heating and cooling demands in opposite directions. As for the supply side, changes in precipitation will affect hydro generation whereas higher temperature will impact cooling facilities and energy efficiency of thermal power plants. To undertake the analysis, we use a Computable General Equilibrium model, the GEMINI-E3 which is a standard CGE model based on the GTAP database. In the first, methodological part of the paper, we present how to integrate within the GEMINI-E3 information related to temperature and precipitation. Future changes in these climate variables are obtained from four couplings of global and regional climate models realized in

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the framework of the European project ENSEMBLES. This project has produced regional climate scenarios at European level for impacts assessments using the high resolution RCM ensemble system and downscaling methods. This information is generally available for the period 1961-2100 at a grid resolution of 25 x 25 km. Based on these simulation data, we show how to derive impacts via econometrically estimated functions and how to construct aggregated indicators, such as cooling and heating degree-days, that are then used as exogenous variables within the GEMINI-E3 model. After the methodological part, we present different scenarios without and with climate change and compare their outcomes for the energy demand and supply at the 2050 time horizon. Whereas detrimental impacts on the supply side seem to remain limited in 2050, partly because of adaptation, we clearly find strong macroeconomic impacts through changes in energy demand for cooling and heating purposes. Furthermore, we show that the reduced energy demand for heating has positive impacts for the Swiss economy that largely outweigh the negative ones created by the increased energy demand for cooling. These results are intimately linked to the Swiss context, where the need for heating is much higher than the need for cooling. The net impact is all the more positive that fossil fuels, which are the main energy source for heating, are entirely imported.

Keywords : Integrated Assessment of climate change, Western Europe

1 Introduction

With the certainty that some amount of climatic warming will occur, the focus in climate change policy has moved gradually from mitigation to impact assessment and adaptation issues. Our research topic is in line with this evolution since our aim is to estimate the impact of climate change on the Swiss energy sector. This sector is expected to be one of the Swiss sectors most at risk from climate change along with the agriculture, tourism, water distribution, health, insurances, and infrastructures sectors (OcCC and ProClim, 2007). Several studies have already analyzed the potential impacts of climate change on the Swiss energy demand (Frank, 2005; Christenson et al., 2006; Aebischer et al., 2007), and their results show that a warming climate could reduce the energy demand for heating, while at the same time also increase the energy demand for cooling. Extensive studies about the effects of climate change on hydropower production in the Swiss Alps have been conducted (Schaefli et al., 2007; Piot, 2005; Horton et al., 2006). One important finding was that the effect of increased evapotranspiration due to higher temperatures outweighs the effect of glacier melting. The expected reduction in runoff varies between 5% and 15% for the different basins. On average, model results show a 7% decrease in runoff for the years 2020-2049.

The aim of this paper is to analyze the impacts of climate change on both the Swiss energy demand and supply with a Computable General Equilibrium model (CGE model). The use of a CGE model allows us to take into account the interactions between supply and demand, and to assess the general equilibrium effects of the impacts of climate change on the Swiss energy sector. For our purposes, we use the CGE model GEMINI-E3 (Bernard and Vielle, 2008). So far, it has been largely used to derive general equilibrium costs and benefits of either European or Swiss energy and climate policies. The model has been recently improved in order to integrate and valuate the impacts of climate change on the Swiss economy and to address adaptation capacities against a warming climate (Gonseth and Vielle, 2012; Faust et al., 2012; Joshi et al., 2012).

The paper is structured as follows: Section 2 presents the main features of the GEMINI-E3 model and how energy demand and supply are represented. We also describe in this section the baseline scenario that is used to perform the simulations. In Section 3, we analyze the impact of climate change on both the Swiss heating and cooling energy demands. We first describe the methodology that is used to determine these impacts and evaluate them for the period 2010-2050. In the following subsection, we introduce these impacts in the GEMINI-E3 model and investigate their economic effects. We analyze, in Section 4, the vulnerability of the Swiss power system to climate change. Higher temperatures will impact cooling facilities and energy efficiency of thermal power plants, while precipitation changes will modify electricity generation from hydropower. We evaluate these two effects and then determine their economic impacts with GEMINI-E3. The final section draws some conclusions.

2 The GEMINI-E3 model

2.1 Overview

GEMINI-E3[1] is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the other CGE models (GREEN, EPPA, MERGE, Linkage, WorldScan) 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 model is built on a comprehensive energy-economy dataset, the GTAP-6 database (Dimaranan, 2006), that 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_2O and F-gases), we employ region- and sector-specific marginal abatement cost curves and emission projections provided by the Energy Modeling Forum within the Working Group 21 (van Vuuren et al., 2006).

For each sector, the model computes the demand on the basis of household consumption, government consumption, exports, investment, and intermediate uses. Total demand is then divided between domestic production and imports, using the Armington assumption (Armington, 1969). Under this convention, a domestically produced good is treated as a different commodity from an imported good produced in the same industry. Production technologies are described using nested CES functions (see Figure 1).

Time periods are linked in the model through endogenous real rates of interest determined by equilibrium between savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses. The main outputs of the GEMINI-E3 model are by country on an annual basis : carbon taxes, marginal abatement costs and prices of tradable permits (when relevant), effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms of trade, pure deadweight loss of taxation, net purchases of tradable permits when relevant), macro-economic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and data at the industry-level (e.g. change in production and in factors of production, prices of goods).

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 Equivalent Variation of Income (EVI) or the Compensating Variation of Income (CVI). It is commonly acknowledged that surplus is preferable to change in GDP or change in Households' Final Consumption because these aggregates are measured at constant prices according to the methods of National Accounting and do not capture the change in the structure of prices, a main effect of climate change policies.

The sectoral structure of the model is being extended for Switzerland in order to assess the eco-

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[1] All information about the model can be found at http ://gemini-e3.epfl.ch, including its complete description.

nomic impacts of climate change on particularly sensitive sectors like energy, tourism, agriculture and water distribution.

The new structure used in this study comprises 28 sectors and is presented in table 1, while the geographical structure is presented in table 2. The model describes five energy goods and sectors : coal, oil, natural gas, petroleum products and electricity.

2.2 Energy demand

Energy demand is equal to the sum of energy consumed by firms as a production factor and of energy consumption coming from households. The production structure of the industrial sectors is shown in Figure 1.

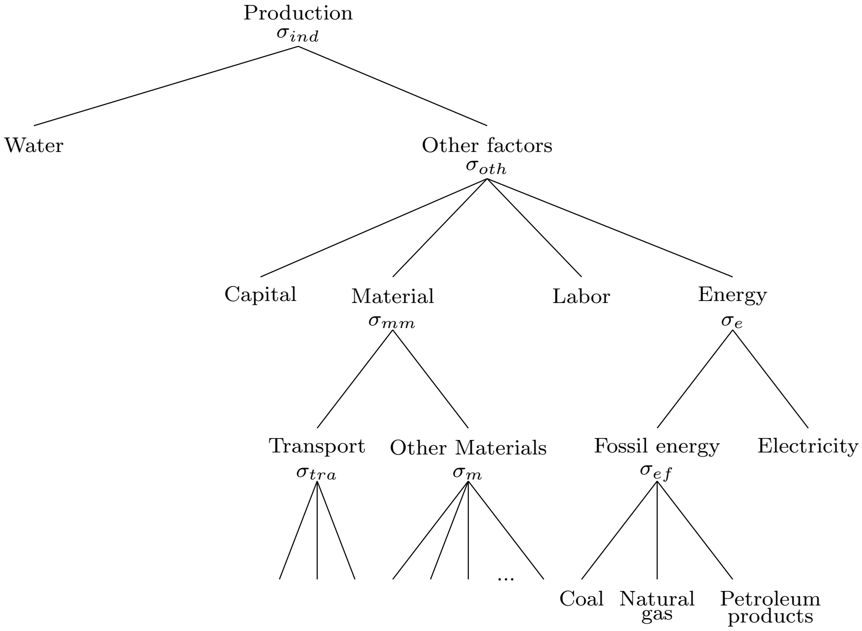

Figure 1 – Production structure of industrial and service sectors.

The representative consumer maximizes a nested CES utility function, which is described in Figure 2. As can be seen, we split energy consumption in two parts, for transportation and housing purposes.

2.3 Energy supply

As in Switzerland coal, natural gas and crude oil are mainly imported from abroad, we only present the modeling of electricity generation. In this version of GEMINI-E3, electricity production is represented by a nested CES function including - besides fossil fuels, nuclear and hydraulic plants - the new capacities installed in the renewable technologies, as shown in Figure 3. Then power generation is separated from the other activities (transmission and distribution) that appear through their factors of production at the top of the nesting structure. Power generation

Table 1 – Industrial classification

1	Coal	15	Paper products publishing
2	Oil	16	Transport nec
3	Gas	17	Sea Transport
4	Petroleum Products	18	Air Transport
5	Electricity	19	Consuming goods
6	Crop	20	Equipment goods
7	Milk	21	Winter overnight tourism
8	Animal product	22	One-day winter tourism
9	Vegetables	23	Other forms of tourism
10	Other agricultural products	24	Insurance and pension funding
11	Forestry	25	Health and social work
12	Mineral product	26	Services
13	Chemical	27	Dwelling
14	Metal and Metal products	28	Water

Table 2 – Regions

CHE	Switzerland
EUR	European Union
USA	United States of America
OEC	Other developed countries
BRI	Brazil, Russia, India and China
ROW	Rest of the world

involves only two factors of production, capital and fuel (only capital for renewables).[2] With this new nesting structure, it is possible to better take into account the power generation portfolio and to represent inter-fuel substitutability as well as substitutability between fossil and renewable power generation (Wing, 2006).

2.4 The reference scenario

Reference scenarios in CGE models are built from forecasts or assumptions on economic growth in the various countries/regions ; the prices of energy in world markets, in particular the oil price ; and national (energy) policies. Future GDP growth rates are from the Swiss State Secretariat for Economic Affairs (SECO) for Switzerland and the US Department of Energy (Energy Information Administration) published in the *2010 International Energy Outlook* (Energy Information Administration, 2011) for all other countries. As shown in Table 3, the Swiss economic growth rate is predicted to be 1.7 percent until 2020 before slowing to about 0.8 percent until 2050, while the world economy will grow at 2.8 percent until 2030 and at 2.6 percent from then on.

Assumptions concerning energy prices are drawn from the *World Energy Outlook* of the International Energy Agency (International Energy Agency, 2010b). As reported in Table 4, the predictions of the International Energy Agency stop in 2035, and in the model energy prices

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[2] Labor in the generation activity is low compared to labor in the other activities (transport, distribution) and of a similar relative size for all plants. It is thus represented as a common factor.

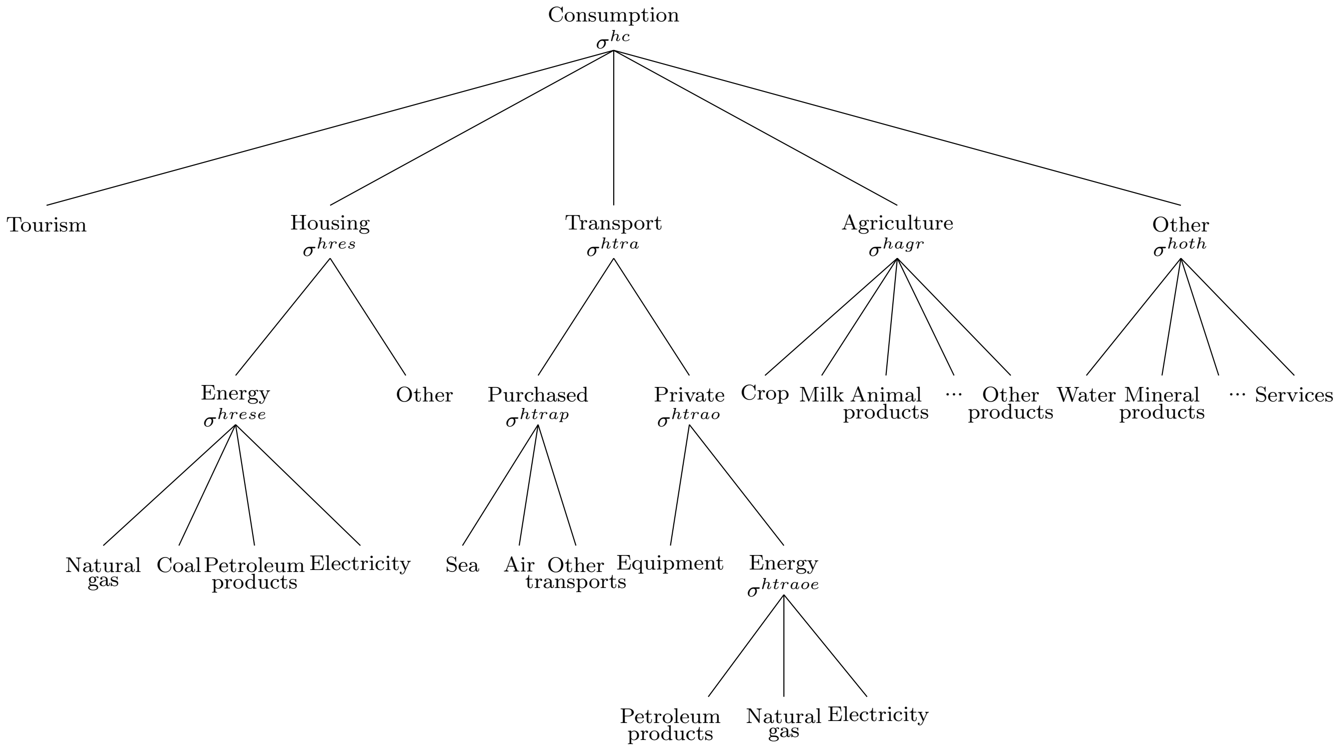

Figure 2 – Nested structure of household consumption

are supposed constant thereafter. The oil price is assumed to reach 135$ in 2035 and to remain stable after, the price of imported gas in Europe is equal to 14.4 $ per Mbtu in 2035, and the price of steam coal imported in OECD countries reaches 115$ per ton.

Table 3 – GDP growth rate (% per year)

	2010-2020	2020-2030	2030-2040	2040-2050
Switzerland	1.7%	0.8%	0.9%	0.8%
European Union	1.5%	1.8%	1.7%	1.7%
United States	2.3%	2.7%	2.5%	2.4%
Other OECD	1.3%	1.1%	1.1%	1.0%
BRIC	6.3%	4.5%	3.6%	3.6%
ROW	3.9%	3.6%	3.3%	3.3%
World	2.8%	2.8%	2.6%	2.6%

Table 4 – Energy prices in the baseline scenario ($ 2009)

	Unit	2000	2009	2015	2020	2025	2030	2040	2050
IEA Crude oil imports	Baril	34.3	60.4	94.0	110.0	120.0	130.0	135.0	135.0
Natural gas imports Europe	Mbtu	3.5	7.4	10.7	12.1	12.9	13.9	14.4	14.4
OECD Steam coal imports	Tonne	41.2	97.3	97.8	105.8	109.5	112.5	115.0	115.0

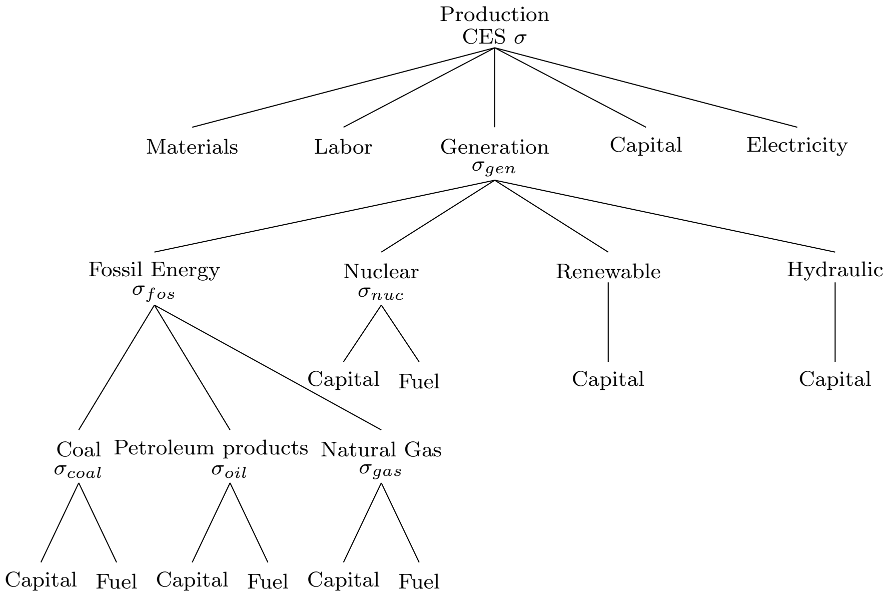

Figure 3 – Nesting CES structure of electricity production

As our study focus on the Swiss energy sector, we only describe the Swiss figures. One important assumption concerning the future configuration of the Swiss energy sector is related to decision on nuclear policies. In May 2011, the Federal Council has decided, after the devastating earthquake in Japan and the disaster at Fukushima, to gradually decommission all Swiss nuclear power plants to reach a complete phase out by 2034. On the basis of this decision, Table 5 gives the operating lives of all 5 existing nuclear power plants, which have been introduced in GEMINI-E3. Electricity generation in Switzerland is currently made up of around 56% hydroelectric power and 39% nuclear power with the remaining 5% shared between various other production methods, including waste incineration and new renewable. Figure 4 shows the evolution of the Swiss electricity generation over the period 2008–2050, where total electricity production remains more or less constant over the time horizon for three main reasons:

- Growth of the Swiss economy is very low over the period (see Table 3), which limits the demand of electricity ;
- We have retained, concerning energy consumption, an *Autonomous Energy Efficient Improvement* (AEEI) (Azar and Dowlatabadi, 1999) significant and equals to 2% per year for Switzerland ;
- The replacement of nuclear power plants by more costly technologies increases the electricity prices and limits the penetration of electricity.

The evolution of the electricity mix is driven by retirement of nuclear power plants and by the assumption that no new hydraulic sites are available in Switzerland, hydraulic power generation is thus flat. In the first period of the simulation (2010-2030), nuclear capacities are mainly replaced by natural gas power plants and to a lesser extent by renewable. In the second half of the scenario time horizon, solar PV is deployed as this technology becomes increasingly competitive, and the share of renewable (including hydro) reaches 72% by 2050. Swiss non-electricity energy consumption remains dominated by oil products whose consumption increases annually by 0.4% (see Figure 5), the consumption of natural gas increases by 0.8% per year mainly driven by the generation of electricity with gas power plants.

Table 5 – Operating lives of Swiss nuclear power plants. (Source : Bundesamt für Energie BFE (2011))

Nuclear Power plant	Operating life 50 years
Beznau I (365 Mwe)	1969-2019
Beznau II (365 Mwe)	1972-2022
Mühleberg (373 Mwe)	1972-2022
Gösgen (985 Mwe)	1979-2029
Leibstadt (1190 Mwe)	1984-2034

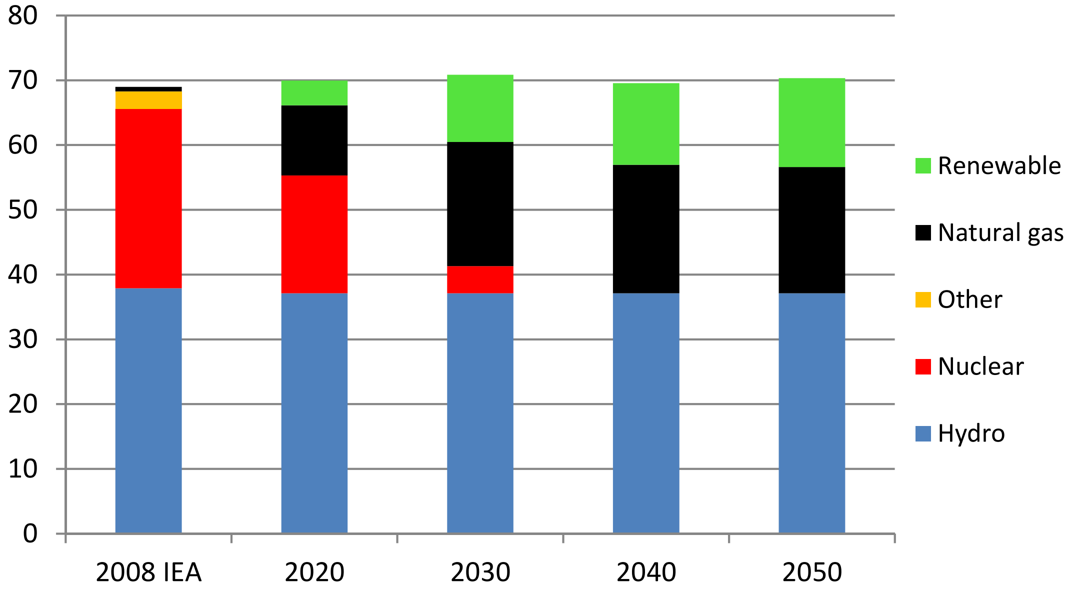

Figure 4 – Electricity generation in Switzerland (in TWh) (*IEA 2008* :International Energy Agency (2010a))

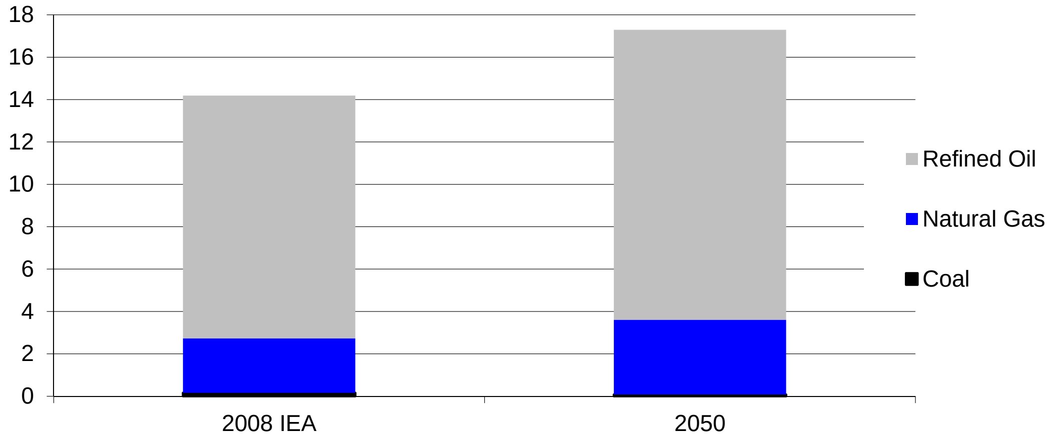

Figure 5 – Fossil energy consumption in Switzerland (in Mtoe) (*IEA 2008* :International Energy Agency (2010a))

3 The impacts of climate change on heating and cooling energy demands

3.1 Energy demand for heating

An important step for calibration consists in defining the amounts of energy consumed for heating purposes in the different sectors of the economy as well as the share of each source of energy in these consumptions. [3] Heating represents a central share of the overall energy consumption of households (72.4%). This share is also high in the sector "Services and Agriculture" (55.0%) whereas it is much lower in the industry sector (14.4%). The overall energy need for heating is covered in its majority by imported fossil fuels (86.1%).

The climate is well-known to be one of the main factor influencing the amount of energy demanded for heating at a given location. Quite logically, a warmer climate is expected to reduce this demand but one has to quantify this effect based on climatic scenarios. The comparison of energy needs for heating with and without climate change are often carried out using a climatic indicator based on average daily temperature, the heating degree-days (Christenson et al., 2006; Isaac and van Vuuren, 2009; Seljom et al., 2011). Following recommendations from SIA, which is the Swiss professional association of engineers and architects, we define the HDD as the quantity resulting from equation 1.

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[3] For Switzerland, three aggregate sectors and the year 2001, this information is available in Kirchner et al. (2010). All the paragraph's figures are drawn from this source.

$$
\begin{aligned}
HDD(\theta_i, \theta_{th}) &= \sum_{k=1}^{365} m_k \cdot (\theta_i - \theta_{e,k}) \qquad (1) \\
with\ m_k = 1 \quad if &\quad \theta_{e,k} \leq \theta_{th} \\
m_k = 0 \quad if &\quad \theta_{e,k} > \theta_{th}
\end{aligned}
$$

θ_i: interior temperature
$\theta_{e,k}$: average daily temperature for day k
θ_{th}: threshold temperature under which heating becomes necessary

The formula for HDD computes and sums daily differences between the interior and outside temperatures, whenever the daily mean temperature is lower than a threshold temperature reflecting the quality of housing insulation. The lower the value of the threshold temperature, the better the insulation of buildings. Values of equation 1's parameters that are commonly used for Switzerland are the following (Christenson et al., 2006; Kirchner et al., 2010): $\theta_i = 20°\text{C}$ $(68°F)$ and $\theta_{th} \in \{8, 10, 12°\text{C}\}$ $(\{46.4, 50, 53.6°F\})$. Following Christenson et al. (2006), we make the assumption that the energy demand for heating is proportional to the climatic indicator's value. This enables us to directly infer percentage changes in heating energy demand from percentage changes in HDD.

3.2 Energy demand for cooling

The degree-days method can also be used in order to assess the quantity of energy required in a given climate for cooling. The ASHRAE formula for CDD, which looks like the one used to compute HDD, is given below (Howell et al., 2005). [4]

$$
\begin{aligned}
CDD(\theta_{bp}) &= \sum_{k=1}^{365} m_k \cdot (\theta_{e,k} - \theta_{bp}) \qquad (2) \\
with\ m_k = 1 \quad if &\quad \theta_{e,k} \geq \theta_{bp} \\
m_k = 0 \quad if &\quad \theta_{e,k} < \theta_{bp}
\end{aligned}
$$

$\theta_{e,k}$: average daily temperature for day k
θ_{bp}: balance point temperature above which cooling becomes necessary

The formula for CDD first determines days for which cooling is necessary based on the threshold temperature θ_{bp} and then sums differences between outside and threshold temperatures across these days. A standard value of θ_{bp} is lacking for Switzerland. Nonetheless, we will use $\theta_{bp} = 18.3°\text{C}$ $(\approx 65°F)$, which in addition of being an ASHRAE standard numerical value, has already been used in the Swiss context (Christenson et al., 2006; Kirchner et al., 2010). To link

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[4] ASHRAE is the abbreviation for the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

CDD values with energy consumption for cooling, we refer to a linear relationship that was estimated using data on a sample of cooled office buildings located in different European countries (Aebischer et al., 2007).

$$D_{spec.} \quad = \quad 12.7 + 0.103 \cdot CDD \tag{3}$$

where $D_{spec.}$ is the specific electricity consumption for cooling given in $KWh/m_c^2 \cdot year$ (m_c^2 is the fully cooled surface).

Equation 3 provides the annual value of electricity consumption for a one square meter of a fully cooled surface as a function of CDD.[5] Because of the positive constant term, it is worth noting that the percentage change in specific electricity consumption is lower than the percentage change in CDD.

Another challenging point with cooling is that the proportion of cooled surfaces is expected to increase in the future, a trend that should be reinforced by climate change. For the service sector, Aebischer et al. (2007) developed a set of assumptions regarding this evolution. They are summarized in Table 6 for their no climate change variant.

Table 6 – Cooled surfaces expressed as percentages of total surfaces in the service sector under a scenario with no climate change. (Source: Aebischer et al. (2007))

	2000	2005	2015	2025	2035	2050[1]
not cooled	61%	59%	54%	49%	44%	36%
partially cooled	20%	22%	25%	27%	30%	36%
fully cooled	19%	19%	21%	23%	25%	28%

[1] Values in this column are obtained by extrapolation from the original data published in Aebischer et al. (2007).

Aebischer et al. (2007) apply some corrective factors to the values displayed in Table 6 when accounting for climate change.[6] By 2035, they assume that half of the non-cooled surfaces under the variant no climate change will be partially cooled while half of the partially cooled surfaces under the variant no climate change will be fully cooled. We apply these corrections to the values of Table 6's last column in order to obtain estimates of the proportion of partially and fully cooled surfaces in the service sector for 2050 under a climate change variant.

According to our estimates, surfaces in the service sector amounted to 60 million m^2 in 2000 against 250 million m^2 in the housing sector. Given that these surfaces grow at the same rate than their respective sector, we estimate future surfaces in 2050 to be equal to 114 million m^2 for the service sector and to 475 million m^2 for the housing sector. To derive the number of square meter of surfaces that are cooled in the latter sector, we cannot apply Table 6's percentages to the overall surface projections. Rather, we based our estimations on the annual energy consumption of Swiss households for cooling, which is equal to 0.1 PJ in 2001 according to Kirchner et al. (2010). In this manner, we find a fully-cooled surface of 1.5 million square meter in 2000, which

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[5] For partially cooled surfaces, the relationship needs to be corrected by scaling down the specific electricity consumption by a factor of 4 (Aebischer et al., 2007).

[6] Their climate change scenario for Switzerland is an intermediate one that predicts a 2°C increase in temperature during summer months and a 1°C increase during the rest of the year over the time span 1990–2035.

represents a share of 0.6% of the sector's overall surfaces. For 2050, we assume a share that ranges, with climate change, from 2% to 10%.

3.3 Evolution of the climatic indicators

Our estimates of HDD and CDD values are based on four climatic scenarios of average daily temperatures drawn from the ENSEMBLES project. They have been chosen in order to get the maximum diversity of models represented and are listed in Table 7.

Table 7 – Four GCM-RCM couplings from the ENSEMBLES project (with indication of the simulation period).

1.	KNMI - ECHAM5-r3 avec RACMO (1951-2100)
2.	SMHI - BCM-RCA (1961-2100)
3.	C4I - HadCM3Q16-RCA3 (1951-2099)
4.	DMI - ARPEGE-HIRHAM (1951-2100)

In addition to the four ENSEMBLES climatic models, we dealt with a fifth model, called "Model Mean", whose prediction values are constructed by averaging those from the four aforementioned models.

We use equation 1 and 2 to transform series of average daily temperature obtained for the reference and scenario periods into values of HDD and CDD.[7] These values are derived for each of the 176 grid points of the ENSEMBLES models that overlap the Swiss territory. They need to be aggregated in order to obtain one single value at the national level. Weights used for this aggregation, which are based on the Swiss population's geographic distribution in 2000, are shown in Figure 6.[8]

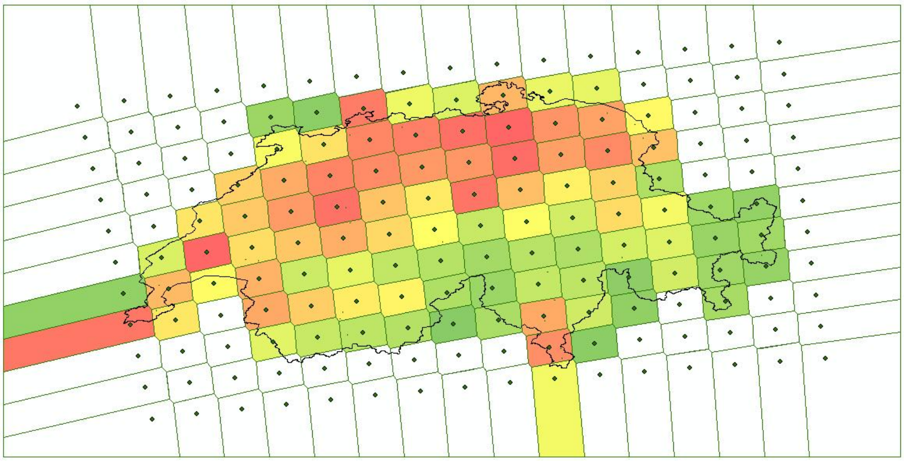

Figure 6 – Weights based on the distribution of the population across Switzerland in 2000. (Source: SFSO)

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[7] The reference period (i.e. period without climate change) taken for our simulations is 1961–1990.

[8] These weights are used for aggregation until 2050. Therefore, we implicitly assume no change in the distribution of the population along this time span. An alternative set of time-invariant weights was derived using information on housing surfaces rather than on population. Using the former set of weights instead of the latter entails no significant differences in the computation of the climatic indicators.

We first begin to present the evolution of the HDD indicator from the reference period 1961–1990 to 2050. Table 7 shows this evolution when the threshold temperature is set equal to 10°C.

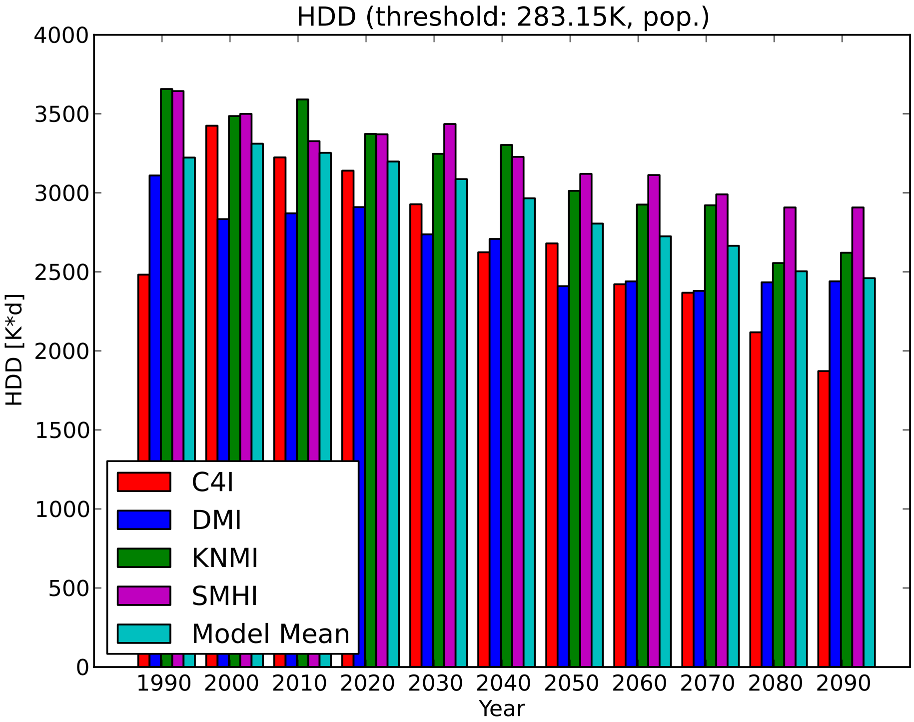

Figure 7 – HDD climatic indicator's evolution from the reference period 1961–1990 (1990 in the graph) to 2050 using $\theta_{th} = 10°C$.

Based on the "Model Mean" scenario's temperature predictions, we present, in Table 8, percentage changes in HDD that were computed for the three different threshold temperatures θ_{th}.

Table 8 – Percentage changes in HDD from the reference period 1961-1990 to 2050.

Threshold	$(\Delta_{2050}/HDD_{ref})^*$
$\theta_{th} = 8°C$	-18.1%
$\theta_{th} = 10°C$	-14.6%
$\theta_{th} = 12°C$	-12.9%

*reference period : 1961-1990

Not surprisingly, the percentage change in HDD depends upon the threshold temperature. Our results show that the former decreases by approximately 30% when the value of the latter goes from 8°C to 12°C. This is probably due to a "basis effect", with the initial value of HDD (i.e. the denominator in the fraction used to compute the percentage change) increasing faster than the absolute difference in HDD when the value of θ_{th} gets higher. In the next subsection, we assume that Table 8's values give the ex-ante reduction in the energy consumption for heating.

The evolution of the CDD climatic indicator over the same period is displayed in Figure 8.

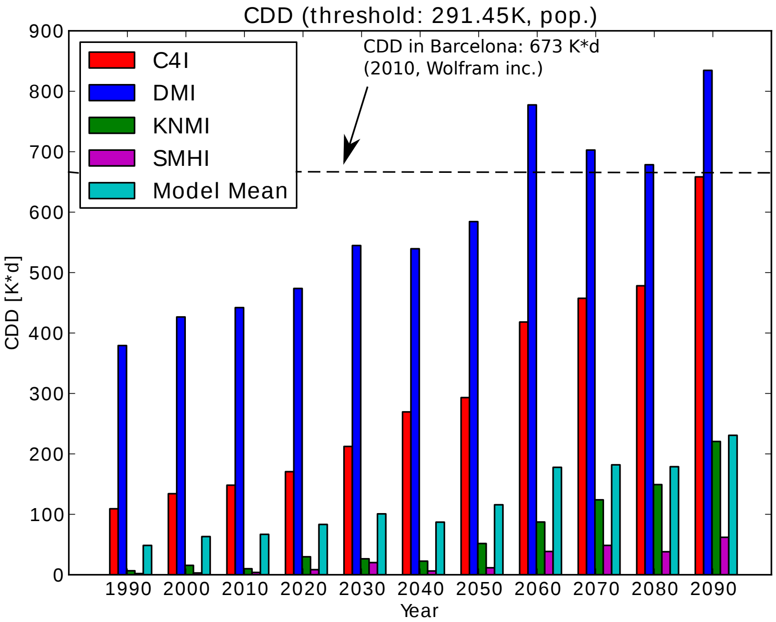

Figure 8 – CDD climatic indicator's evolution from the reference period 1961–1990 (1990 in the graph) to 2050 using $\theta_{bp} = 18.3°\text{C}$.

Computations made with different climatic scenarios provide dramatically different values of CDD. In particular, values obtained with the model "DMI - ARPEGE-HIRHAM" seem overwhelmingly large. The value of CDD computed with this model for the reference period is in the range of the value calculated by Kirchner et al. (2010) for the year 2003 (=346), which is renowned for the heat wave over Europe. However, even the value of CDD computed with this model for 2050 does not reach the current levels of the Mediterranean region or the Iberian peninsula (cf. Figure 8). Based on the "Model Mean" scenario's temperature predictions, we present, in Table 9, the percentage change in CDD that was computed for the threshold temperature $\theta_{bp} = 18.3°\text{C}$.

Table 9 – Percentage change in CDD from the reference period 1961-1990 to 2050.

Threshold	$(\Delta_{2050}/CDD_{ref})^*$
$\theta_{bp} = 18.3°\text{C}$	+138.5%

*reference period : 1961-1990

Using Table 9's percentage change, climate change induced increases in energy consumption for cooling are evaluated to amount to 0.6 TWh in the service sector and in the range from 0.1 to 0.8 TWh in the housing sector for 2050.

3.4 General equilibrium effects

In this section, we investigate the economic impacts of climate change induced changes in energy consumption for both heating and cooling. These changes, which mainly rely on the evolution of two climatic indicators, were derived in the former subsection.[9] They were introduced sequentially in the model in order to distinguish their economic effects. Our basis simulations take an ex-ante decrease in the energy consumption for heating equal to -14.6% for all sectors (this is the median case corresponding to the use of a threshold temperature equal to $\theta_{th} = 10°\text{C}$). In contrast to heating, the ex-ante increase in the energy consumption for cooling is sector specific with values set to 0.4 TWh for the housing sector and to 0.6 TWh for the service sector. In addition, we have also simulated a "high scenario" regarding the energy consumption increase in the housing sector (+0.8 TWh). Overall, this leads us to simulate 11 scenarios, which are summarized below:[10]

- decrease in the heating energy consumption of the housing sector,
- decrease in the heating energy consumption of the service sector,
- decrease in the heating energy consumption of the industry sector,
- decrease in the heating energy consumption of all sectors,
- decrease in the heating energy consumption of all sectors using $\theta_{th} = 8°\text{C}$,
- decrease in the heating energy consumption of all sectors using $\theta_{th} = 12°\text{C}$,
- increase in the cooling energy consumption of the housing sector,
- increase in the cooling energy consumption of the service sector,
- increase in the cooling energy consumption of both the housing and service sectors,
- increase in the cooling energy consumption of the housing sector in the "high scenario" case,
- combination of the decrease in heating energy consumption with the increase in cooling energy consumption.

The first scenario introduces a deviation from the baseline regarding household consumption of fossil fuels for their house. This consumption is reduced by 12.7% in 2050.[11] Ex-post, this reduction is equal to 8.2%. The difference stems from a rebound effect, which is well-documented in the economic literature (Dimitropoulos, 2007). At the national level, the consumption of oil and gas products are reduced, by respectively 2.3% and 0.6%. In contrast, this scenario boosts household consumption for the other products (+0.2%), which entails an increase of 0.7% in electricity consumption. At the aggregate level, the scenario results in large welfare gains of 613 million USD. The effect on the environment is also positive, since CO_2 emissions are reduced by 2.1% in 2050.

In the service sector, a climate change reduced heating energy consumption would result in smaller decreases of fossil fuels consumption: -1.2% for oil products and -0.6% for natural gas. In this occurrence, the Swiss economy benefits from reduced production costs in the service sector and the aggregate welfare change is evaluated to amount to 250 million USD. In addition to the economic improvement, CO_2 emissions is reduced by 1.0% in 2050.

As regards the industry sector, a reduced energy consumption for heating only affects slightly its overall consumption of fossil fuels. This is due to the fact that heating only accounts for a small part of its energy uses. The reduced production costs, though smaller than in the service

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[9] There, we also discuss the fact that climate change will trigger more investments in cooling facilities. Note, however, that the general equilibrium effect of these additional investments are not accounted for in the simulations reported in this paper.

[10] As shown in the following list of scenarios, some of them assume different levels of insulation of the Swiss building stock, i.e. different values of θ_{th}. It is worth noting that their effects are estimated based on different baselines since different assumptions on building insulation entail different overall heating energy consumption.

[11] It is slightly lower than -14.6% because fossil fuels in the residential sector are also used for other purposes, e.g. to heat water.

sector, decrease prices and also contribute to make the Swiss economy more competitive thereby generating a welfare gain of 57 million USD.

When taking into account the impacts on the three sectors simultaneously, the welfare gain amounts to 918 million USD, which corresponds roughly to the sum of the welfare gains derived for the three previous scenarios. Table 10 also presents the simulation results when θ_{th} is equal to 8 and 12°C. These results enclose those obtained with $\theta_{th} = 10$°C.

Table 10 – Impacts of a climate change induced reduction in heating energy consumption in 2050*

	Impacted sector (θ_{th}=10)			All sectors		
	Housing	Service	Industry	θ_{th}=12	θ_{th}=10	θ_{th}=8
Energy consumption						
Petroleum products	-2.3%	-1.2%	-0.1%	-3.2%	-3.6%	-4.4%
Natural gas	-0.6%	-0.6%	-0.2%	-1.3%	-1.4%	-1.7%
Electricity	0.7%	-0.2%	0.0%	0.4%	0.5%	0.6%
CO_2 emissions	-2.1%	-1.0%	-0.1%	-2.9%	-3.2%	-3.9%
Welfare change in Mio USD_{2010}	613	250	57	848	918	1080
As a % of consumption	0.15%	0.06%	0.01%	0.20%	0.22%	0.26%

* percentage change with respect to the reference scenario

With respect to cooling, the increase in electricity consumption has detrimental effects on the Swiss economy but at seemingly low levels. Looking first at this impact on the housing sector, we found that the increase in electricity consumption of households is equal to 1.2% ex-post, which raises the overall consumption of electricity in Switzerland by 0.40%. This increase is covered at 58% by more electricity production from thermal power plants fueled with natural gas and at 42% by renewables. This is the reason of the 0.34% increase in natural gas consumption reported in Table 11. Though moderate, higher expenditures for cooling also divert households from consuming oil products (-0.06%). Therefore, the net effect on CO_2 emissions is neutral. At the aggregate level, welfare losses would amount to 55 million USD. The impacts of higher cooling needs are larger for the service sector. In this case, the Swiss consumption of electricity would be raised by 0.58% resulting in a higher level of natural gas consumption for electricity production. The welfare effect is estimated to be equal to -62 million USD. Table 11 also reports results obtained with two other scenarios. The first one analyzes the effect of increasing electricity needs for cooling in both the housing and service sector. The second one assumes a “high hypothesis” concerning the ex-ante increase of electricity consumption for cooling in the housing sector.

Table 11 – Impacts of a climate change induced increase in cooling electricity consumption in 2050*

	Housing	Service	Total	Housing high hypothesis
Energy consumptions				
Petroleum products	-0.06%	0.03%	-0.03%	-0.14%
Natural gas	0.34%	0.54%	0.88%	0.76%
Electricity	0.40%	0.58%	0.98%	0.90%
CO_2 emissions	0.00%	0.11%	0.12%	0.01%
Welfare change in Mio USD_{2010}	-55	-62	-116	-122
As a % of consumption	-0.01%	-0.01%	-0.03%	-0.03%

* percentage change with respect to the reference scenario

Eventually, Table 12 presents the combined effect of higher energy requirements for cooling with lower energy requirements for heating. [12]

Table 12 – Impacts of climate change induced variations in both heating and cooling energy needs in 2050*

Energy consumption	
Petroleum products	-3.6%
Natural gas	-0.5%
Electricity	1.5%
CO_2 emissions	-3.1%
Welfare change in Mio USD_{2010}	801
As a % of consumption	0.19%

* percentage change with respect to the reference scenario

Looking at the overall climate change impacts on the demand side of the Swiss energy system, we can conclude that the net effect is probably going to be significant and positive, with welfare gains reaching 801 million USD by 2050.

4 Climate change impacts on electricity generation from thermal power plants and hydropower

4.1 Impacts on thermal power plant production

In this subsection, we look at the impact of higher temperatures on the electricity production of thermal power plants. We proceed using the results of a recent econometric analysis: Linnerud et al. (2011) analyzes the impact of ambient air temperature on the production of nuclear power plants. [13] They estimated several linear panel data regression models based on monthly

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[12] This scenario relies on average assumptions both for the insulation of the building stock and the rate of equipment in cooling facilities.

[13] Water rather than ambient air is the cooling medium in thermal power plant. Accordingly, the interest should lie in assessing the impact of climate change on the cooling water's temperature. However,

data of nuclear electricity production. These data were obtained from a panel of 7 European countries tracked from 1995 to 2008.[14] As for any other type of thermal power plant, the increase in temperature has two potentially detrimental effects on nuclear production. It reduces the plant's efficiency and may force operators to run the plant at partial load or to shut it down. This second effect arises during droughts or heat waves, mainly because the access to cooling water is reduced or because of legal restrictions concerning the cooling water's temperature that is brought back to the environment. Therefore, the effect of temperature on production is expected to be non-linear, with the impacts being more pronounced at higher temperatures. To account for this non-linearity, estimated models in Linnerud et al. (2011) include both the variable "monthly ambient temperature" and its square. Identification of the causal effect of temperature on production is made difficult by different aspects of the specific problem at hand. First, maintenance activities, which entails a reduced load, are carried out during the summer months. Therefore, they have to be accounted for in the model in order not to mix their effects with the "pure effect" of temperature on production. Second, it is better for the estimation to be made within the time dimension of the dataset rather than across countries because the latter approach could fail to differentiate the effect of different technologies, whose choice depends upon the climate, from that of increased temperature. Finally, temperature changes might also affect the demand, which causes new equilibrium price and quantity on the electricity market. Linnerud et al. (2011) introduced a dummy variable for the summer months and country fixed effects in their models in order to solve for the first two problems. For the last issue, they show that the exogenous part of electricity price, i.e. the price variations that arise from shifts in the demand curve, does not significantly affect capacity utilization at the national level.

To estimate the effect of a temperature change on monthly production, we use the following two equations, which are based on estimation results presented in Linnerud et al. (2011). Equation 4 is used to derive estimated effects on nuclear production of a change in temperature for the winter months whereas Equation 5 is used to derive the same estimated effects for the winter months:

$$\widehat{\Delta q/q} = \frac{-0.666 \cdot \Delta T - 0.023 \cdot \left((T+\Delta T)^2 - T^2\right)}{92.440 - 0.666 \cdot T - 0.023 \cdot T^2} \tag{4}$$

$$\widehat{\Delta q/q} = \frac{-0.666 \cdot \Delta T - 0.023 \cdot \left((T+\Delta T)^2 - T^2\right)}{69.830 - 0.666 \cdot T - 0.023 \cdot T^2} \tag{5}$$

To compute the climate change impacts on electricity generation from thermal power plants, we need data on average monthly temperatures for the reference and scenario periods. These data are obtained using the same ENSEMBLES's climatic scenarios as in section 3. To aggregate data on average monthly temperature across the 176 grid points, we used a set of weights reflecting the location of nuclear power plants in Switzerland. The monthly temperatures obtained in

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it is clear that water temperature is closely linked to that of the ambient air. For a specific plant that they analyze in their paper, which is endowed with a cooling tower, Linnerud et al. (2011) notes that: "*According to the plant management, a 1°C raise in the ambient temperature raises the cooling water temperature by about 0.4 to 0.5°C within an hour*". In Switzerland, two out of the five nuclear power plants have a cooling tower whereas the remaining three use fluvial water in their cooling device.

[14] These countries are the following: Germany, Belgium, Spain, Finland, France, United-Kingdom and Sweden.

this manner serve to compute monthly production losses at different scenario periods, based on both equation 4 (winter months) and 5 (summer months). Finally, the annual production loss is obtained by aggregating monthly production losses in proportion to each month's average share of the year's total nuclear electricity production.[15]

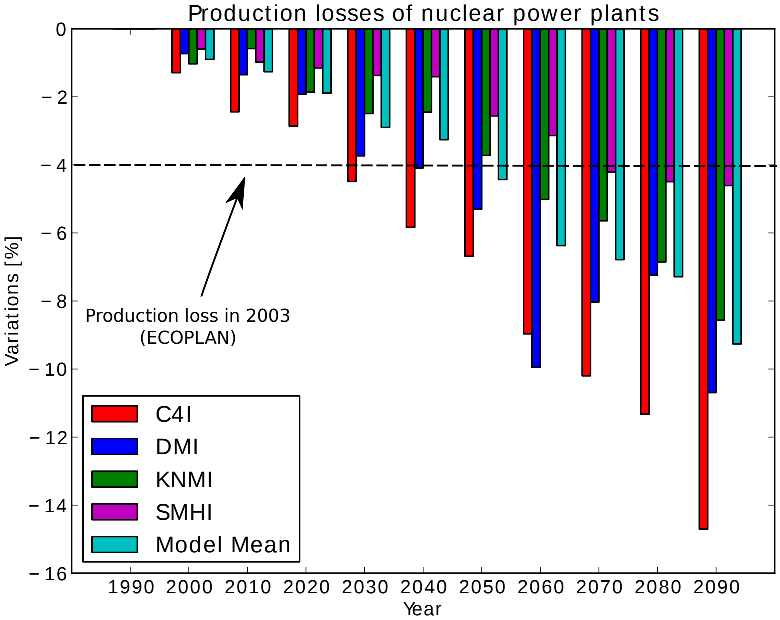

Figure 9 – Estimated climatic change induced losses in nuclear electricity production up to 2090.

When using the "Model Mean" scenario, it is interesting to note that the estimated production loss by 2050, which is equal to -4.4%, is roughly equal to the production loss observed during the year 2003.

As already written, we suppose that Switzerland will apply a moratorium on the building of new nuclear power plants and also that the shutting down of all existing plants will be done by 2035. In other words, there is no more nuclear electricity production in our reference scenario by 2050. Why should we then use the estimated impacts shown in Figure 9? Actually, these impacts could still be used based on two considerations. Since nuclear power plants are partly replaced by natural gas-fired power plants, we note first that the switch will not decrease the sensitivity of the Swiss electricity supply sector to climate change. In fact, temperatures affect nuclear and natural gas-fired power plants in the same way. Second, there are good reasons to think that the location of thermal power plants will remain nearly unchanged because of the technical constraints associated to the current configuration of the electricity network.

4.2 Impacts on hydropower production

Our approach to assess climate change impacts on the Swiss hydropower production is quite similar to the one used in Ecoplan/Sigmaplan (2007). The approach first consists in estimating changes in runoff based on changes in precipitation derived from the ENSEMBLES's climatic scenarios. Once runoff changes are determined, we make the simple assumption that they are equivalent to the changes in hydropower production.

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[15] The latter information is drawn from the annual electricity statistics publications of the Swiss federal office of energy.

The linear relationship linking runoff changes with temperature changes in Switzerland is estimated for each month as well as annually using the simulation results from the CCHydro project.[16] We report in Table 13 how good is the result from fitting a line to both the monthly and annual data.

Table 13 – Coefficients of determination for the regressions of runoff changes on precipitation changes both at the monthly and annual levels.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
R^2	0.84	0.82	0.38	0.53	0.14	0.55	0.93	0.94	0.94	0.87	0.84	0.69
R^2 (Year)=0.99												

The coefficients of determination (R^2) for the monthly fits are variable as they reflect changes in the hydrological regime of rivers throughout the year. In particular, months that coincide with the period of snow and ice melting have lower values of R^2. At the annual level, the relationship between runoff changes and precipitation changes is nearly perfectly linear with a R^2 equal to 0.99.

Using the estimated linear relationship based on annual data, we compute changes in runoff by 2050 for precipitation changes obtained from the five climatic scenarios that we have been using so far. The results are shown in Table 14.

Table 14 – Percentage change in runoff by 2050 for five different climatic scenarios.

	Model Mean	C4I	DMI	KNMI	SMHI
$\%var$	-2.2	-1.2	-9.4	-1.9	1.3

4.3 General equilibrium effects

Based on the impacts derived with the "Model Mean" scenario, Table 15 displays the economic consequences for the Swiss economy of a decrease in the production of thermal power plants.

In GEMINI-E3, the impact on natural gas-fired power plants is modeled as a decrease in efficiency, with more inputs being needed to produce the same amount of electricity.[17] This raises production costs thereby making the technology less attractive. Consequently, electricity production from thermal power plants decreases by 418 GWh. The decrease is partially compensated by an increase of 145 GWh from the renewables. The final impact would be an increase in the price of electricity of 1.58%, which would lead to a 0.39% decrease in electricity production. Altogether, the Swiss consumption of natural gas would increase by 1.37%. This is due to the fact that the decreased efficiency effect outweighs the reduced electricity production from thermal power plants. At the aggregate level, the scenario entails a welfare loss of 108 million USD.

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16. Based on 10 ENSEMBLES's climatic scenarios, this project provides simulation results from hydrological models for the scenario periods 2021–2050 and 2070–2099. We thank Massimiliano Zappa, who has given us access to these data.

17. It is as if climate change were only impacting the production of thermal power plants through a reduced efficiency. In this sense, the estimated impacts that we derived in subsection 4.1 for 2050 are applied in a somewhat incoherent manner. In fact, they also reflect the effect of temperature on the load at which plants are operated.

Table 15 – Impacts of a climate change induced reduction in the production of thermal power plants in 2050*

Energy consumption	
Petroleum products	0.00%
Natural gas	1.37%
Electricity	-0.39%
CO_2 emissions	0.24%
Welfare change in Mio USD_{2010}	-108
As a % of consumption	-0.03%
Production change given in GWh	
Natural gas	-418
Hydropower	0
Renewables	145
Total	-272

* percentage change with respect to the reference scenario

As regards hydropower, we simulate the impact of the “Model Mean” scenario in accordance with the value given in Table 14. In order to compensate for the reduced production of hydropower, Switzerland would increase its electricity production from both natural gas and renewables. Given the optimistic assumptions about the cost of electricity from photovoltaic cells in the baseline (cf. section 2.4), the increase in the price of electricity would be limited to 0.58%. This price increase would have nearly no effect on electricity consumption as shown in Table 16. Consistent with these very moderate effects, welfare losses would amount to 65 million USD.

Table 16 – Impacts of a climate change induced reduction in hydropower production in 2050*

Energy consumption	
Petroleum products	0.02%
Natural gas	1.25%
Electricity	-0.14%
CO_2 emissions	0.24%
Welfare change in Mio USD_{2010}	-65
As a % of consumption	-0.02%
Production change given in GWh	
Natural gas	420
Hydropower	-816
Renewables	297
Total	-100

* percentage change with respect to the reference scenario

5 Conclusion

Our aim with this paper was to analyze the economic effects of climate change induced impacts on the Swiss energy system using a computable general equilibrium model. These impacts concern both the demand and the supply sides of the energy system. The former impacts typically modify energy requirements for heating and cooling whereas the latter affect the electricity generation from virtually all sources. We found significant and positive effects from reduced requirements for heating purposes. In fact, the money, which is not spent anymore on imported fossil fuels, is used by household to expand their consumption of other goods and services. In addition, reduced production costs in the industry and services sectors decreases prices, which is also beneficial to households. This effect largely outweighs that of the increased energy demand for cooling. This result is consistent with those obtained from other studies carried out for Switzerland but also for other countries that share some climatic similarities with Switzerland (Aebischer et al., 2007; Seljom et al., 2011). As regards electricity generation, we investigated the impacts on both nuclear- and hydro-power. A reduction in runoff by 2050 negatively affects hydropower production while higher temperatures reduce the efficiency and also potentially the load at which thermal power plants are operated. However, these impacts are small and only entail moderate welfare losses by 2050. The climate effects on the other renewable resources are not included in this study. Eventually, Table 17 presents the net economic effects of all the aforementioned impacts of climate change. As can be seen, the net effect is largely positive, with welfare gains for the Swiss economy amounting to roughly 704 million USD by 2050. The environment would also be better off, with CO_2 emissions decreasing by 2.6%.

Table 17 – Net climate change impact on the energy sector in 2050*

Energy consumption	
Petroleum products	-3.6%
Natural gas	2.2%
Electricity	1.3%
CO_2 emissions	-2.6%
Welfare change in Mio USD_{2010}	704
As a % of consumption	0.2%
Production change given in GWh	
Natural gas	497
Hydropower	-816
Renewables	920
Total	601

* percentage change with respect to the reference scenario

References

Bernard Aebischer, Giacomo Catenazzi, George Henderson, and Martin Jakob. Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. In *Saving energy - just do it!* European Council for an Energy Efficient Economy ECEEE, 2007. 3, 12, 23

Paul S. Armington. A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers*, 16 :159–78, 1969. 4

Christian Azar and Hadi Dowlatabadi. A review of technical change in assessment of climate policy. *Annual Review of Energy and the Environment*, 24(1) :513–544, 1999. doi : 10.1146/annurev.energy.24.1.513. URL `http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.energy.24.1.513`. 8

A. Bernard and M. Vielle. GEMINI-E3, A General Equilibrium Model of International-National Interactions between Economy, Energy and the Environment. *Computational Management Science*, 5(3) :173–206, May 2008. 3

Bundesamt für Energie BFE. Grundlagen für die Energiestrategie des Bundesrates ; Frühjahr 2011, Aktualisierung des Energieperpektiven 2035. Technical report, Schweizerische Eidgenossenschaft, 2011. 9

M. Christenson, H. Manz, and D. Gyalistras. Climate warming impact on degree-days and building energy demand in Switzerland. *Energy Conversion and Management*, 47 :671–686, 2006. 3, 10, 11

B. V. Dimaranan. *Global Trade, Assistance, and Production : The GTAP 6 Data Base*. Center for Global Trade Analysis Purdue University, Center for Global Trade Analysis, Purdue University, December 2006. 4

John Dimitropoulos. Energy productivity improvements and the rebound effect : An overview of the state of knowledge. *Energy Policy*, 35(12) :6354 – 6363, 2007. ISSN 0301-4215. doi : 10.1016/j.enpol.2007.07.028. 16

Arbeitsgemeinschaft Ecoplan/Sigmaplan. Auswirkungen der Klimaänderung auf die Schweizer Volkswirtschaft (nationale Einflüsse). Technical report, Swiss Federal Office for the Environment and Swiss Federal Office of Energy, Bern, 2007. 20

Energy Information Administration. International Energy Outlook. Technical report, U.S. Department of Energy, september 2011. 6

Anne-Kathrin Faust, Camille Gonseth, and Marc Vielle. The economic impact of climate driven changes in water availability in switzerland. Technical report, EPFL-REME, 2012. 3

Th. Frank. Climate change impacts on building heating and cooling energy demand in switzerland. *Energy and Buildings*, 37(11) :1175 – 1185, 2005. ISSN 0378-7788. doi : 10.1016/j.enbuild.2005.06.019. URL `http://www.sciencedirect.com/science/article/pii/S0378778805001106`. 3

Camille Gonseth and Marc Vielle. The general equilibrium impacts of climate change for the Swiss ski industry. Technical report, EPFL-REME, 2012. 3

Pascal Horton, Bettina Schaefli, Abdelkader Mezghani, Benoît Hingray, and André Musy. Assessment of climate-change impacts on alpine discharge regimes with climate model uncertainty (2070-2099). *Hydrological Processes*, 20 :2091–2109, 2006. 3

Ronald H. Howell, Harry J. Sauer, and William J. Coad. *Principles of heating, ventilating, and air conditioning.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA., 2005. 11

International Energy Agency. *Energy Balances of OECD Countries.* OECD/IEA, Paris, 2010a. 9, 10

International Energy Agency. *World Energy Outlook 2010.* 2010b. 6

Morna Isaac and Detlef P. van Vuuren. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 37(2) :507 – 521, 2009. ISSN 0301-4215. doi : 10.1016/j.enpol.2008.09.051. URL `http://www.sciencedirect.com/science/article/pii/S0301421508005168`. 10

Santosh Joshi, Marc Vielle, Frédéric Babonneau, Neil Edwards, and Phil Holden. Examining general equilibrium effects of climate change on human health. Technical report, EPFL-REME, 2012. 3

Almut Kirchner, Andreas Kemmler, Peter Hofer, Mario Keller, Martin Jakob, and Giacomo Catenazzi. Analyse des schweizerischen Energieverbrauchs 2000–2009 nach Verwendungszwecken. Technical report, Bundesamt für Energie BFE, Dezember 2010. 10, 11, 12, 15

Kristin Linnerud, Torben K. Mideksa, and Gunnar S. Eskeland. The Impact of Climate Change on Nuclear Power Supply. *The Energy Journal*, 32(1) :149–168, 2011. 18, 19

OcCC and ProClim. Climate change and Switzerland 2050 : Expected impacts on environment, society and economy. Technical report, Organe consultatif sur les changements climatiques, Berne, 2007. 3

Michel Piot. Auswirkungen der Klimaerwärmung auf die Wasserkraftproduktion in der Schweiz. *Wasser Energie Luft. Eau énergie air*, 11/12 2005. 3

Bettina Schaefli, Benoît Hingray, and André Musy. Climate change and hydropower production in the Swiss Alps : quantification of potential impacts and related modelling uncertainties. *Hydrology & Earth System Sciences*, pages 1191–1205, 2007. 3

Pernille Seljom, Eva Rosenberg, Audun Fidje, Jan Erik Haugen, Michaela Meir, John Rekstad, and Thore Jarlset. Modelling the effects of climate change on the energy system — a case study of Norway. *Energy Policy*, 39(11) :7310 – 7321, 2011. ISSN 0301-4215. doi : 10.1016/j.enpol.2011.08.054. URL `http://www.sciencedirect.com/science/article/pii/S0301421511006513`. 10, 23

Detlef P. van Vuuren, John Weyant, and Francisco de la Chesnaye. Multi-gas Scenarios to Stabilize Radiative Forcing. *Energy Economics*, 28(1) :102–120, January 2006. 4

Ian Sue Wing. The synthesis of bottom-up and top-down approaches to climate policy : Electric power technologies and the cost of limiting US CO2 emissions. *Energy Policy*, 34 :3847–3869, 2006. 6