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COSTS AND BENEFITS OF CLIMATE CHANGE IN SWITZERLAND

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Understanding the economic magnitude of climate change (CC) impacts is a prerequisite for developing adequate adaptation strategies. In Switzerland, despite new climate scenarios and impact studies, only few impacts have been monetized. Our objective is to assess costs and opportunities of CC for Switzerland by 2060, while enhancing the assessment methods. Using inputs from bottom-up impact studies, we simulate the economic consequences of climate scenarios in a computable general equilibrium (CGE) framework. We cover health, buildings/infrastructure, energy, water, agriculture, tourism, the spill-overs to other sectors, and international effects. Due to data constraints, significant impacts have not been quantified, e.g., for heat waves and droughts more extreme than the 2060 average climate. For the considered impacts, welfare decreases by 0.37% to 1.37% in 2060 relative to a reference without CC. Higher summer temperatures increase mortality and decrease productivity. Contrariwise, tourism benefits from extended summer seasons. Regarding energy, increased demand for cooling is overcompensated by savings in heating.

Keywords: Climate change impacts; adaptation; Switzerland; computable general equilibrium model.

1. Introduction

For Switzerland, as for other continental regions, climatologists expect a temperature increase much higher than the global average. Even up to 2011, Switzerland has experienced an increase by 1.7°C since the beginning of institutionalized temperature measurements in 1864, while the average on-land warming in the northern hemisphere amounted to 1.1°C (Perroud and Bader, 2013). Under these circumstances, it is necessary to inquire about climatic effects in Switzerland and their economic magnitude. Understanding these effects is a prerequisite for developing adequate adaptation strategies, with the objective to reduce damages and to reap opportunities of climate change (CC). Despite this, there has been little research that would include attempts for monetization over a long period of time.[1] One of the reasons is the complexity and heterogeneity of the subject: Many sectors are involved in very different ways, requiring different types of analyses.

This paper summarizes the results of a research program on the possible costs and opportunities of CC for Switzerland by 2060. The main goal of this program is to bundle, update and complete earlier assessments with a view to producing a full picture of the economic consequences of CC in Switzerland by 2060. This evaluation is performed with a computable general equilibrium (CGE) model, perturbated by a selected number of CC hazards which, based on other studies or our earlier research, are expected to be important in terms of impacts and quantifiable in terms of data availability. Indeed, we cover the majority of significant trend-related hazards. Insufficient data prevent us from simulating the impacts of weather extremes, which are known to be important causes of climate damage.

In order to keep the impacts of the many CC hazards traceable, we simulate them separately in six domains: health, buildings and infrastructure, energy, water management, agriculture, and tourism. The simulations include the spill-over effects from these domains to other sectors. In addition, we simulate all of the modeled hazards jointly to determine interaction effects.

The remainder of the paper is organized as follows. Section 2 briefly details the existing assessments of expected impacts of CC in Switzerland. Section 3 describes the methodology used in this paper. In Sec. 4, we explain how a selected number of CC hazards can affect the Swiss economy and evaluate for each of them the resulting economic impacts. Section 5 provides an overall view of CC impacts in Switzerland and a ranking of the sectoral impacts. The last section concludes the paper.

2. Earlier Economic Assessments of Climate Change Impacts in Switzerland

Although Meier (1998) made a first crude attempt to monetize the possible impacts of CC in Switzerland, it was not before 2007 that the first considerable and encompassing estimation of the costs of CC for the Swiss economy was conducted by

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[1] See the literature overviews in Secs. 2 and 3.1.

Ecoplan/Sigmaplan (2007). This study focused on CC occurring in Switzerland, while another study (INFRAS *et al.*, 2007) estimated the impacts on Switzerland of CC hazards occurring in the rest of the world (ROW). These were the last all-encompassing economic assessments to date of the possible consequences of CC for Switzerland. Ecoplan/Sigmaplan (2007) estimated that there would be hardly any impacts by 2030 and moderate impacts until 2050 (0.15% of gross domestic product (GDP)), but that they would grow substantially until the end of the century, to reach 0.5% of GDP with a large margin of uncertainty, from 0.15% to 1.6%. The authors attributed 40% of that uncertainty to that of the climate scenarios and 60% to the translation of these scenarios into economic losses.

Since the 2007 studies, new climate scenarios were developed (CH2011, 2011) and new impact studies were published. Swiss Confederation (2012) was a first global assessment of the challenges facing all policy fields of Switzerland due to CC hazards. The assessment of the impacts is qualitative, based on published results and expert statements. The report identified priorities for action. It was elaborated by 10 Swiss federal offices and other units and designed as the first part of the national adaptation strategy. The CH2014-Impacts report (CH2014-Impacts, 2014) presents research advancements for various sectors individually, such as tourism, agriculture and energy demand. Its authors translated the climate scenarios CH2011 into quantitative hazards for the cryosphere, hydrology, biodiversity, forests, agriculture, energy use and health. Very few of these hazards are translated into monetized impacts. Comprehensive economic assessments of risks induced by CC were completed in a series of eight cantons that were selected to be each representative of a main geographical region of Switzerland.[2]

3. Methodology

Different approaches can be taken to analyze the impacts of CC in an economic setting, which all have their advantages and shortcomings. Approaches can be descriptive, semiquantitative (e.g., multi-criteria analysis), or quantitative (bottom-up, partial equilibrium, general equilibrium, macroeconomic/econometric models).

The cantonal case studies indicate that CC impacts should not just be considered individually, but also in their interactions. A striking result of these studies is that for individual sectors, socioeconomic changes and their uncertainties are often more important than climate hazards and their uncertainties. These considerations call for an integrated assessment of CC impacts, combining the predicted climate modifications and the expected socioeconomic trends into a coherent model of the Swiss economy.

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[2] The reports for these seven cantons are available: Aargau, Basel-Stadt, Fribourg, Geneva, Graubünden, Ticino and Uri. They are: Ernst Basler + Partner *et al.* (2013), INFRAS and Egli Engineering (2014a,b), INFRAS *et al.* (2015), Bergwelten 21 and GRF Davos (2015), IFEC *et al.* (2016) and Ernst Basler and Partner/CSD Ingenieurs (2015).

3.1. *Literature review*

Recently, Tol (2018) reviewed estimates of the total economic impacts of CC. He distinguished three methods to analyze the economic effects of CC.

Most studies use the so-called *enumerative method*, where several physical effects of CC are multiplied by a price (i.e., a cost) and then summed. The result is an estimate of the direct cost, which does not take into account any interactions between sectors and economic markets.

Some other estimates adopt a *statistical approach*, linking economic variables (through statistical methods) to climate variables and then computing the impact of deviations on the climate variables. For example, some researchers have chosen to estimate economy-wide impacts by regressing GDP or GDP growth per capita for panels of countries on climatic variables such as average temperature or extreme events in addition to other standard determinants of growth (e.g., Burke *et al.*, 2015; Du *et al.*, 2017; Zhao *et al.*, 2018).

Finally, a growing number of studies use CGE models. They take physical effects of CC obtained from natural sciences (like in the *enumerative method*) and integrate them into the CGE model by shocking some associated variables. CGE models are based on neo-classical economic theory and model the whole economy and hence take into account feedback between the different economic agents. They have been used widely for the analysis of CC mitigation policies, and more recently are involved in the estimation of economic effects of CC.

An early study that used a CGE model to estimate economy-wide impacts of CC is that of Jorgenson *et al.* (2004), who estimated the costs of CC for the USA for a range of climate scenarios up to 2100. The climate effects are captured through percentage changes in unit production costs (or total factor productivity) for the agriculture, forestry, energy and water sectors. Sea-level rise is expressed as a diversion of investment from other uses and the health and mortality impacts are expressed as reductions in the numbers of consumers and potential labor supply. The impacts for other sectors such as tourism are not taken into account, nor trade effects from CC impacts in other parts of the world. Abler *et al.* (2009) used a dynamic CGE calibrated to the State of Pennsylvania, the USA and world economies to assess statewide market impacts of CC. They represented 32 sectors of which 16 were defined as climate sensitive, of which 13 represent food and wood production and processing and the other water supply and energy demand. Sectoral estimates of CC impacts are used to modify the productivity of the concerned sectors. In this study, trade with the rest of the USA and the world plays some role. However, the direct impacts of CC on some sectors such as tourism and on health and labor productivity are not represented. A third assessment of CC impacts in the USA based on a CGE was obtained by the large team of Houser *et al.* (2015). They examine first CC impacts in a range of areas, before aggregating them to macroeconomic effects up to 2100. The CC impacts on agriculture are represented as a percentage decrease in total factor productivity. Health effects are captured through changes in the size and composition of the population and in labor supply. Impacts on energy demand are represented by proportional changes in expenditure. The rising sea level reduces exposed capital stocks. Impacts on tourism and international trade are ignored in the simulations.

Studies taking into account an international perspective involve world multi-sector CGE models where several regions are represented. Ciscar *et al.* (2012) used the GEM-E3 model to estimate the impacts of CC in Europe on agriculture, river floods, coastal systems and tourism. They found that the EU welfare loss ranges from 0.2% to 1% depending on the climate scenario. OECD (2015) extended the analysis by adding impacts on health and energy demand and by considering not only Europe but also 22 other regions. They concluded that net economic consequences are projected to be negative in 23 of the 25 regions. They are especially large in Africa and Asia. Finally, Roson and Sartori (2016) aimed at systematizing the analysis and estimated for all 140 countries and regions of the GTAP model the impacts of CC. Their findings confirm that the negative effects of CC will be mainly borne by developing countries, located in tropical regions.

3.2. ***A general equilibrium framework***

Adding to this stream of literature, we choose to investigate the CC costs and benefits with the help of a general equilibrium framework and present options to model CC impacts and adaptation within that framework. Based on an analysis of existing research gaps, we opt for an approach which builds up information and model inputs sector by sector, such that, at least in principle, the analysis integrates information from all kinds of studies. Of course, this is hardly possible without any consistency issues, although we build our approach as much as possible on sources which use the same or similar scenarios as well as compatible methods. The need to combine sources with very different methodological backgrounds reflects the state of affairs in the research on the impacts of CC: detailed sector-by-sector approaches to determine economic impacts of CC are still relatively new (e.g., Dowling, 2013; Faust *et al.*, 2015; Gonseth *et al.*, 2017; Gonseth and Vielle, 2018; Holzkämper *et al.*, 2015; Wiebe *et al.*, 2015). At the same time, the field involves many sectors, individual impacts, determinants and uncertainties. As a consequence, the research field will remain lively and challenging for many years to come.

We build on the existing literature, but take things further with a more comprehensive quantitative assessment. We use a general equilibrium approach, because intersectoral dependencies, feedbacks within the economy and international impacts are crucial for the analysis of impacts of CC in Switzerland. Indeed, due to the fact that sectors compete for factors of production and that the outputs of some sectors might serve as intermediate inputs for other sectors, the impact of CC on one sector of the economy might have noticeable effects on related sectors. Also, domestic CC impacts could be small for some sectors. However, due to international trade, significant impacts of CC in other countries could be transmitted to Switzerland and have non-negligible effects on the economy.

3.3. *The GEMINI-E3 model*

GEMINI-E3[3] is a multi-country, multi-sector, recursive CGE model comparable to many other CGE models as e.g., EPPA (Henry Chen *et al.*, 2017) and OECD Env–Linkage (Château *et al.*, 2014) built and implemented by other modeling teams and institutions, and shares 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 the 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 endogenous) and the microeconomic or sector markets (goods, factors of production). The model is built on the Swiss input–output table (Nathani *et al.*, 2011) and the GTAP database version 8 (Narayanan *et al.*, 2012) for the other countries.

For each sector, the model computes the demand for its production on the basis of household consumption (HC), 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 domestic product is distinguished from an imported product of the same industry. All goods are traded in world markets and bilateral trade flows are also represented through the Armington assumption. Production technologies are described by nested constant elasticity of substitution (CES) functions.

Time periods are linked through endogenous real interest rates that equate savings and investment. Capital is not mobile across regions. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses.

The sectoral structure of the model has been extended in order to assess the economic impact of CC hazards on particularly vulnerable sectors, such as tourism, agriculture and water distribution. We represent 21 sectors: Appendix A presents this classification. With regard to the regions represented by this model, we use an aggregated version of GEMINI-E3 that describes six countries/regions: Switzerland (CH), the European Union (EU), the United States of America (USA), other developed countries (OECD), BRIC (Brazil, Russia, India and China) and the ROW.

3.4. *Climate scenarios*

For the sake of comparability, we based our analysis on the three scenarios used in CH2011 (2011) and CH2014-Impacts (2014): A1B, A2 and RCP3PD. Climate projections for the A1B scenario are based on a combination of global and regional circulation models used in the ENSEMBLES project (van der Linden and Mitchell,

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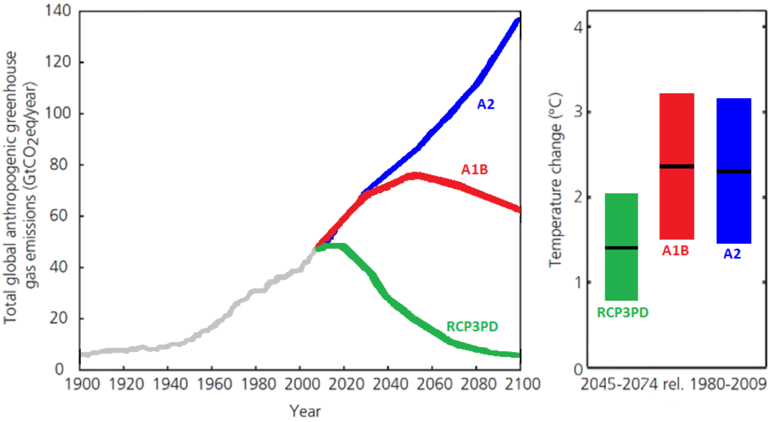
[3] All information about the model can be found at http://gemini-e3.epfl.ch/, including its complete description.



Source: CH2011 (2011).

Figure 1. Pathways of past and future anthropogenic greenhouse gas emissions and projected annual mean warming for Switzerland for the 30-year average centered at 2060.

2009), while A2 and RCP3PD data were obtained using a pattern scaling method (CH2011, 2011). Figure 1 shows the assumed global greenhouse gas emissions pathways and the corresponding projected mean temperature changes for Switzerland (average of 2045–2074 relative to the average of 1980–2009) as presented in CH2011 (2011).

A2 assumes high population growth and continued use of fossil fuels. By contrast, the A1B scenario assumes rapid economic growth and high technical progress. This reduces the dependence on fossil fuel and slows down population growth in the second half of the century. For 2060, the reference year of this analysis, temperature differences between A2 and A1B are very small. RCP3PD is an ambitious climate mitigation scenario, which has a 2/3 likelihood of limiting global warming to 2°C above the preindustrial level.

For each of the three scenarios, we simulate impacts from the medium projected climate as well as from the upper and lower ends of a range corresponding formally to the 95% confidence interval generated by the climate model simulations. In fact, according to CH2014-Impacts (2014), “the expected chance that actual observed values will fall between the upper and the lower values is two in three for temperatures, and one in two for precipitation.” Adding socioeconomic uncertainties to the picture further reduces the probability that the actual values will fall within the depicted ranges. This means that “upper” and “lower” should not be interpreted as confidence intervals. Rather, they represent possible ranges, which are consistent with the available data.

3.5. *Socioeconomic assumptions*

To simulate the evolution of the economy until 2060, GEMINI-E3 uses projections of population growth, GDP and energy prices. We use the evolution of the Swiss population as defined by the scenario from the Federal Statistical Office. In 2060, 10.6 million inhabitants are projected to live in Switzerland. For the ROW, assumptions on population are based on the latest forecast by the United Nations. We use the "median-fertility variant." In 2060, the world population reaches 10.2 billion inhabitants.

For Switzerland, GDP growth is forecasted by the State Secretariat for Economic Affairs by multiplying the labor force (coming from the demographic scenario) with a labor productivity increase of 0.9% per year. For the ROW, we apply a similar methodology that is calibrated from the World Energy Outlook (WEO) (International Energy Agency, 2015).

Finally, assumptions concerning energy prices are also drawn from the WEO. The scenarios presented in this report assume, for the sake of simplification, that no stringent climate policy is implemented. Therefore, we retain the WEO scenario called "Current Policies Scenario." The predictions of the WEO stop in 2040. After that, we assume that energy prices will continue to grow at the rate of the previous decade. The oil price and the price of imported gas in Europe are assumed to reach 198 US$ per barrel and 16.7 US$ per Mbtu in 2060, respectively.

The basic assumptions about demographic and economic growth are not modified between scenarios. Sectoral impacts are taken into account in the general equilibrium analysis, but the fundamental drivers of growth can be considered robust to the CC impacts up to 2060. This avoids that differences in results arise mainly because of differences in socioeconomic assumptions rather than because of the CC hazards we are interested in.

4. Climate-Sensitive Areas

4.1. *Health*

A major part of CC impacts on health comes along with extreme weather events such as heat waves, droughts and floods. According to the literature, heat waves constitute the highest CC hazard for human health in Switzerland (OcCC and ProClim, 2007; Ecoplan/Sigmaplan, 2007). Data availability and the challenge of monetization are the key issues when including health effects in a CGE analysis. Given the available data, we consider two health impacts in our model. Each of them can be attributed to very high temperatures during summer months:

- Excess mortality from cardiovascular and respiratory diseases due to heat stress;
- Loss of productivity of the workforce due to heat stress.

We also considered including increased health expenditures through hospitalizations due to heat stress. However, we abandoned the idea after our first calculations showed increases well below 0.01%, at least in the absence of extreme heat events.

Table 1. CC impacts on additional premature deaths due to cardiovascular and respiratory diseases in 2060.

	RCP3PD			A1B			A2		
	Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
Premature deaths	213	380	532	402	662	928	337	641	877
In million CHF 2016	2145	3820	5352	4045	6658	9331	3389	6449	8818
HC (%)	0.33	0.59	0.82	0.62	1.02	1.43	0.52	0.99	1.35

Note: HC: Household consumption.

4.1.1. *Mortality*

We use the linear relationships between the number of days with daily maximum temperature above a certain threshold and an increase of mortality computed from Paci (2014). We compute the impacts by differentiating the population with respect to age and gender. Table 1 shows the impact of additional premature deaths that can be attributed to CC in 2060. For the A1B and A2 scenarios, about 650 premature deaths are estimated for the medium case, whereas the upper extremes with 928 (A1B) and 877 (A2) reach the level of excess mortality caused by the 2003 and 2015 heat waves. These figures show the number of premature deaths caused by cardiovascular and respiratory diseases on days with maximum temperature above certain thresholds. They do not cover heat wave effects that arise during a period of consecutive days with high temperatures.[4] In the high emission scenarios, excess mortality reaches a level in 2060 which today is attained only by exceptional heat waves. Thus, we were not able to project damages and return periods for a heat event which would be more extreme than the 2060 average climate. However, as such events could come with a large death toll, it would be important to include them in the analysis.

The welfare cost associated with these premature deaths is calculated by multiplying the number of deaths by the standard value of a statistical life (VSL) in Switzerland. This VSL, used for the planning of natural hazard protection, is equal to 6.5 million CHF.[5] Taking into account income growth equal to our GDP projection, the VSL reaches 10 million CHF in 2060. Like in the PESETA project (Ciscar *et al.*, 2012), this cost is not introduced in the GEMINI-E3 model, but simply added to the final welfare change computed by the model (see Sec. 5). Table 1 shows the CC impact on mortality in 2060.

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[4] The magnitude of heat wave effects varies with duration and intensity of heat waves and geographical location. An analysis of nine European cities by D'Ippoliti *et al.* (2010) showed an average increase in mortality among people over 65 years on heat wave days between 12.4% in the North Continental and 21.8% in the Mediterranean area.

[5] It is based on recent international transfer of values (Ecoplan, 2016) from a large willingness-to-pay meta-study (OECD, 2012).

4.1.2. *Productivity*

A causal link between temperature and labor productivity is documented in various studies based on biological evidence relating to human physiology (e.g., Seppänen *et al.*, 2006). Other research has investigated correlations of temperature with economic variables such as labor supply, wages, GDP, and highlights the need to integrate behavioral responses and cross-sectoral effects (see the overview in Heal and Park, 2016). Exposure-response functions relating temperature to labor productivity allow for differentiating by work intensity and indoor versus outdoor workplaces (Costa *et al.*, 2016). Since the influence of humidity is essential for the reaction of the human body to temperature, these functions are based on Wet Bulb Globe Temperature (WBGT), which entails both temperature and humidity. Unfortunately, WBGT data are not available for Switzerland.[6]

We are thus confined to simplified approaches. Following the cantonal case studies, we set the productivity loss on a day with maximum temperature at 30°C or higher at 7%. This does not take into account how long or how far above the threshold temperature rises, which may lead to an underestimation of the impact. Furthermore, we do not consider any depreciation in physical or mental capacity in the temperature range from 26°C to 30°C. We assume that economic activity is distributed evenly over the 365 days of a year and that every member of the workforce is affected in the same manner independent of the location of the workplace (indoor/outdoor) or air-conditioning. The latter simplification is necessary, because there is no data available on the share of outdoor workers for Switzerland, neither for other countries. The impact of CC is calculated by deducting the number of hot days in the reference scenario from the respective numbers in the climate scenarios. Table 2 depicts the results of the CGE simulations with respect to productivity loss on hot days. It shows that high temperatures are going to have tangible effects on the economy in the course of CC. In the RCP3PD scenario, the decrease of HC due to productivity loss is still relatively small,

Table 2. CC welfare impacts due to productivity loss — percentage change with respect to reference case in 2060.

	RCP3PD			A1B			A2		
	Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
Welfare change[a]	−0.09	−0.17	−0.23	−0.17	−0.31	−0.41	−0.14	−0.31	−0.42

Note: [a]In % of households consumption.

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[6] In an exploratory analysis, we approximated WBGT with data of air temperature, wind speed, solar radiation and relative humidity from MeteoSwiss (hourly data for the worktime 8–12 h and 13–17 h), following the algorithm of Liljegren *et al.* (2008). We confined the analysis to the year 2003, which had a particularly hot summer. In the end, we have to accept that it is infeasible within our study to apply this approach to the climate scenarios in this paper.

ranging from 0.09% at the lower bound to 0.23% at the upper bound. However, at the upper ends of the A1B and A2 scenarios, it reaches more than 0.4% of HC.

4.2. *Energy*

4.2.1. *Domestic impacts*

CC affects the energy sector on both the demand and the supply sides.

On the supply side, the literature focuses on the effects of CC on hydropower production through a change in water flow regimes. Changes in runoff regimes are caused by changes in precipitation schemes as well as by temperature changes that affect melt water runoff from glaciers and snow cover. Hydropower is currently the most important source of electricity in Switzerland, accounting for approximately 60% of total electricity generation. While some seasonal shifts in runoff patterns may occur, the overall effect on hydropower production is expected to be small until 2060 (CH2014-Impacts, 2014). In a synthesis report on the impacts of CC on hydropower, Weingartner *et al.* (2011) present temporally and spatially heterogeneous effects; while the Southern regions, especially Valais, can expect a slightly negative development of hydropower production volumes, the opposite is true for the alpine foothills. In the temporal dimension, increased meltwater flow from glaciers may continue pushing production volumes, but this effect may eventually revert, when many of those glaciers will have disappeared and cease producing meltwater altogether. The report concludes that near future changes in production volumes can be expected to be small, while producing country-wide results for the more distant future remains difficult. Economic valuations are presented by the cantonal case studies, which quantify the expected hydropower production change in 2060 with mixed results. The Aargau case study (Ernst Basler + Partner *et al.*, 2013), for example, projects the expected economic impact on hydropower production due to a changed precipitation regime to be small in comparison to the impacts on the energy demand side. Hydropower production is projected to rise by 0.4% to 2.4%. Fribourg, on the other hand, expects precipitation and hydropower production to decrease by 2.5% to 4.9%. Even stronger decreases are projected for the Canton Ticino, in the range of 4.2% to 6.8%. As these regional results are ambiguous in a national setting and of rather small magnitude, we assume for the simulations that the Swiss electricity production sector would not be affected by CC.

We thus concentrate on energy demand, where the literature focuses on the effects of CC for energy demand for heating and for cooling, due to the expected increase in average temperatures in winter and summer. Recently, approximately a third of Switzerland's total final energy use is directed toward space heating, while around 2.5% is used for space cooling and ventilation (Kemmler *et al.*, 2015). About three quarters of heating energy come from oil and natural gas.

The change in heating and cooling energy demand is incorporated into GEMINI-E3 using the methodology developed by Gonseth *et al.* (2017). The numbers of heating degree days (HDDs) and cooling degree days (CDDs) sum up differences between the outside temperature and a given interior target temperature to approximate energy demand for that particular year. For our target year 2060, HDDs are calculated as follows:

$$\mathrm{HDD}_{2060}(\theta^*, \theta_{\mathrm{th}}) = \sum_{k=1}^{365} m_k(\theta_{\mathrm{th}}) \cdot (\theta^* - \theta_k) \tag{1}$$

with $m_k(\theta_{\mathrm{th}}) = 1$ if $\theta_k \leq \theta_{\mathrm{th}}$ and $m_k(\theta_{\mathrm{th}}) = 0$ otherwise.

In this equation, θ^* is the target interior temperature, θ_k is the average daily temperature for day k and θ_{th} is the threshold outside temperature under which heating becomes necessary. The formula for HDD computes and sums daily differences between the target inside temperature and the outside temperature, but only when the daily mean temperature is lower than the threshold temperature in order to account for housing insulation. Values of the parameters of Eq. (1) that are commonly used for Switzerland are: $\theta^* = 20°\mathrm{C}$ and $\theta_{\mathrm{th}} = 12°\mathrm{C}$ (Christenson *et al.*, 2006; Kirchner *et al.*, 2010). Following Christenson *et al.* (2006), we assume that the energy demand for heating is proportional to the value of HDD.

The same method is applied for cooling energy demand and CDD. Cooling is only required when the outside temperature rises above the chosen threshold of 18.3°C (Christenson *et al.*, 2006; Kirchner *et al.*, 2010; Gonseth *et al.*, 2017). With the help of a linear relation, the summed up CDD are then converted to specific electricity demand per surface, D_{spec}. More specifically, this relationship is quantified using the same approach as in the article by Gonseth *et al.* (2017), which in turn relies on a method presented by Aebischer *et al.* (2007):

$$D_{2060}^{\mathrm{spec}} = \frac{12.7 + 0.103 \times \mathrm{CDD}_{2060}}{(1 + \tau_{\mathrm{cooling}})^{2060-b}}. \tag{2}$$

Equation (2) presents the estimation of the annual specific electricity demand in kWh per m^2 for cooled surfaces in 2060, D_{2060}^{spec}. Ceteris paribus, an additional CDD, thus increases electricity demand by 0.103 kWh per cooled m^2. τ_{cooling} represents technical progress, which is assumed to decrease specific energy requirement by 0.5% annually, starting from base year b (2008). In addition to this demand change by surface area, future cooling energy demand depends on the development of the total commercial and residential area. A special challenge with cooling energy demand is that the currently low share of cooled surfaces is likely to increase with CC. To incorporate this effect, we use the estimation by Aebischer *et al.* (2007) for the future share of cooled area, which projects partially cooled surfaces to reach 40% and fully cooled surfaces 30% by 2060 (up from 20% and 19%, respectively, in 2000). Putting the pieces together, total electricity demand from cooling in 2060, E_{2060}, is projected using the following equation:

$$E_{2060} = D_{2060}^{\mathrm{spec}} \times \mathrm{Surface} \times \left(\alpha^{\mathrm{full}} + \frac{\alpha^{\mathrm{part}}}{4}\right), \tag{3}$$

where α^{full} and α^{part} correspond to the share of fully and partly cooled surfaces, respectively.

In Switzerland, global warming leads to a decrease in heating energy demand, which is partly countered by an increased energy demand for space cooling. The GEMINI-E3 simulation shows that the overall energy demand would decrease in 2060 under all three CC scenarios (see Table 3). The effect is more pronounced for the scenarios A1B and A2 (-1.74% and -1.70% energy consumption in the medium cases), which exhibit stronger warming than the RCP3PD scenario (-1.02%). This implies not only that the decrease in energy demand for heating outweighs the increase in energy demand for cooling, but also that this gap widens as temperature increases. The changing pattern of energy usage can also explain the shift in the energy mix. The decrease in petroleum products can be attributed to a lower demand in heating oil. The projection with the weakest CC effect, RCP3PD lower, shows a decrease in petroleum product consumption of 1.13%, while the projection for A1B upper, which contains the strongest CC signal, shows a decrease of 4.68%. Electricity consumption, on the other hand, increases relatively strong (1.81–5.05%), which is due to the sharply increasing demand for cooling being predominantly powered by electricity. By 2060, a considerable part of this additional electricity is assumed to be generated from natural gas, counteracting some of the CO_2 emission decreases caused by lower overall fossil fuel consumption. In total, the lower net energy consumption involves a welfare gain from 0.15% (RCP3PD medium) to 0.25% (A1B medium). Such positive welfare effects in the energy sector as we project for Switzerland can also be expected in other countries where the reduction in heating demand dominates. Nevertheless, these results should be regarded in the light of the underlying uncertainties. On the demand side, the future development of cooling is particularly hard to estimate, as current levels are very low. Hot summers, such as experienced recently in 2015 and 2018, could spur a quick increase in cooling in commercial and residential buildings. On the supply side, seasonal changes in run-off patterns may have a profound impact on hydropower production.

Table 3. CC impact on heating and cooling demand in Switzerland, change to reference in 2060.

	RCP3PD			A1B			A2		
	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)
Energy consumption	−0.40	−1.02	−1.62	−0.97	−1.74	−2.42	−0.93	−1.70	−2.38
Petroleum products	−1.13	−2.11	−3.11	−2.12	−3.42	−4.68	−2.05	−3.36	−4.61
Natural gas	−0.90	−2.06	−3.19	−1.99	−3.45	−4.77	−1.92	−3.39	−4.70
Electricity	1.81	2.51	3.30	2.68	3.78	5.05	2.63	3.71	4.95
District heating	−2.37	−4.39	−6.44	−4.41	−7.10	−9.71	−4.27	−6.97	−9.55
Welfare change[a]	0.07	0.15	0.22	0.15	0.25	0.34	0.14	0.24	0.33

Note: [a]In % of HC.

Table 4. CC impact on European electricity prices, change to reference in 2060.

	RCP3PD			A1B			A2		
	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)
EU	1.23	3.08	4.93	−0.49	−0.79	−1.22	−0.46	−0.78	−1.24
Germany	1.65	4.11	6.58	−6.14	−9.83	−15.23	−5.72	−9.72	−15.44
France	2.88	7.20	11.51	1.72	2.75	4.26	1.60	2.72	4.32
Italy	0.41	1.03	1.64	0.74	1.18	1.83	0.69	1.17	1.85
Austria	−0.41	−1.03	−1.64	0.49	0.79	1.22	0.46	0.78	1.24

Source: Calculations on the basis of data from Dowling (2013).

However, such seasonal shifts are outside the scope of this study. Furthermore, these numbers reflect the CC impact only, while the mitigation effort is kept constant between the climate scenarios.

4.2.2. *International price effects*

As Switzerland is a landlocked country and possesses large capacity for international power exchange,[7] development of electricity prices in the neighboring countries also affect Swiss prices and ultimately demand. For this reason, we incorporate the development of the electricity prices of Switzerland's European neighbors into GEMINI-E3, as predicted with the POLES model (Dowling, 2013). This study states relative CC cost impacts for individual European countries. Furthermore, the model is run under two climate scenarios and with four different climate models. Incorporated into the POLES model are both supply and demand side climate effects. On the supply side, the following CC effects are modeled:

- efficiency decrease of thermal power plants due to a lack of cooling water;
- change in productivity of renewable generation systems (hydro, wind and photovoltaic) due to an altered climate regime.

On the demand side, the effects of the changing temperature regime on both heating and cooling energy demand are modeled. The relative change resulting in the electricity production cost from all these effects in each country is then incorporated into GEMINI-E3's price signal for the electricity traded with other countries.

Dowling (2013) reported the values for both 2030 and 2050 for the A1B and the E1 CC scenarios. The E1 climate scenario was created by the European ENSEMBLES[8]

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[7] In 2015, Switzerland imported 42.3 TWh (73% of end use) and exported 43.3 TWh (74% of end use), with the largest part of imports coming from France and the largest outward flows directed to Italy.

[8] http://ensembles-eu.metoffice.com/data.html.

Table 5. Impacts of foreign electricity price changes on Switzerland, change to reference in 2060.

	RCP3PD			A1B			A2		
	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)
Electricity cons. price	0.61	1.52	2.42	−0.09	−0.14	−0.22	−0.08	−0.14	−0.22
Electricity generation	0.13	0.32	0.51	−0.02	−0.03	−0.05	−0.02	−0.03	−0.05
Welfare change[a]	−0.01	−0.02	−0.03	0.00	0.00	0.00	0.00	0.00	0.00

Note: [a]In % of HC.

project and is similar to RCP3PD. We use the 2050 values presented in the work by Dowling (2013) as a basis to estimate the values for 2060 for the three scenarios simulated in this study (A1B, A2 and RCP3PD). We made adjustments along two dimensions to obtain the data for our purposes: the climate scenario and the temporal dimensions. For both dimensions, we assumed linear relationships between the change in the electricity price and the radiative forcing and inflated or deflated the results obtained by Dowling (2013) along radiative forcing. Table 4 shows the results of this calculation, that is the changes that are applied to European electricity prices in the GEMINI-E3 model runs.

Although electricity prices change significantly in some countries, due in particular to mitigation costs for scenario RCP3PD, the impacts of these price changes for Switzerland are very small (see Table 5). The main reasons for this are the following:

- Import prices do not change much on average. Especially for A1B and A2, price increases in France are more than compensated by price decreases in Germany.
- The international exchange of electricity increased considerably in recent years. Swiss imports and exports each almost match domestic electricity generation. Yet, the net balance of trade in electricity is small. Depending on the future regulation of electricity markets, Swiss generation costs, which we assume to remain unaffected by CC, will continue to influence end-user prices to a considerable extent, especially for households. In scenario RCP3PD, Swiss generation even gains importance. It increases by about 0.3%, because mitigation efforts abroad become a comparative disadvantage for foreign producers.
- While wholesale electricity prices are rather closely linked to generation costs, this is less true for end-user prices, especially for households.
- Electricity consumption represents a small and shrinking share of household budgets, about half a percent in 2060.

While the changes in French and German electricity markets will be an issue for managers in the Swiss electricity sector, the effects on Swiss consumers are very small. Where they exist, they are mostly a consequence of foreign mitigation measures in the electricity sector (scenario RCP3PD), not of modified climatic conditions.

4.3. *Agriculture*

Agricultural production is exposed to a variety of CC hazards. The Federal Council's adaptation strategy (Swiss Confederation, 2012) identifies six such hazards: site suitability, heavy rainfall, drought, heat stress, pests and price volatility. Henne *et al.* (2018) provided a recent compilation of CC impacts in Switzerland with a focus on agriculture. They state that due to the variety of factors that influence performance in agricultural production, such as breeding, management options, etc., it is difficult to attribute impacts to CC. Further, due to the complex topography of Switzerland and resulting local variations in weather outcomes, inference about potential impacts of CC can only be drawn for subregions of Switzerland. Such an example is provided by Holzkämper *et al.* (2015), where impacts of a changing climate on potential grain maize yields for the temporal scope of 2036–2065 are projected for three climatic regions in Switzerland. Results indicate that there are large uncertainties from both climate model chains and impact model approaches. For the case of grain maize, yield increases are projected for two regions, and a decrease for one region. Overall, Swiss agriculture could benefit from improved site suitability resulting from rising temperatures in some regions, and be adversely affected by changes in precipitation patterns (Henne *et al.*, 2018). However, since the empirical basis for an economic quantification of impacts is still scarce and does not allow for a level of aggregation that is necessary for CGE modeling, we concentrate on international price effects in the quantitative assessment.

Some world regions, e.g., South America and parts of Asia, are highly exposed and vulnerable to negative impacts of CC (Rosenzweig *et al.*, 2014). As one-third of Switzerland's agricultural imports originate from these regions, the impacts could be significant for Switzerland, e.g., in the form of higher prices for agricultural imports (INFRAS *et al.*, 2007) and thus shifts in agricultural terms of trade.

Several studies offer information about CC induced price changes (Nelson *et al.*, 2014; Rosenzweig *et al.*, 2014). Wiebe *et al.* (2015) combine multiple climate and economic models to estimate the global and regional impacts of CC on agricultural yields and prices. To our knowledge, it is the only study that models different emission scenarios as well as price impacts for several crops. Thus, we use the price impacts derived in that study as data basis. Wiebe *et al.* (2015) make projections for four socioeconomic and climate scenarios: no CC, SSP1-RCP4.5, SSP2-RCP6.0 and SSP3-RCP8.5. Prices are reported for 2030 and 2050, and the percent deviations for the different emission scenarios are calculated relative to values without CC.

To derive input data from Wiebe *et al.* (2015) for our emission scenarios and temporal scope, some data treatment is necessary. According to IPCC (2013), RCP4.5 results in approximately the same temperature change in 2040 as RCP3PD in 2060. In the absence of better information, we simply assume that the impacts on prices in the agricultural sector are linearly correlated with temperature increases. We thus project prices for RCP3PD in 2060 based on prices for RCP4.5 in 2040:

$$\triangle P_{2060}(\text{RCP3PD}) = \triangle P_{2030}(\text{RCP4.5}) + \frac{\triangle P_{2050}(\text{RCP4.5}) - \triangle P_{2030}(\text{RCP4.5})}{2}. \quad (4)$$

Further, as an estimation for price deviations in scenarios A1B and A2 in 2060, a linear function is derived from temperature change and price deviations of RCP6.0 in 2050 and applied to temperature change in A1B and A2.

Wiebe *et al.* (2015) model impacts on the crops coarse grains, rice, wheat, oilseeds and sugar, with the first four being aggregated to the group "grains and oil seeds." They simulate 15 model runs (3 climate models combined with 5 economic models); we take the lowest/highest value for lower/upper and the mean of the 15 model runs. The projections for 2060, which are used as inputs to GEMINI-E3, are shown in Table 6.

The price changes presented above originate from costs and production changes for grains and oilseeds in the different world regions. They are replicated endogenously in GEMINI-E3 through changes in the productivity of inputs used in agriculture. The nested CES structure that is used to represent agricultural production is shown in B. These productivity changes lead to higher production costs and production declines in most regions (see Fig. 2), such that market prices change as defined in Table 6. On a global average, the production of grains and oilseeds declines by 3.4% in the A1B scenario. For Switzerland, we assume no direct CC impacts on production; nevertheless, it increases by about 4% for A1B and A2 due to the comparative productivity improvement implied by productivity reductions abroad.

The changes in prices and quantities translate into considerable welfare changes at least for some parts of the world (see Fig. 3). For example, the welfare reductions for BRIC and ROW countries are about 0.4% and 0.5%, respectively, in the A1B and A2 scenarios. The impacts are more severe in developing and emerging countries since their economies rely heavily on agriculture, especially grains and oilseeds productions. The projected welfare losses for Switzerland are 0.02% for A1B and A2 (up to 0.05%

Table 6. Price deviations for grains and oil seeds (% deviation from reference scenario in 2060).

	RCP3PD			A1B			A2		
	Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
CH	—	—	—	—	—	—	—	—	—
EU	1.3	7.1	16.1	2.7	13.4	31.6	2.5	13.3	32.0
OECD	−1.0	7.8	29.6	0.6	11.2	36.3	0.6	11.1	36.8
USA	0.9	6.0	13.9	0.8	7.2	23.7	0.8	7.2	24.0
BRIC	−3.6	5.8	14.8	4.8	15.8	30.8	4.5	15.6	30.8
ROW	0.3	6.9	15.8	4.3	13.4	30.6	4.0	13.2	31.0

Source: Calculations on the basis of data from Wiebe *et al.* (2015).

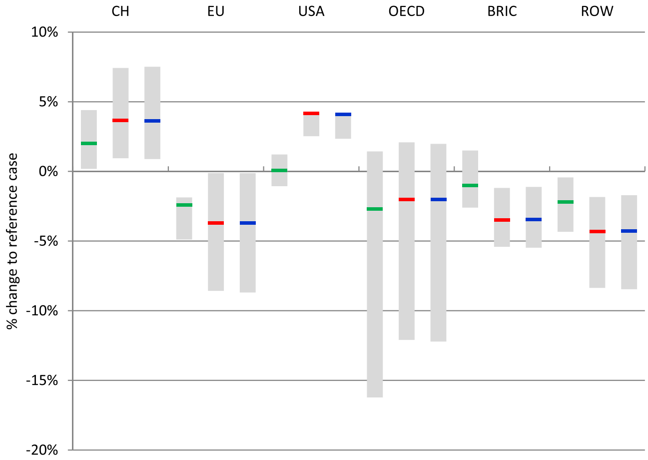

Figure 2. Production of grains and oilseeds under the three scenarios in 2060 (% deviation from reference scenario).

in the upper range, 0.03% for RCP3PD medium). This reflects the low dependency of the Swiss economy on agriculture.

4.4. *Water management*

We include in water management the preparation and distribution of drinking water and industrial water (used in irrigation, production and cooling), as well as the collection, treatment and disposal of waste water. According to the CH2014-Impacts (2014) report, Swiss total annual river runoff will remain approximately constant in 2060. However, seasonal patterns of water resources will shift, decreasing in summer and increasing in winter. This will mainly affect the irrigation of crop farming and

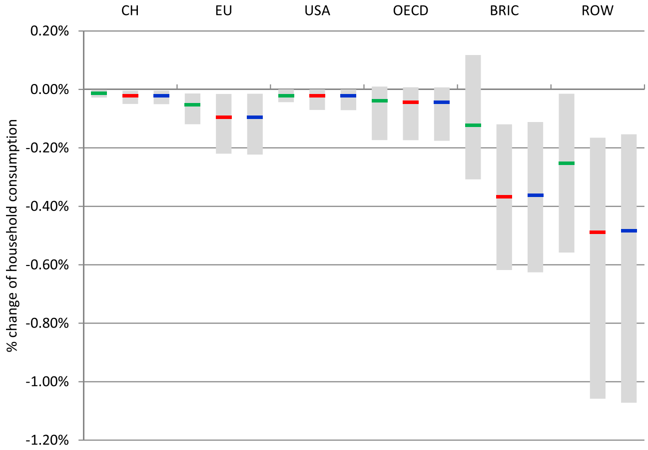

Figure 3. Regional welfare changes due to impacts on agriculture under the three scenarios.

horticulture (i.e., plant production). We thus concentrate on climate-induced changes in summer river runoff used for plant production in Switzerland.

Raw water resources are introduced as a production factor into the model and a drinking water distribution sector is specified for Switzerland to allow for a precise analysis of the economic consequences of restricted water supply (see for more details, Appendix B and Faust *et al.* (2015)).

In the absence of extreme droughts, water scarcity is an issue in only few agricultural areas of Switzerland. Regions where demand potentially reaches a critical share of river runoff supply are identified by Fuhrer and Calanca (2014). For eight critical regions and based on cantonal data, we estimate vulnerable plant production as a share of total plant production in Switzerland in 2015. Summer runoff changes are only applied to the affected shares of Swiss plant production. The weighted changes in the critical regions are aggregated to attain numbers for Switzerland as a whole. Given that the critical regions contribute only 21% of total plant production, the change in critical summer runoff is small relative to total summer runoff in Switzerland. In addition, we consider that summer runoff accounts for 60% of the total irrigation water resource, the remainder being groundwater. As a result, critical changes of the irrigation water resource represent only a small fraction of the total irrigation water resource for Switzerland (see Table 7).

With the input data presented above, it comes as no surprise that the macroeconomic impacts are extremely small. Welfare changes in terms of total consumption do not exceed 5.4 million CHF of 2016 (Table 8). Even if price changes for raw irrigation water are large, impacts are modest, because price levels for raw water and the cost share in agricultural production are extremely low. Hence, the low welfare effect and the high price changes for raw water can both be explained, because there is no need for agricultural producers to change their decisions, even if prices change. Moreover, the small macro-economic importance of plant production further limits the significance of the impacts.

4.5. *Tourism*

Being highly dependent on weather and climate, the tourism industry is particularly vulnerable to CC impacts. It represents a significant part of the Swiss economy,

Table 7. Critical changes of the irrigation water resource (% deviation from total irrigation water resource in the reference scenario in 2060).

RCP3PD			A1B			A2		
Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
−0.50%	−4.73%	−8.04%	−2.62%	−6.49%	−10.89%	−2.19%	−6.06%	−10.46%

Source: Own calculations based on information and data from.
CH2014-Impacts (2014), Fuhrer and Calanca (2014) and Köplin *et al.* (2012).

Table 8. Impacts of changes in the irrigation water resource (% deviation from reference scenario in 2060).

	RCP3PD			A1B			A2		
	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)	Lower (%)	Medium (%)	Upper (%)
Raw water prices	6.7	73.7	139.3	37.9	107.0	206.2	31.2	98.5	195.4
Raw water consumption									
Grains and oil seeds	−0.5	−4.5	−7.7	−2.5	−6.2	−10.5	−2.1	−5.8	−10.1
Other crops	−0.6	−5.1	−8.7	−2.8	−7.0	−11.7	−2.4	−6.5	−11.3
Production									
Grains and oil seeds	0.0	−0.2	−0.3	−0.1	−0.2	−0.4	−0.1	−0.2	−0.4
Other crops	0.0	−0.1	−0.1	0.0	−0.1	−0.2	0.0	−0.1	−0.2
Welfare change[a]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: [a]In % of HC.

accounting for 2.6% of GDP and for 4.1% of total employment in 2015 (FSO), with high regional disparity. Regarding CC, winter tourism seems particularly affected. The increase in temperatures will decrease the annual mean snow depth by about 50% in 2060, and the number of snow-reliable ski areas could decrease by 29% in the A2 scenario and without snowmaking (CH2014-Impacts, 2014). On the other hand, tourism in general could benefit from a longer summer season. The emergence of new lakes in the alpine regions, the development of new trails and climbing routes due to glacier retreat and an improvement of the thermal comfort could make Switzerland more attractive (Matasci, 2010).

Gonseth and Vielle (2018) performed a detailed study of the CC impacts on winter tourism using GEMINI-E3. They disaggregated total tourism into three sectors: winter overnight tourism (WOT), one-day winter tourism (ODT) and other forms of tourism (OFT). We build on their work, keeping the same representation, updating the analysis for winter tourism and extending it for summer tourism.

4.6. *Winter tourism*

The WOT sector represents skiers spending one or several nights in a ski resort. A consumer can take a ski trip in any of the regions included in GEMINI-E3. The ODT sector represents skiers spending only one day in a ski resort. In the model, only Swiss agents consume this good, because the respective consumption of foreign residents is almost negligible. The production function of the winter tourism sectors includes as a production factor natural snow that can be substituted with artificial one (i.e., snowmaking facilities, see Appendix C). The ODT sector is more vulnerable to a snow decrease than the WOT sector. Indeed, one-day skiers mainly go to close to home ski resorts, which are located at lower altitudes. Since it is more difficult to produce artificial snow at lower altitudes due to shorter and less frequent periods of cold

Table 9. Impacts of CC for the Swiss winter tourism sector and welfare (% deviation from reference scenario in 2060).

	RCP3PD (%)	A1B (%)
Variations in snow endowment for WOT		
CH	−2.0	−12.5
EU	−3.4	−23.4
OECD	−4.0	−20.0
USA	−4.0	−20.0
BRIC	−4.0	−20.0
ROW	−4.0	−20.0
Variations in snow endowment for ODT		
CH	−4.0	−21.8
Swiss WOT		
Production	0.0	0.0
Consumption	−0.2	−1.2
Exports	0.2	2.3
Imports	−0.4	−3.7
Artificial snow	1.4	10.5
Producer price	0.2	1.6
Swiss ODT		
Production	−0.4	−2.8
Consumption	−0.4	−2.8
Artificial snow	1.0	7.2
Producer price	0.7	5.1
Welfare change[a]	0.0005	0.0281

Note: [a]In % of HC.

weather, the ODT sector has a limited adaptation capacity (Gonseth and Vielle, 2018). This greater vulnerability is represented in GEMINI-E3 through a lower elasticity of substitution between natural and artificial snow for the ODT sector.

We calculate the variation in snow endowment using the variable “Fractional Snow Cover” from ENSEMBLES and CORDEX projects.[9] We extract data for Switzerland, Germany, Austria, France and Italy and aggregate them to GEMINI-E3 regions (Switzerland and Europe). Only two climate scenarios, RCP3PD and A1B, are represented in these databases. Outside Europe, without additional information, we assume as Gonseth and Vielle (2018) that the reductions in snow resources are approximately similar to the ones computed for the EU (respectively, −4% in the RCP3PD scenario and −20% in the A1B scenario).

In scenario A1B (see Table 9), the producer price increases by 5.1% for ODT and by 1.6% for WOT. The two price increases are not similar since the CC impacts on the

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[9] http://www.cordex.org/.

snow resource vary across segments (−21.8% for ODT and −12.5% for WOT). The difference also arises, because adaptation capacities on the supply and demand sides are different in the two segments. Due to these price variations, production decreases by 2.8% in ODT, but increases by 0.6% in WOT. Indeed, Swiss WOT benefits from relative competitiveness improvements, as the impacts of CC on winter tourism are more significant outside Switzerland. Therefore, Swiss exports (foreign tourists visiting Switzerland) increase and Swiss imports (Swiss tourists abroad) decrease. This induces some welfare improvement, which is, however, limited (<0.01%).

In the RCP3PD scenario, the decrease in snow endowment is very small, as are the economic impacts on Swiss winter tourism. WOT production change ranges between −0.1% and 0.0% and ODT production decreases by 0.4%. Welfare remains essentially unchanged with respect to the baseline scenario.

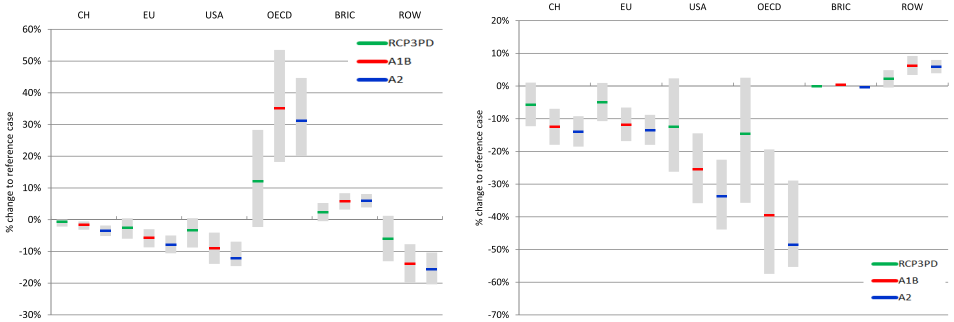
In short, even if welfare impacts are slightly positive, the situation is mixed among segments. Production of the ODT sector decreases in all scenarios, highlighting the greater vulnerability of ski resorts located at low altitudes, since they suffer from a greater natural snow loss. Higher ski resorts benefit from their comparative advantage with respect to lower altitude resorts in Switzerland and in the EU. However, their vulnerability also increases, because the decrease in natural snow raises their production costs.

4.7. *Summer tourism*

In order to model the variations in tourism flows, we use the Hamburg Tourism Model (HTM) developed by Hamilton *et al.* (2005). The purpose of the model is to understand how the current pattern of tourism flows may change under scenarios of future population growth, economic growth and CC. Results from the model have already been implemented successfully in CGE models to analyze scenarios of CC and climate policies (Berrittella *et al.*, 2006; Bosello *et al.*, 2012).

Since we focus on CC effects, we remove the socioeconomic scenario effects (increase of population and GDP) to allow for meaningful comparisons between CC scenarios A1B, A2 and RCP3PD. To do this, we calculate the variations of tourists with respect to the same scenario without CC. The results of the simulations with the HTM are then used as input data for GEMINI-E3. The destination flows computed from CES functions in GEMINI-E3 are modified according to the variations calculated with the HTM. We assume that the results of the HTM simulations correspond to the OFT sector, because the HTM is calibrated on summer tourism.

International tourism flows change according to the new temperature pattern. Cooler countries like Canada, Norway or Russia become more attractive. Thus, regions OECD and BRIC get more arrivals. On the other hand, temperature increase reduces international tourism flows, i.e., total international departures and arrivals decrease while domestic tourism increases. On aggregate, the Swiss tourism sector benefits from this effect. Indeed, even if international tourists spend less in Switzerland, Swiss



(a) (b)

Figure 4. International touristic arrivals (a) and departures (b) (% deviation from reference scenario in 2060).

tourists also spend less outside Switzerland and more at home. For example in 2060 in scenario A2, arrivals decrease by 1.9% to 5.2% while departures decrease by 9.6% to 18.9% (Fig. 4).

The reallocation of tourism flows translates into welfare changes. In 2060, Switzerland is better off in all scenarios except RCP3D lower. Switzerland benefits from larger increases in temperature, although to a lesser extent than GEMINI-E3's OECD region, which is the main winner. One explanation for the benefits to Switzerland is that more tourists will enjoy cooler mountain areas at the expense of hot city or seaside destinations. Moreover, the summer tourism season in alpine areas could expand to spring and autumn. Thus, the decrease in arrivals is more than compensated for by the decrease in departures and the increase in domestic tourism. The projected welfare gain is moderate, with a maximum of 0.21% in scenario A1B upper.

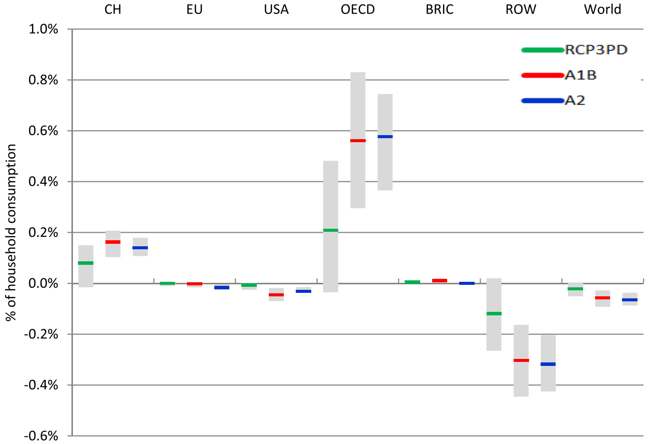


Figure 5. Regional welfare changes due to impacts on summer tourism under the three scenarios in 2060.

5. Aggregated Impacts

To include interaction effects between the considered impacts and arrive at a rough and still incomplete estimate of total impacts, we simulate the different selected CC hazards together.

For winter tourism, only medium scenarios RCP3PD and A1B are simulated due to the lack of data on snow projections. Without additional information, we assume that the impacts are the same for lower, medium and upper cases. Finally, the monetary costs of premature deaths are directly added to the welfare changes computed by the model.

Table 10 depicts the aggregated impacts of CC in Switzerland in 2060. Considering the omission of important impacts (especially weather events more extreme than the 2060 average), the numbers must be interpreted with caution. For scenarios A1B and A2, the GDP loss caused by the selected impacts is significant, between 0.15% and 0.41%. Even in the ambitious climate stabilization scenario RCP3PD, Switzerland will suffer from CC impacts, but the cost is only between 0.08% and 0.25% of GDP. The welfare loss is more important, reaching between 2 and 9 billion CHF in the A1B and A2 scenarios. In the most pessimistic warming scenario, it represents around 1.4% of HC in 2060. International trade effects (i.e., changes in Swiss imports and exports) are mainly driven by the impacts of CC on agriculture (mainly on imports) and summer tourism (both on exports and imports).

At the sectoral level, sectors related to energy consumption for heating (district heating, natural gas and refined petroleum products) are affected most. They are followed by ODT. Then come the "other" agricultural sectors, industry, insurance and land transport. Production increases in few sectors. That is the case for summer tourism, electricity and for the grains and oil seeds sector, which benefits from comparative productivity improvements with respect to other world regions.

It is interesting to decompose the welfare impact by areas. This is done in Table 11, where the welfare changes computed for each impact represented in this paper are detailed. They are computed from the simulation results realized in the previous sections. Health impacts (i.e., mortality and productivity loss) are the most serious CC impacts, with a cost ranging from 5 to 12 billion of CHF in scenarios A1B and A2. Losses in agriculture are also significant and reach 0.3 billion of CHF in the worst case (A2 upper). The simulations also show some positive impacts. With a warmer climate, less energy will be needed to heat buildings, the estimated gain ranges from 0.9 to 2.2 billion of CHF in scenarios A1B and A2. Tourism will also benefit from better climate conditions compared with other regions, the gain ranging from 0.7 to 1.3 billion of CHF in the same scenarios.

The other impacts studied in this paper are of lesser importance.

We can compare the benefits of limiting global warming estimated in this paper with the costs associated with a deep decarbonization pathway for Switzerland. These mitigation costs have been estimated with GEMINI-E3 in scenarios that assume 76%

abatement with respect to 1990 levels and are thus considered compatible with the 2°C long-term target (Babonneau *et al.*, 2018). The estimated mitigation costs lie thin the range of 1.45% to 1.93% of HC in 2050. This is of comparable magnitude to the costs of CC for Switzerland computed in this paper. However, this formal cost–benefit analysis does not integrate several aspects that would increase the benefits of limiting CC. They include the precautionary principle, the impacts of extreme events, the loss of nonmonetary assets (e.g., natural ecosystems) and the benefits of reducing CC abroad (e.g., in developing countries). Taking them into account would clearly tilt the balance in favor of deep decarbonization in Switzerland. Furthermore, one can argue that the more relevant cost–benefit analysis is at the global level, with individual

Table 10. Aggregated impacts of CC (% deviation from reference scenario in 2060).

	RCP3PD			A1B			A2		
	Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
GDP	−0.08%	−0.17%	−0.25%	−0.18%	−0.30%	−0.41%	−0.15%	−0.29%	−0.40%
Imports	−0.01%	−0.22%	−0.49%	−0.13%	−0.37%	−0.69%	−0.19%	−0.44%	−0.75%
Households cons.	−0.06%	−0.06%	−0.07%	0.00%	−0.06%	−0.12%	0.03%	−0.07%	−0.16%
Government cons.	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Investment	−0.09%	−0.13%	−0.21%	−0.05%	−0.16%	−0.31%	−0.03%	−0.19%	−0.35%
Exports	−0.04%	−0.36%	−0.69%	−0.35%	−0.67%	−1.03%	−0.41%	−0.71%	−1.04%
Change in % of production									
Natural gas	−1.33%	−2.76%	−4.17%	−2.97%	−5.03%	−6.97%	−2.85%	−4.93%	−6.86%
Petroleum products	−0.84%	−1.37%	−1.91%	−1.43%	−2.30%	−3.10%	−1.36%	−2.27%	−3.09%
Electricity	1.13%	1.65%	2.22%	1.47%	1.99%	2.63%	1.45%	1.97%	2.59%
District heating	−2.36%	−4.56%	−6.75%	−4.63%	−7.48%	−10.24%	−4.49%	−7.31%	−10.04%
Grains and oil seeds	0.14%	1.65%	3.80%	0.63%	3.07%	6.55%	0.59%	3.09%	6.69%
Other crops	−0.01%	−0.39%	−0.75%	−0.41%	−0.78%	−1.22%	−0.43%	−0.73%	−1.15%
Animals	−0.04%	−0.21%	−0.32%	−0.31%	−0.44%	−0.48%	−0.29%	−0.39%	−0.42%
Forestry	−0.04%	−0.24%	−0.38%	−0.31%	−0.46%	−0.55%	−0.30%	−0.41%	−0.49%
Industry	−0.07%	−0.42%	−0.65%	−0.64%	−0.91%	−1.03%	−0.61%	−0.80%	−0.88%
Land transport	−0.07%	−0.23%	−0.35%	−0.24%	−0.42%	−0.57%	−0.21%	−0.40%	−0.56%
Sea transport	−0.07%	−0.05%	−0.02%	0.01%	0.00%	−0.04%	0.07%	0.02%	−0.05%
Air transport	−0.06%	−0.19%	−0.31%	−0.17%	−0.32%	−0.49%	−0.13%	−0.29%	−0.49%
Insurance	−0.05%	−0.31%	−0.58%	−0.36%	−0.64%	−0.99%	−0.29%	−0.49%	−0.72%
Health	−0.06%	−0.05%	−0.05%	−0.01%	−0.06%	−0.10%	0.01%	−0.08%	−0.14%
Services	−0.05%	−0.13%	−0.21%	−0.13%	−0.24%	−0.34%	−0.12%	−0.24%	−0.34%
WOT	0.02%	−0.26%	−0.49%	0.33%	0.11%	−0.13%	0.35%	0.17%	−0.07%
ODT	−0.41%	−0.46%	−0.50%	−2.84%	−2.88%	−2.92%	−2.84%	−2.91%	−2.95%
OFT	−0.38%	0.97%	1.94%	1.54%	2.28%	2.73%	1.64%	1.79%	1.91%
Drinking water	−0.03%	−0.03%	−0.03%	−0.03%	−0.06%	−0.08%	−0.02%	−0.07%	−0.10%
Welfare change									
In million CHF	−2388	−3659	−4860	−3546	−6116	−8756	−2709	−6071	−8561
In % of HC	−0.37%	−0.57%	−0.76%	−0.55%	−0.96%	−1.37%	−0.42%	−0.95%	−1.34%

Note: HC: Household consumption.

Table 11. Decomposition of welfare impacts of CC in million CHF_{2016} in 2060.

	RCP3PD			A1B			A2		
	Lower	Medium	Upper	Lower	Medium	Upper	Lower	Medium	Upper
Mortality	−2145	−3820	−5352	−4045	−6658	−9331	−3389	−6449	−8818
Productivity loss	−574	−1086	−1489	−1107	−1950	−2607	−919	−1958	−2713
Heating–cooling	454	944	1432	930	1566	2161	898	1537	2127
International energy prices	−55	−133	−211	8	12	19	7	11	19
Agriculture	−9	−80	−179	−30	−138	−318	−28	−137	−322
Water management	0	−3	−4	−1	−4	−5	−1	−3	−5
Winter tourism	3	3	3	35	35	35	35	35	35
Summer tourism	−64	520	953	667	1032	1314	691	900	1137

countries' contributions to mitigation following the UNFCCC's principle of common, but differentiated responsibilities.

6. Conclusion

This paper presents a comprehensive overview of economic impacts of CC in Switzerland to be expected in 2060. Next to a thorough appraisal of the existing literature, we improved the monetary quantification of the impacts of CC in Switzerland in the context of general equilibrium analysis. In particular, we newly included the most important trade-related cross-border impacts, notably in summer tourism, grain agriculture and electricity supply. Analyses for domestic impacts have been updated to reflect the latest literature and data.

We concentrated in the simulations on a selection of impacts that are important according to the existing literature and for which adequate data are available. Some potentially significant impacts have not yet been quantified in a satisfactory way, e.g., impacts of disastrous extreme events such as heat waves and droughts which would be more extreme than the 2060 average climate. Thus, simulations of aggregate impacts do not serve the purpose to generate meaningful numbers for total CC impacts in Switzerland, but to include interaction effects between different sectoral impacts. Admittedly, such interaction effects result to be very small for the impacts considered.

For the individual impacts, numbers are somewhat more reliable than at the aggregate level. We provide ranges of results, covering different climate scenarios and ranges of results from bottom-up simulations and studies, which we used to derive input data for our applied general equilibrium analysis. Formally departing from 95% confidence intervals for temperature and precipitation changes, combined multi-level uncertainties imply that the ranges of results are merely rough indications. For some sectors, we can at least be highly confident in the overall direction of the welfare change: health (−), agricultural imports (−), tourism (+) and energy demand (+).

Impacts on human health are among the most serious of CC impacts in Switzerland, with summer heat waves being the main cause. Agriculture and forestry are particularly sensitive to climate and weather conditions. Despite these risks, the overall vulnerability of Swiss agriculture seems to be rather small. Tourism is another sector where international aspects are particularly important, given that more than 9 million foreign tourists visit Switzerland per year, more than its entire population. The main concern for tourism with respect to CC is the retreating snow cover, which constitutes a serious challenge to ski resorts, especially below an altitude of about 1800 m. At the same time, Swiss summer tourism benefits from new climatic conditions, and its activity is likely to increase in the future decades, thus overcompensating losses that will occur in some segments of winter tourism. Concerning energy demand, we found significant welfare gains, mainly from the fact that the income no longer spent for imported fossil heating fuels is used by households to expand their consumption of other goods and services.

Our results are roughly in line with the estimates made by Ecoplan/Sigmaplan (2007), but differ from the study published recently by Roson and Sartori (2016). The latter use damage functions and a CGE model to estimate for 140 countries and six specific damages (sea-level rise, agricultural productivity, labor productivity, human health, tourism flows and household energy demand) the change in GDP for a temperature increase of 3°C. They find for Switzerland a positive impact on GDP equal to 1.42%, mainly driven by an increase in tourism attractiveness. However, their estimates do not include the excess mortality, which represents in our analysis the most important cost of CC. The differences in results between the studies also indicate that the thorough use of available local information at national and subnational scales is important when we try to quantify and monetize CC impacts.

Uncertainties about the overall impacts of CC are still enormous. Especially, the full consequences of future extreme weather events remain unknown. Despite the estimates presented in this paper, we still know too little about the repercussions of global consequences of CC in Switzerland. The monetization of nonmarket goods, such as biodiversity or scenic beauty, is another very challenging issue. Obvious limitations of our study include an incomplete set of simulated impacts, an overly simple relationship between high temperatures and labor productivity, and linear scaling of results from studies that use different (but similar) climate scenarios.

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Sole responsibility for the content of this paper lies with the authors.

Appendix A. Industrial Classification

The GEMINI-E3 model was initially designed to assess climate and energy policies aiming at reducing CO_2 emissions. Then, the model was extended to the analysis of the economic impacts of CC. Therefore, the disaggregation of sectors was chosen according to these two purposes. First, we disaggregate the energy supply/demand into

Table A.1. Industrial classification.

1	Coal
2	Crude oil
3	Natural gas
4	Petroleum products
5	Electricity
6	District heating
7	Grains and oil seeds
8	Other crops
9	Livestock
10	Forestry
11	Industry
12	Land transport
13	Water transport
14	Air transport
15	Insurance
16	Health
17	Other services
18	WOT
19	ODT
20	OFT
21	Drinking water

six sectors/goods: coal, crude oil, natural gas, petroleum products, electricity and district heating. Transportation was represented through three sectors: land, sea and air transports. Then, we define the sectoral structure of the model in order to assess the economic impact of CC hazards on particularly vulnerable sectors at the Swiss national level, such as tourism, agriculture, human health, insurance and water distribution. For agriculture, the model describes four agricultural activities (i.e., grains and oil seeds, livestock, forestry and other crops) according to their contributions to Swiss agriculture production and their vulnerabilities to CC. The tourism sector includes all activities (accommodation, transport, retail sector, etc.) that are linked to tourism. Tourism is disaggregated into three segments: WOT, ODT and OFT.

Appendix B. Production Structure of Agricultural Sectors in GEMINI-E3

In GEMINI-E3, the production structure (see Fig. B.1) distinguishes water as an input and allows sectors to choose between employing drinking water and extracting water themselves. In the agricultural sector, land is combined with irrigation to form an irrigation-land aggregate. The model distinguishes between raw water for irrigation and raw water for other uses. Raw water for irrigation corresponds to water mainly used from the beginning of spring to the beginning of autumn, which corresponds to the main growing season of the plants. These factors are mobile between sectors, but

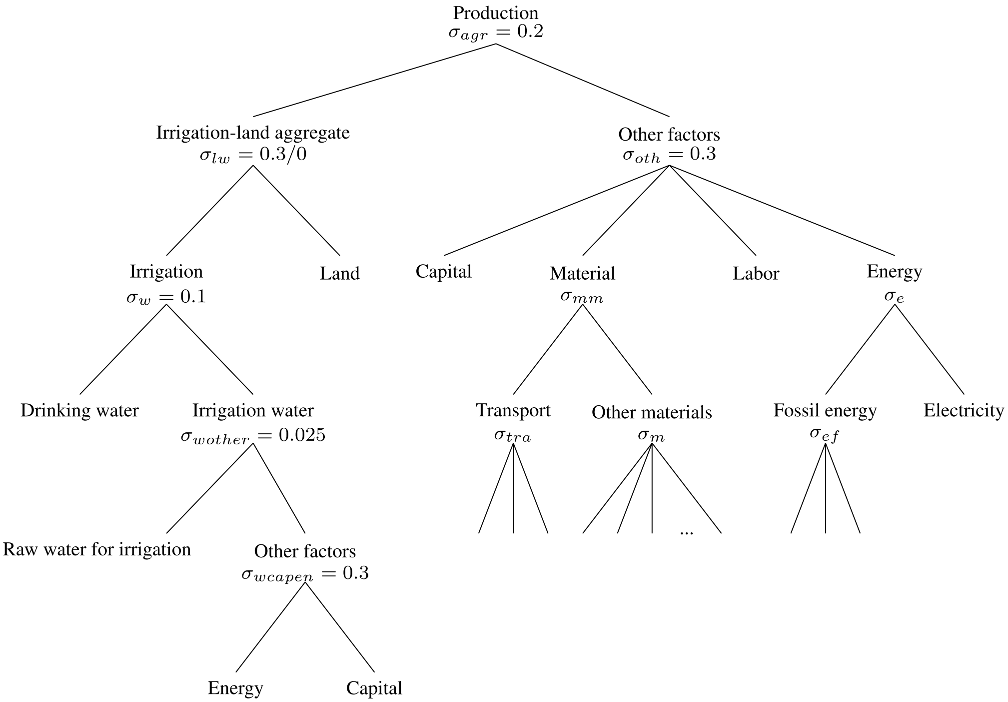

Figure B.1. Nested CES production function used for agricultural sector.

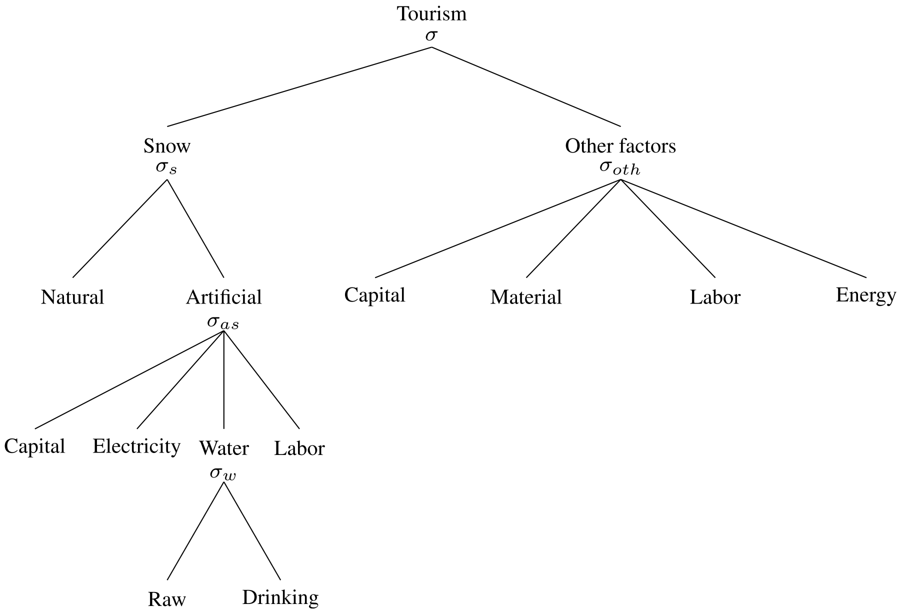

Figure C.1. Nested CES production function used for the winter tourism.

modeled as distinct goods, so raw irrigation water cannot be taken for any other use and vice versa. More details can be found in Faust *et al.* (2015).

Appendix C. Production Structure of Winter Tourism in GEMINI-E3

The production structure of the winter tourism sectors is shown in Fig. C.1. A natural snow resource has been introduced into the model. The chosen structure assumes that winter tourism sectors can respond to a reduction in natural snow availability by producing more artificial snow. This artificial snow requires a mix of capital, electricity, labor and water inputs. More details can be found in Gonseth and Vielle (2018).

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