# Adding climate impacts and adaptation possibilities to an economic computable general equilibrium model

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

NCCR CLIMATE
Swiss Climate Research

# Outline

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# Project goals

- The research project is a mandate from the FOEN which aims at:
  - identifying the Swiss sectors most at risk from climate change
  - introducing and detailing these sectors in the CGE model GEMINI-E3
  - using GEMINI-E3 to assess the general equilibrium costs of specific climate change impacts for Switzerland
  - studying the role of adaptation processes and measures to alleviate climate change costs

# Project scope

- The research project focuses on the following sectors:
  - Agriculture ; **Energy** ; Tourism ; Water
- Motives for using GEMINI-E3:
  - General equilibrium effects ⇒ market driven adaptation
  - Representation of the tax system ⇒ simulate exogenous adaptation measures (e.g. subsidies)
  - International dimension ⇒ indirect impacts of climate change

# The GEMINI-E3 model

- World computable general equilibrium model
- Fifth version
- Dedicated to the analysis of climate change & energy policies
- Recursive dynamic model
- 28 regions (including Switzerland)
- 5 energy sectors
- 13 non-energy sectors
- All GHG emissions (EMF 21 - US-EPA)
- Database GTAP 6 (2001)
- gemini-e3.epfl.ch

# An aggregated regional classification

- Switzerland (CHE)
- European Union (EUR)
- United States of America (USA)
- Other industrialized countries:
  Canada+Japan+Australia+New Zealand (OEC)
- BRIC: Brazil+Russia+India+China (BRI)
- Rest of the World (ROW)

# New classification of GEMINI-E3

- We have used a new classification concerning goods/sectors described by the model by adding sectors/activities that will be affected by climate change in Switzerland

TABLE 1: Sectoral 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 | Crops n.e.c. | 20 | Equipment goods |
| 7 | Raw milk | 21 | Winter overnight tourism |
| 8 | Animal products | 22 | One-day winter tourism |
| 9 | Vegetables, fruits and nuts | 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 distribution |

# Database

Like other CGE models, GEMINI-E3 is based on Social Accounting Matrices which have been built on several statistical sources:

- Swiss Input-output table: SIOT (2001)
- GTAP 6 (2001)
- With other various sources (IMF, IEA, OECD)
- For some sectors, we have done an extensive work to integrate them into the SAM (tourism and water distribution)
  - Tourism: tourism satellite accounts, tourism balance of payments, etc.
  - Distribution water: GTAP & Swiss Gas and Water Industry Association
- We have added into the SAM new natural resources (snow, raw water)
- Raw water: industrial uses (Swiss Gas and Water Industry Association), irrigation water (Federal Office for Agriculture)

# Household consumption function

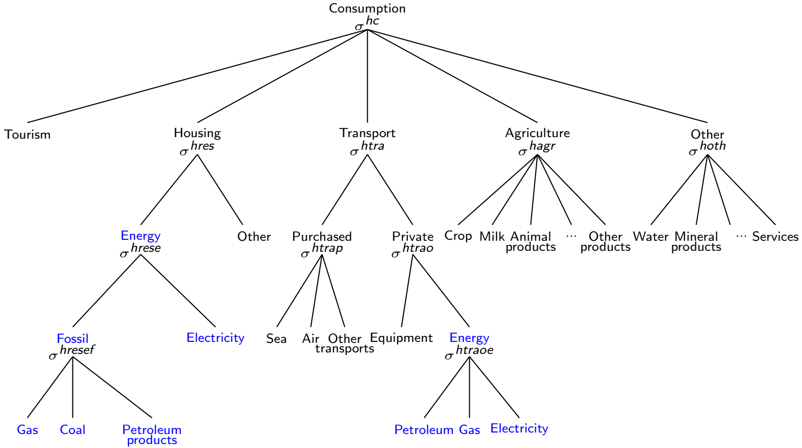



Figure 1: Structure of Household Consumption

# Structure of Production in Industrial Sectors

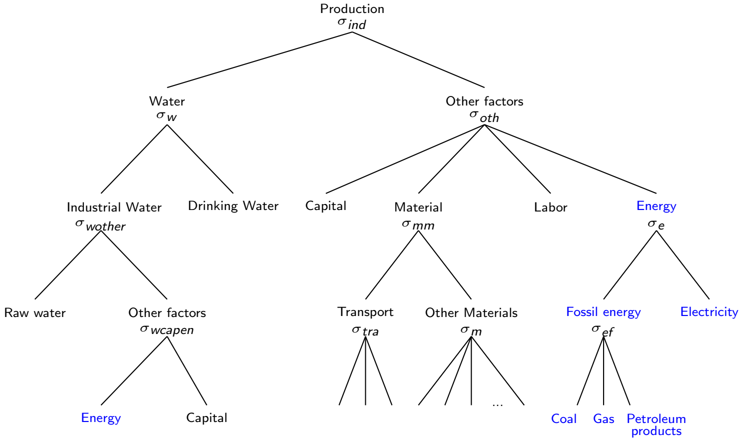



FIGURE 2: Structure of Production in Industrial Sectors

# Structure of Electricity Production

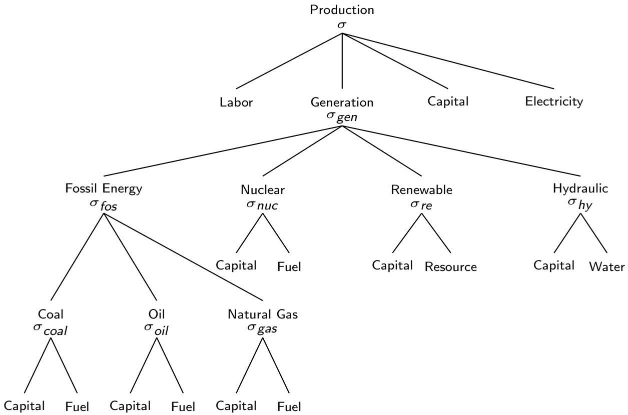



FIGURE 3: Structure of Electricity Production

# Energy prices and GDP assumptions

*Energy Prices ($ 2009):* based on World Energy Outlook 2010 (*current policies scenario*), International Energy Agency

| | Unit | 2009 | 2015 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| IEA Crude oil imports | Baril | 60.4 | 94.0 | 110.0 | 130.0 | 135.0 | 135.0 |
| Natural gas imports Europe | Mbtu | 7.4 | 10.7 | 12.1 | 13.9 | 14.4 | 14.4 |
| OECD Steam coal imports | Tonne | 97.3 | 97.8 | 105.8 | 112.5 | 115.0 | 115.0 |

*GDP Assumptions:* mainly based on International Energy Outlook 2011, Energy Information Administration, DOE USA.

| | 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% |
| USA | 2.3% | 2.7% | 2.5% | 2.4% |
| Other OECD Countries | 1.3% | 1.1% | 1.1% | 1.0% |
| BRIC | 6.3% | 4.5% | 3.6% | 3.6% |
| Rest of the World | 3.9% | 3.6% | 3.3% | 3.3% |
| World | 2.8% | 2.8% | 2.6% | 2.6% |

# Swiss Electricity generation

- Nuclear moratorium after the decommission of all Swiss nuclear power plants (with an operating life of 50 years)
- No new hydraulic sites available in Switzerland
- Cost of renewable electricity generation based on the last Swiss energy perspectives

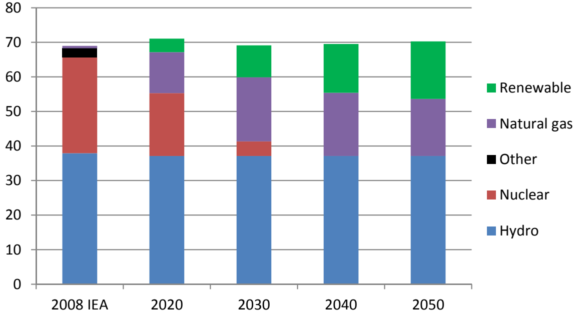



FIGURE 4: Electricity generation in Switzerland (in TWh)

# Swiss Fossil Energy consumption

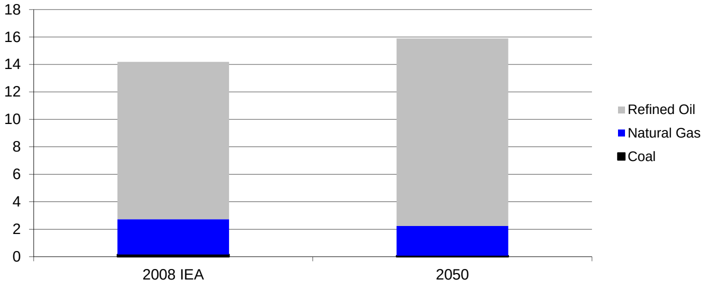



FIGURE 5: Fossil energy consumption in Switzerland (in Mtoe)

# Outline

# Regionalization of climate change

- Our baseline is built on a storyline comparable to the A1B scenario. Therefore, GHG emissions are close to the ones in this scenario
- We downscale our climate change impacts by using data from the ENSEMBLES European project and from the new Swiss climatic scenarios CH2011
- ENSEMBLES: grid with a mesh of 25x25km over Europe
- CH2011: regional scenarios at daily resolution based on probabilistic method
- ENSEMBLES and CH2011 scenarios differ in terms of geographical scope, variable coverage, reference period, emissions scenarios

# The ENSEMBLES data

TABLE 2: 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) |

- The models have the same rotated grid
- Maximize the diversity of models represented
- The "Model Mean" scenario is built by averaging the prediction values from the four aforementioned models

# The ENSEMBLES grid

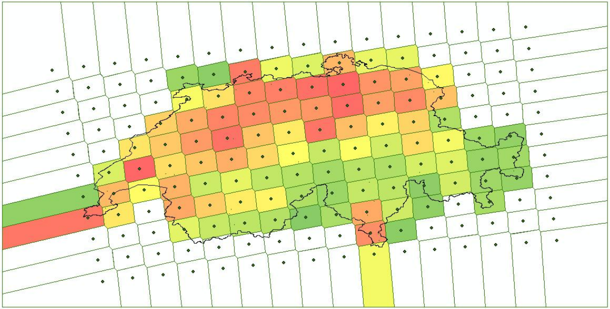


FIGURE 6: The ENSEMBLES grid together with a set of weights representing the distribution of the population across Switzerland

# The climatic variables

Table 3: Climatic variables and their fields of application

| | |
|---|---|
| **Energy** | |
| Heating energy demand in buildings<br>Cooling energy demand in buildings | *Daily mean temperature* |
| Hydro power supply | *Monthly precipitation* |
| Nuclear power supply | *Monthly mean temperature* |
| **Tourism** | |
| Snow-dependent winter tourism segments | *Fractional snow cover* |
| **Agriculture** | |
| Crops (Barley, Maize, Wheat) | *Monthly precipitation*<br>*Monthly mean temperature* |
| **Water resource and the water distribution sector** | |
| Water resource | *Monthly precipitation* |

# Outline

# Methodology

1. Derive the evolution of two climatic indicators:
   - Heating Degree-Days (HDD) for heating
   - Cooling Degree-Days (CDD) for cooling
2. Compute ex-ante changes in energy demand compared to the baseline
3. Generation of a set of scenarios where the different changes in energy demand are introduced sequentially

# Heating – evolution of HDD

- HDD computation (using the standard SIA formula):

$$HDD(\theta_i, \theta_{th}) = \sum_{k=1}^{365} m_k \left(\theta_i - \theta_{e,k}\right) \qquad (1)$$
$$\text{with } m_k = 1 \quad \text{if} \quad \theta_{e,k} \leq \theta_{th}$$
$$m_k = 0 \quad \text{if} \quad \theta_{e,k} > \theta_{th}$$

- Standard values for CH: $\theta_i = 20°\mathrm{C}$ et $\theta_{th} \in \{8, 10, 12°\mathrm{C}\}$
- The lower the value of the threshold temperature, the better the insulation of buildings

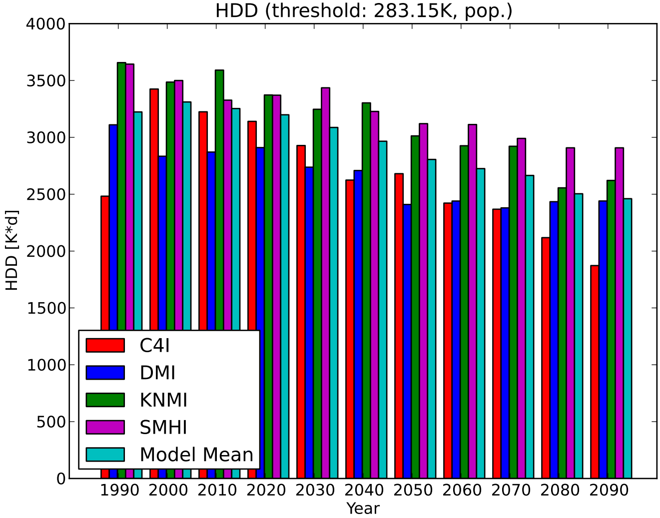
# Heating – evolution of HDD

TABLE 4: Percentage changes in HDD between 1961-1990 and 2050 for the scenario "Model Mean" and different threshold values

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

$^*$reference period: 1961-1990

# Heating – evolutions of HDD



# Heating – evolutions of HDD

TABLE 5: Percentage changes in HDD between 1980–2009 and 2050 based on the CH2011 scenarios

| | | $\theta_{th} = 8^{\circ}C$ | $\theta_{th} = 10^{\circ}C$ | $\theta_{th} = 12^{\circ}C$ |
|---|---|---|---|---|
| Reference period (1980–2009) | Observed | 2836.1 | 3101.7 | 3328.3 |
| CH2011 (2050) | A2 lower | 2548.7 *-10.1%* | 2870.6 *-7.4%* | 3057.4 *-8.1%* |
| | A2 medium | 2304.0 *-18.8%* | 2646.4 *-14.7%* | 2844.4 *-14.5%* |
| | A2 upper | 2068.2 *-27.1%* | 2409.9 *-22.3%* | 2643.4 *-20.6%* |
| | A1B lower | 2533.9 *-10.7%* | 2855.2 *-7.9%* | 3041.9 *-8.6%* |
| | A1B medium | 2282.4 *-19.5%* | 2625.8 *-15.3%* | 2825.1 *-15.1%* |
| | A1B upper | 2040.1 *-28.1%* | 2380.2 *-23.3%* | 2617.0 *-21.4%* |

# Heating – evolutions of HDD

TABLE 6: Percentage changes in HDD between 1980–2009 and 2050 based on the CH2011 scenarios

| | | $\theta_{th} = 8^{\circ}$C | $\theta_{th} = 10^{\circ}$C | $\theta_{th} = 12^{\circ}$C |
|---|---|---|---|---|
| Reference period (1980–2009) | Observed | 2836.1 | 3101.7 | 3328.3 |
| CH2011 (2050) | A2 lower | 2548.7 *-10.1%* | 2870.6 *-7.4%* | 3057.4 *-8.1%* |
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| | A1B medium | 2282.4 **-19.5%** | 2625.8 **-15.3%** | 2825.1 **-15.1%** |
| | A1B upper | 2040.1 *-28.1%* | 2380.2 *-23.3%* | 2617.0 *-21.4%* |

# Heating – evolutions of HDD

TABLE 7: Percentage changes in HDD between 1980–2009 and 2050 based on the CH2011 scenarios

| | | $\theta_{th} = 8^{\circ}\mathrm{C}$ | $\theta_{th} = 10^{\circ}\mathrm{C}$ | $\theta_{th} = 12^{\circ}\mathrm{C}$ |
|---|---|---|---|---|
| Reference period (1980–2009) | Observed | 2836.1 | 3101.7 | 3328.3 |
| CH2011 (2050) | A2 lower | 2548.7 *-10.1%* | 2870.6 **-7.4%** | 3057.4 *-8.1%* |
| | A2 medium | 2304.0 *-18.8%* | 2646.4 *-14.7%* | 2844.4 *-14.5%* |
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| | A1B lower | 2533.9 *-10.7%* | 2855.2 *-7.9%* | 3041.9 *-8.6%* |
| | A1B medium | 2282.4 *-19.5%* | 2625.8 *-15.3%* | 2825.1 *-15.1%* |
| | A1B upper | 2040.1 **-28.1%** | 2380.2 *-23.3%* | 2617.0 *-21.4%* |

# Heating – ex-ante changes in energy demand

- We assume heating demand to be approximately proportional to the number of HDD (*Christenson et al., 2005*)
- Therefore, % decreases in HDD are assumed to give ex-ante % decreases in annual heating energy demand (compared to the baseline in 2050)

# Heating : Simulation results

TABLE 8: Impacts of a climate change induced reduction in heating energy consumption (-14.6%) in 2050*

| | Impacted sector ($\theta_{th} = 10^{\circ}\mathrm{C}$) Housing | Service | Industry | All sectors |
|---|---|---|---|---|
| *Energy consumption* | | | | |
| Petroleum products | -2.4% | -1.2% | -0.1% | -3.7% |
| Natural gas | -1.8% | -0.7% | -0.5% | -3.0% |
| Electricity | 0.8% | -0.2% | 0.0% | 0.5% |
| $CO_2$ emissions | -2.5% | -1.1% | -0.1% | -3.6% |
| Welfare change in Mio $USD_{2010}$ | 668 | 254 | 55 | 976 |
| As a % of consumption | 0.16% | 0.06% | 0.01% | 0.23% |

* percentage change with respect to the reference scenario

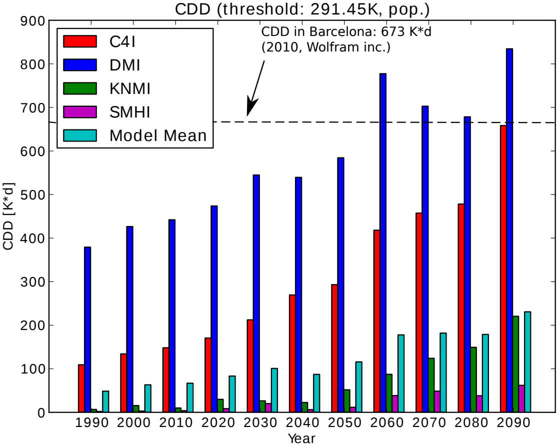
# Cooling – evolutions of CDD

- CDD computation using the ASHRAE formula (cf. *Howell et al., 2005*):

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

- CDD are computed using $\theta_{bp} = 18.3^\circ$ (ASHRAE standard numerical value)
- Percentage changes in CDD between 1961-1990 and 2050 for the scenario "Model Mean": $+138\%$

# Cooling – evolutions of CDD



# Cooling – evolutions of CDD

Table 9: Percentage changes in CDD between 1980–2009 and 2050 based on the CH2011 scenarios

| | | $\theta_{bp} = 18.3^\circ C$ | $\theta_{bp} = 20^\circ C$ | $\theta_{bp} = 22^\circ C$ |
|---|---|---|---|---|
| Reference period (1980–2009) | Observed | 45.4 | 7.2 | 0.3 |
| CH2011 (2050) | A2 lower | 109.0 *140.1%* | 29.9 *317.1%* | 3.3 *834.6%* |
| | A2 medium | 158.3 *248.5%* | 55.7 *676.3%* | 7.9 *2161.9%* |
| | A2 upper | 216.1 *375.8%* | 93.3 *1201.6%* | 17.9 *5052.6%* |
| | A1B lower | 113.6 *150.2%* | 32.0 *345.9%* | 3.6 *933.3%* |
| | A1B medium | 165.4 *264.2%* | 60.2 *740.0%* | 8.8 *2428.3%* |
| | A1B upper | 226.4 *398.4%* | 100.9 *1307.3%* | 20.5 *5802.5%* |

# Cooling – evolutions of CDD

Table 10: Percentage changes in CDD between 1980–2009 and 2050 based on the CH2011 scenarios

| | | $\theta_{bp} = 18.3^\circ\mathrm{C}$ | $\theta_{bp} = 20^\circ\mathrm{C}$ | $\theta_{bp} = 22^\circ\mathrm{C}$ |
|---|---|---|---|---|
| Reference period (1980–2009) | Observed | 45.4 | 7.2 | 0.3 |
| CH2011 (2050) | A2 lower | 109.0 **140.1%** | 29.9 *317.1%* | 3.3 *834.6%* |
| | A2 medium | 158.3 *248.5%* | 55.7 *676.3%* | 7.9 *2161.9%* |
| | A2 upper | 216.1 *375.8%* | 93.3 *1201.6%* | 17.9 *5052.6%* |
| | A1B lower | 113.6 *150.2%* | 32.0 *345.9%* | 3.6 *933.3%* |
| | A1B medium | 165.4 *264.2%* | 60.2 *740.0%* | 8.8 *2428.3%* |
| | A1B upper | 226.4 **398.4%** | 100.9 *1307.3%* | 20.5 *5802.5%* |

# Cooling – ex-ante changes in energy demand

- Cooling demand is proportional to CDD only under strong assumptions
- Climate change entails higher specific electricity use per square meter of cooled surface *and* a higher proportion of cooled surfaces compared to the baseline
  - Specific electricity use: empirical linear relationship with CDD for office building (*Aebischer et al., 2007*)
  - Cooled surfaces in the service sector: % of surface according to *Aebischer et al., 2007*
  - Cooled surfaces in the residential sector: in 2050, the % of cooled surface is equal to 1.1% in the baseline and ranges from 2% to 10% in the variant with climate change (own estimations)

# Cooling – ex-ante changes in energy demand

- The hypothesis are used to derive ex-ante increases in the energy demand for cooling in 2050 compared to the baseline
- Service sector:
  - ENSEMBLES: +0.6 TWh
  - CH2011: +0.6 to +1.2 TWh
- Residential sector:
  - ENSEMBLES: +0.1 to +0.8 TWh
  - CH2011: +0.1 to +1.3 TWh

# Cooling : Simulation results

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% | -0.04% | -0.14% |
| Natural gas | 0.13% | 0.27% | 0.40% | 0.28% |
| Electricity | 0.41% | 0.58% | 0.99% | 0.92% |
| $CO_2$ emissions | -0.04% | 0.05% | 0.00% | -0.10% |
| Welfare change in Mio $USD_{2010}$ | -46 | -50 | -96 | -101 |
| As a % of consumption | -0.01% | -0.01% | -0.02% | -0.02% |

* percentage change with respect to the reference scenario

# Outline

# Climate change impacts : nuclear/gas power plants

We use the following equations to estimate the effect of a temperature change on the monthly production of nuclear power plants (based on estimation results provided in *Linnerud et al., 2011*).

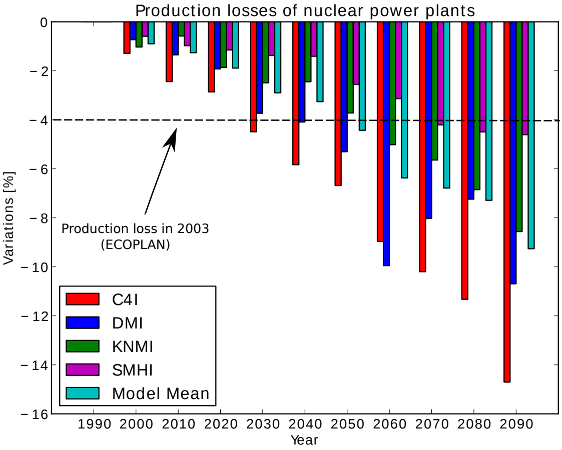
For the winter months:

$$\widehat{\Delta q/q} = \frac{-0.666 \cdot \Delta T - 0.023 \cdot \left((T+\Delta T)^2 - T^2\right)}{92.440 - 0.666 \cdot T - 0.023 \cdot T^2} \tag{3}$$

For the summer months:

$$\widehat{\Delta q/q} = \frac{-0.666 \cdot \Delta T - 0.023 \cdot \left((T+\Delta T)^2 - T^2\right)}{69.830 - 0.666 \cdot T - 0.023 \cdot T^2} \tag{4}$$

# Climate change impacts : nuclear/gas power plants



# Climate change impacts : nuclear/gas power plants

Table 12: Annual percentage changes in nuclear power production between 1980–2009 and 2050 based on the CH2011 scenarios

| | | 2035 | 2050[1] | 2060 | 2085 |
|---|---|---|---|---|---|
| CH2011 | A2 lower | -0.7% | -1.3% | -2.3% | -4.3% |
| | A2 medium | -1.7% | -2.3% | -3.7% | -6.4% |
| | A2 upper | -2.7% | -3.3% | -5.1% | -8.7% |
| | A1B lower | -0.8% | -1.4% | -2.4% | -3.7% |
| | A1B medium | -1.9% | -2.4% | -3.8% | -5.5% |
| | A1B upper | -3.0% | -3.5% | -5.2% | -7.4% |

[1] These values are obtained by interpolation.

# Simulation results : thermal power plants

TABLE 13: Impacts of thermal power production losses (-4.4%) measured as percentage or absolute deviations from the 2050 baseline values

| | |
|---|---|
| *Energy consumption* | |
| Oil refined products | 0.00% |
| Natural gas | 0.67% |
| Electricity | -0.16% |
| | |
| *$CO_2$ emissions* | 0.08% |
| | |
| *Welfare impacts* | |
| Surplus in Mio $USD_{2010}$ | -9 |
| As a % of total household consumption | 0.00% |
| *Variations in production (GWh)* | |
| Natural gas | -432 |
| Hydropower | 0 |
| Renewable energies | 320 |
| Total | -112 |

# Climate change impacts : hydropower

Based on the CCHydro project:

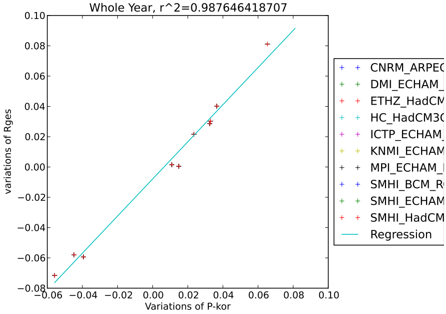



TABLE 14: Estimated variations in river runoffs at the 2050 time horizon

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

# Simulation results : hydropower

Table 15: Impacts of hydropower production losses (-2.2%) measured as percentage or absolute deviations from the 2050 baseline values

| | |
|---|---|
| *Energy consumption* | |
| Oil refined products | 0.00% |
| Natural gas | 0.52% |
| Electricity | -0.04% |
| | |
| *$CO_2$ emissions* | 0.06% |
| | |
| *Welfare impacts* | |
| Surplus in Mio $USD_{2010}$ | -5 |
| As a % of total household consumption | 0.00% |
| *Variations in production (GWh)* | |
| Natural gas | 302 |
| Hydropower | -816 |
| Renewable energies | 486 |
| Total | -29 |

# Conclusion

- Sectoral disaggregation together with the introduction of the water and snow resources now allow using the GEMINI-E3 model to compute climate change costs for a set of important sectors
- Our results show that adaptation significantly reduces climate change costs
- In the tourism context, climate change impacts abroad have been shown to greatly influence the results. This result argues in favour of broadening this type of analysis to other sectors (e.g. agriculture)
- We found relatively moderate impacts because of adaptation, the chosen period scenario (2050), the emission scenario (A1B), and the fact that some important aspects of climate change impacts are missing in the analysis (e.g. extreme events, biodiversity, permafrost, health).
- We computed macroeconomic impacts which are aggregated at the national level. Regional impacts can be much more important.
- External costs of adaptation are not taken into account (artificial snow)

# Conclusion

- The most important impact of climate change on the Swiss energy sector is a lower demand of heating which dominates the other aspects
- Cooling demand also increases but the economic impact is rather limited in comparison to change in heating demand
- The impacts on electricity generation are moderate and entail small welfare losses
- Limitations and uncertainties
  - Some aspects are missing : extremes events with impacts on electricity network, impacts on renewable (wind, solar)
  - We do not integrate the impacts of climate change on the other regions
  - We use optimistic assumption on the cost of electricity generation done with renewable
  - The penetration of air conditioner in the reference case is uncertain (depends to socioeconomic factors and technological assumptions)