Defining deep decarbonization pathways for Switzerland: An economic evaluation based on the computable general equilibrium model GEMINI-E3☆

Frédéric Babonneau[a,b], Philippe Thalmann[a], Marc Vielle[a,*]

[a] *LEURE, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*
[b] *ORDECSYS, Place de l'Etrier 4, CH-1224 Chêne-Bougeries, Switzerland*

Abstract

This paper presents the Swiss contribution to the Deep Decarbonization Pathways (DDP) project which is an international collaborative initiative aiming at understanding and showing how individual countries might define a roadmap paving the way to reaching a low carbon economy and how the world can keep global mean temperature increase below 2°C. The Swiss analysis relies on macro-economic simulations of GEMINI-E3, a computable general equilibrium model used to assess the energy and economic impacts of a Swiss low carbon society. The DDP scenarios assume a CO_2 emissions target of 1 ton per Swiss inhabitant following the Swiss climate target which represents a 76% abatement with respect to 1990 levels. The paper discusses several options/scenarios compatible with this emissions target that appears to be quite challenging. The scenarios are compared to a reference scenario which assumes that Switzerland will reach a 20% reduction of CO_2 emissions relative to 1990 levels, using instruments that have already been defined (buildings refurbishment program, regulation on CO_2 emission for new cars, CO_2 tax on stationary fuels, Swiss ETS market).

Keywords: Climate policy, Energy policy, Switzerland, Computable general equilibrium model, CCS, Renewable, Nuclear power

☆The research leading to these results has received funding from the Swiss Federal Office for the Environment. We would like to thank José Romero, Rolf Iten, Jürg Füssler, Almut Kirchner, Patrick Criqui, Pierre-Alain Bruchez, the DDPP Swiss working group and the participants of the CERE seminar (Umeå University) for their helpful comments and suggestions.

*Corresponding author
Email address: marc.vielle@epfl.ch (Marc Vielle)

1. Introduction

As part of the Deep Decarbonization Pathways (DDP) project[1], the present paper presents simulation results of deep decarbonization pathways for Switzerland. DDP project is an international collaborative initiative aiming at understanding and showing how individual countries might define a roadmap paving the way to reaching a low carbon economy and how the world can keep global mean temperature increase below 2°C. The project is led by the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. More precisely, the DDP project objective is to explore and analyze for each country possible transitions to a low-carbon economy, taking into consideration national socio-economic conditions, development aspirations, infrastructure stocks, resource endowments, and other relevant factors. An economic modeling part complements the analysis. Up to now, 15 countries (Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, UK, and USA) are involved in this initiative.

The Swiss Federal administration and, in particular, the Federal Office for the Environment (OFEV) has decided to contribute to the project and therefore to develop a national Deep Decarbonization Pathway analysis to 2050 for Switzerland.

The paper discusses several options/scenarios compatible with this Deep Decarbonization Pathway. The paper is structured as follows: Section 2 presents briefly the GEMINI-E3 model used to perform the economic simulations. Sections 3 and 4 detail the storylines and the assumptions, respectively, of possible Deep Decarbonization Pathway scenarios. Section 5 provides results and analysis and, finally, the last section concludes.

2. The GEMINI-E3 Model

GEMINI-E3[2][6] is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the other CGE models (EPPA, OECD-Env-Linkage, etc) built and implemented by other modeling teams and institutions, and sharing the same long experience in the design of this class of economic models. The standard model is based on the assumption of total flexibility in all markets, both macroeconomic markets such as the capital and the exchange markets (with the associated prices being the real rate of interest and the real exchange rate, which

[1] `http://unsdsn.org/what-we-do/deep-decarbonization-pathways/`

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

are then endogenous), and microeconomic or sector markets (goods, factors of production).

In the last 20 years, GEMINI-E3 has been extensively used to assess future climate and energy strategies at global and regional levels The current version is built on the last Swiss input-output table 2008 [17] and the GTAP database 8 [5] for the other countries. The industrial classification used in this study comprises 11 sectors and is presented in Table 1. The model describes five energy goods and sectors: coal, oil, natural gas, petroleum products and electricity. Concerning the regions represented by the model we use an aggregated version of GEMINI-E3 that describes only 5 countries/regions: Switzerland, European Union, United States of America, BRIC (Brazil, Russia, India and China) and the rest of the World.

Table 1: Industrial and regional classifications

Sectors/goods	Countries/regions
01 Coal	CHE Switzerland
02 Crude oil	EUR European Union
03 Natural gas	USA United States of America
04 Petroleum products	BIC Brazil-Russia-India-China
05 Electricity	ROW Rest of the world
06 Agriculture	
07 Energy intensive industries	
08 Other goods and services	
09 Land transport	
10 Sea transport	
11 Air transport	

2.1. Energy demand

Domestic energy demand is equal to the sum of energy consumed by firms as a production factor and of energy consumed by households as a final good. The production structure of the industrial sectors is shown in Figure 1.

The representative consumer maximizes a nested CES utility function, described in Figure 2. Energy consumption is split in two parts, for transportation and housing purposes. In each nest, energy can be substituted by spending more on a capital good represented by cars in the first case and by shelters in the second one, i.e. by purchasing more energy-efficiency but also more expensive cars and housing units.

2.2. Energy supply

As in Switzerland coal, natural gas and crude oil are mainly imported, we only present the modeling of electricity generation. In this version of GEMINI-E3,

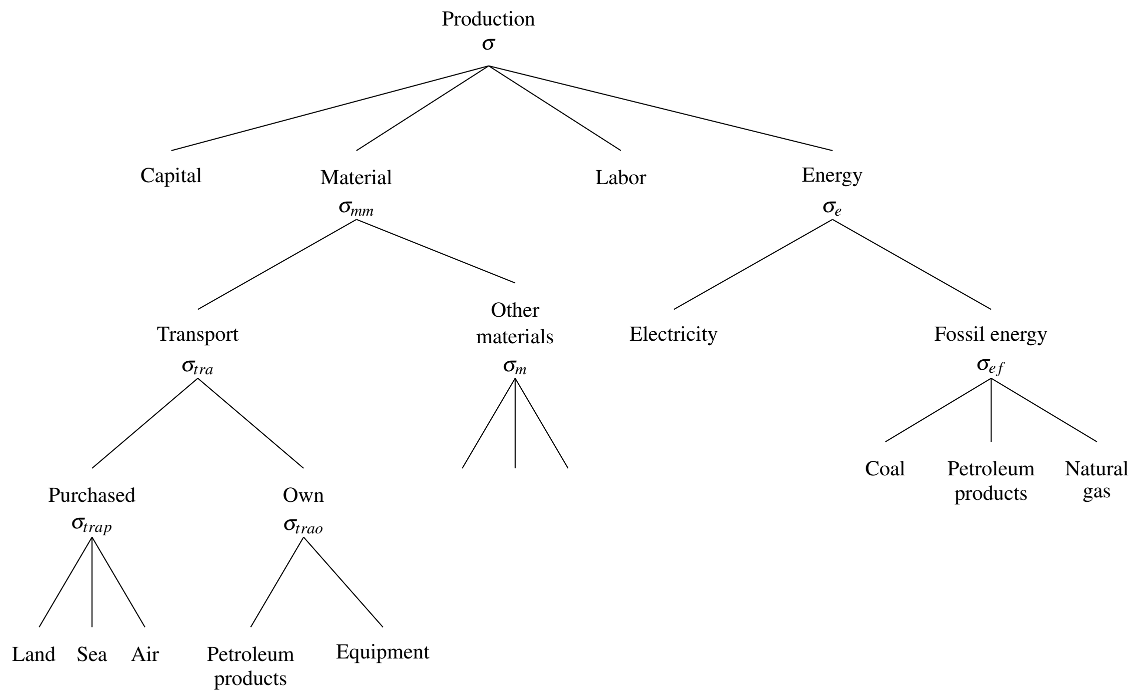


Figure 1: Nested CES production structure

electricity production is represented by a nested CES function including - besides fossil fuels, nuclear and hydraulic plants - the new capacities installed in the renewable technologies. “Renewable” aggregates wind, solar, geothermal and other renewable. Power generation is separated from the other activities (transmission and distribution) that appear through their factors of production at the top of the nesting structure. Power generation involves only two factors of production, capital and fuel (only capital for renewables)[3]. With this nesting structure it is possible to better take into account the power generation portfolio and to represent interfuel substitutability as well as substitutability between fossil and renewable power generation [21].

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

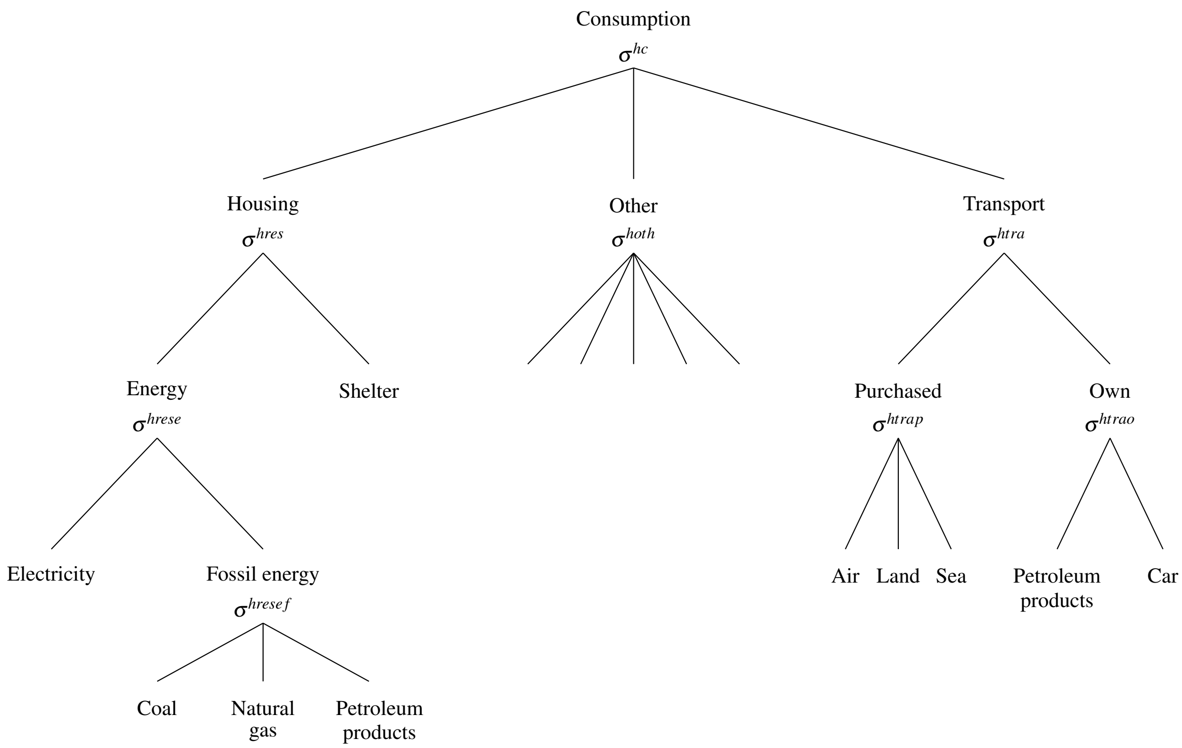


Figure 2: Nested CES consumption structure

3. Defining storylines

In this analysis, we have defined and analyzed two sets of scenarios:

- The first one, called "reference scenario", assumes that Switzerland will achieve by 2020 a 20% reduction of GHG emissions relative to 1990 levels in 2020, using instruments that have already been defined (Building Program, regulation on CO_2 emission for cars, etc). After 2020, we suppose that no additional policy will be implemented but the existing instruments would remain applied with their 2020 levels;
- The other ones, called the "DDP scenarios", all suppose that Switzerland will reach by 2050 a CO_2 emissions target of 1 ton of CO_2 per Swiss inhabitant but use alternative assumptions on the technologies available.

Following the Swiss CO_2 law these respective CO_2 targets concern CO_2 emissions from all sources, except international aviation. For the purpose of simplification, we assume in these scenarios that no climate policies are implemented in the rest of the world.

Up to 2020, the two scenarios make the same set of assumptions that are mainly drawn from the Swiss climate policy presented in “Switzerland’s Sixth National Communication and First Biennial Report under the UNFCCC” [19]. More precisely, we assume that the following measures and instruments are implemented up to 2020 in both scenarios:

1. The path for nuclear phase-out is applied;
2. The Building Program is extended up to 2020;
3. Car regulation on CO_2 emissions standard is implemented up to 2020;
4. Electric cars significantly penetrate the passenger cars market as well as the other road transport vehicles;
5. No Carbon Capture and Storage (CCS) technology is available;
6. A Swiss emission trading scheme for energy intensive industries is implemented. The cap is lowered every year by the same amount (1.74% of the cap set in 2010). GEMINI-E3’s sectors that participate in the ETS are the electricity generation sector and the energy intensive industries;
7. The present CO_2 levy is increased following the official rule, i.e. when the abatement is not sufficient to reach the CO_2 target in 2020;
8. After 2012, the *climate cent* on fuels for transport is replaced by a new instrument. From 2014, the revised CO_2 Act obliges oil importers to offset directly a part of the CO_2 emissions from transport fuel use. The offset will be financed by a levy that shall not exceed CHF 0.05 per liter of fuel. The share of transport emissions to be offset may vary from 5% to a maximum of 40%. The Federal Council determined the shares as 2% in 2014-2015, 5% in 2016-2017, 8% in 2018- 2019, and 10% in 2020.

After 2020 the two sets of scenarios diverge. The reference scenario does not integrate new targets on CO_2 emissions and does not assume new regulation on energy efficiency; it freezes the carbon prices to their 2020 levels. It should be noted that the last energy projection done by European Union [2] follows the same philosophy for the years after 2020. Therefore we use the following assumptions in the reference scenario:

1. The carbon prices (ETS price, CO_2 tax) and levy charged on fuels for transport remain constant and equal to their 2020 levels;
2. The Building Program remains constant at its 2020 levels;
3. The CO_2 emissions standard for new cars remains constant at its 2020 levels.

The DDP scenarios assume a much more stringent climate policy that will be achieved mainly by the implementation of a uniform carbon tax. However as the scenario is based on significant shifts in climate policy we believe that new technological options need to be considered. The DDP scenario will assume the following:

1. CCS option becomes available in 2025;
2. The Building Program is terminated in 2020;
3. Car regulation on CO_2 emissions standard is extended after 2020;
4. The CO_2 prices (ETS price, carbon tax) and the levy charged on fuels for transport are replaced by a uniform carbon tax applied to fossil energy consumption in order to reach the CO_2 target by 2050.

Figure 3 gives the emissions profile of the DDP scenarios as well as past emissions and the emissions of the reference scenario[4] that are presented in section 5.

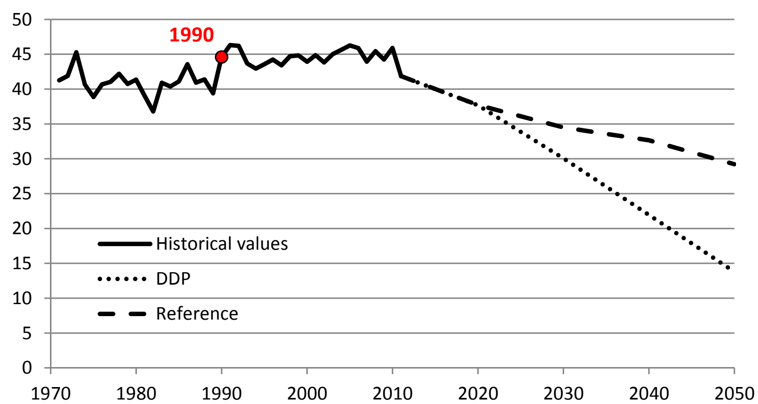


Figure 3: Swiss CO_2 emissions in the two scenarios (Reference and DDP) in Mt CO_2

The next section detail all these assumptions. Subsection 4.1 presents the common assumptions to both scenarios while subsections 4.2 and 4.3 give scenario specific ones.

4. Scenarios assumptions

4.1. Common assumptions

To simulate the evolution of the economy until 2050, GEMINI-E3 uses forecasts of population growth, GDP and energy prices, as well as assumptions on

[4]The emissions reported in Figure 3 include those coming from international aviation.

electricity generation as detailed below.

4.1.1. Demography

We use the evolution of the Swiss population as defined by the A-17-2010 scenario from the Federal Office of Statistic (OFS) [8]. This scenario is based on the median scenario called A-00-2010 until 2030. After that date, the scenario assumes a net immigration of population equal to 40 000 persons per year until 2060. Table 2 gives the evolution of the Swiss population. In 2050, 9.8 million inhabitants will live in Switzerland.

Table 2: Swiss Population in thousands

	2010	2030	2040	2050	2060
Swiss Population	7’864	9’225	9’568	9’820	9’999

For the rest of the world, assumptions on population are based on the 2010 forecast made by United Nations [20]. We use the “median-fertility variant”. In 2050, the World population will reach 9.27 billions of inhabitants.

4.1.2. GDP growth

For Switzerland, we compute the GDP growth rate by multiplying the labour force (given by the demographic scenario done by OFS) with labour productivity. This yields the potential GDP. We suppose that the labour productivity increases by 0.5% per year in Switzerland over the whole period.

For the rest of the World, we apply a similar methodology. We use the GDP growth rates computed in the last World Energy Outlook (WEO) [14] of the International Energy Agency (IEA) up to 2035. After 2035 we multiply the labour force by labor productivity based on what is retained by the IEA for the period 2011-2035. Table 3 shows the GDP growth used in the reference scenario.

Table 3: Annual GDP growth rate in percentage

	2010-2020	2020-2030	2030-2040	2040-2050	2050-2060
CHE	1.3%	0.7%	0.8%	0.7%	0.6%
EUR	1.3%	1.8%	1.7%	1.4%	1.2%
USA	2.8%	2.2%	2.1%	2.0%	1.8%
BIC	7.6%	4.5%	4.3%	3.7%	3.3%
ROW	5.4%	4.5%	4.4%	4.4%	4.3%
World	4.0%	3.4%	3.4%	3.4%	3.3%

4.1.3. World energy prices

Assumptions concerning energy prices are drawn from the WEO of the IEA [14]. The first preliminary scenarios presented in this report assume that only Switzerland implements a climate policy, therefore we retain the scenario called "current policies scenario" of the IEA. called "450 scenario". The predictions of the IEA stop in 2035. After that, we assume that energy prices will continue to grow and converge to a growth rate of 0.7% per year at the end of the simulation (i.e. 2050). Table 4 shows the energy prices used in the reference scenario. The oil price and the price of imported gas in Europe are assumed to reach 162$ and 5.1$/Mbtu in 2050, respectively.

Table 4: Fossil fuel import prices (dollar per unit) - Source: WEO [14] (*Current policies scenario*)

	2012	2020	2030	2040	2050
Real terms (2012 prices)					
IEA crude oil imports (barrel)	109.0	120.0	136.0	150.9	161.8
Natural gas EU imports (MBtu)	11.7	12.4	13.4	14.6	15.1

4.1.4. Electricity generation

In May 2011, the Federal government decided, after the devastating earthquake in Japan and the disaster at Fukushima, to gradually decommission all nuclear power plants. The strategy is to decommission five nuclear power plants when they reach the end of their service life and not to replace them with new ones. However, the Swiss government does not fix the end of their lifetime. The operator of the Mühleberg power plant already decided to cease all electrical generation in 2019. For the 4 remaining power plants we decided to use a lifetime of 60 years. Table 5 shows the operating lifes of the 5 existing nuclear power plants that have been introduced in GEMINI-E3. Table 6 shows the renewable potential that we use in this study. The main source is a publication of the BFE [12] adjusted by INFRAS (on solar P.V. and biomas & biogas). The electricity generation prices for new renewable capacities are given in Table 7. The expected decline in generation costs guarantees that the potentials are used.

4.2. Specific assumptions of the reference scenario

4.2.1. Transportation

We assume that the CO_2 emissions standards for new vehicles will be 130 grams of CO_2 per kilometer in 2015 and 95 grams in 2020. The regulation remains constant afterwards. Figure 4 shows the evolution of the emissions standards for passenger cars in the reference and the DDP scenarios.

Table 5: Operating life of Swiss nuclear power plants

Nuclear power plant	Operating life
Beznau I (365 Mwe)	1969-2029
Beznau II (365 Mwe)	1971-2031
Mühleberg (373 Mwe)	1972-2019
Gösgen (985 Mwe)	1979-2039
Leibstadt (1190 Mwe)	1984-2044

Table 6: 2050 potential of new renewables in GWh - Source: [12]

Solar P.V.	14000
Wind	4012
Geothermal	4378
Biomass and Biogas	4000
Other	2163
New Hydro	3160
Sum	26714

Table 7: Electricity generation cost in Swiss cents per kWh - Source: [18]

	2010	2020	2030	2040	2050
Hydro	8.9	10.8	11.5	10.9	11.1
Solar P.V.	31.7	16.4	13.0	11.1	9.9
Wind	24.1	20.1	15.7	13.9	12.0
Geothermal	12.3	10.5	9.8	9.2	8.6

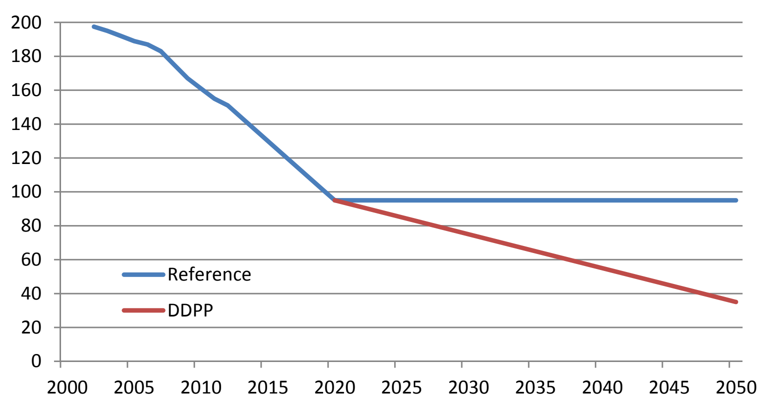


Figure 4: CO_2 emissions standards in grams of CO_2 per km for new passenger cars in Switzerland (historical values, Source: [4])

For other vehicles (i.e. light commercial vehicles, buses, trucks) we assume a same rate improvement in CO_2 emissions. We suppose that electric cars will penetrate the market of passenger cars in the forthcoming decades and that the share of passengers cars using electricity will be equal in 2020 to 5% and in 2050 to 40%. For other vehicles the share would be equal to 30% in 2050.

The Federal Building Program initiated[5] in 2010 by the Confederation and the cantons aims at reducing significantly the energy consumption and the CO_2 emissions of Swiss buildings. The objective is relevant and reasonable as in Switzerland around 40% of the energy consumption and CO_2 emissions are generated by the building sector and about 1.5 million of houses and buildings require urgent energy retrofit. The program is divided into two streams in the period 2010-2019. The first one (Part A) includes federal subsidies for mainly thermal insulation works while the second stream (Part B) encourages investments in renewable electricity generation in buildings. In the reference scenario we assume that the Building Program remains constant after 2020, i.e. that 200 millions of CHF will be spent every year. In the following, we estimate the direct contribution of Part A on CO_2 savings up to 2050 based on 2011-2013 statistics (yearly subsidies, CO_2 savings, etc) available at `http://www.dasgebaeudeprogramm.ch/index.php/fr/le-programme-batiments/en-bref` and summarized in Table 8. Note that the column "Total expected CO_2 savings" gives the CO_2 savings over all the effective duration of the measures (about 37 years).

Table 8: Statistics of the Building Program (Part A) on 2011-2013.

	Subsidies (MCHF)	Total expected CO_2 savings(Mt of CO_2)	Efficiency ratio (Mt of CO_2 / MCHF)
2011	136	1.57	0.0115
2012	174	2.10	0.0121
2013	131	1.73	0.0132

To estimate the global impact of the Building Program from 2011 until 2050, we made the following assumptions:

- The budget for federal subsidies will attain 200 MCHF per year between 2014 and 2050.
- The efficiency ratio (ie, CO_2 savings per MCHF) of the implemented measures will decrease by 50% between 2014 and 2050.

[5] See `http://www.dasgebaeudeprogramm.ch/index.php/fr/le-programme-batiments/en-bref`

In Table 9, we report our forecasts on CO_2 savings. The column "Cumulative effective CO_2 savings" indicates the CO_2 savings in the corresponding year obtained by current and past retrofit subsidized by the Building Program. In 2050, these amount to 46.71 millions tons.

The analysis leads to 46.71 Mt of CO_2 savings for the full program duration (2011-2050).

Table 9: Forecasted CO_2 savings resulting from the Building Program.

	Subsidies (MCHF)	Total expected CO_2 savings (Mt of CO_2)	Efficiency ratio (Mt of CO_2 / MCHF)	Cumulative effective CO_2 savings (Mt of CO_2)
2015	200	2.57	0.0128	0.83
2020	200	2.38	0.0119	3.30
2025	200	2.19	0.0110	7.35
2030	200	2.00	0.0100	12.85
2035	200	1.81	0.0091	19.68
2040	200	1.63	0.0081	27.72
2045	200	1.44	0.0072	36.82
2050	200	1.25	0.0063	**46.71**

4.3. Specific assumptions of the DDP scenario

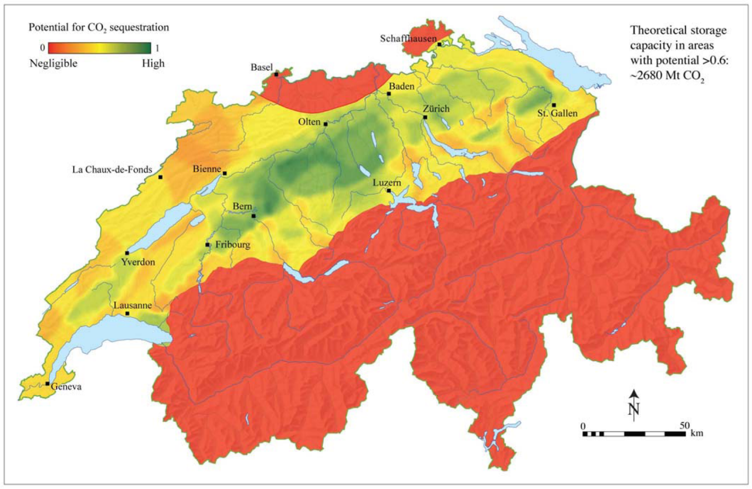
4.3.1. Transportation

We assume that the regulation regarding the CO_2 emissions of new vehicles is reinforced after 2020. The new emissions standard is equal to 35 grams per kilometer in 2050 (see Figure 4) which is in line with the assumption used in the "Neue Energiepolitik" (NEP) scenario of the Energieperspektiven [18]. The emissions standard is applied to new vehicles including electric ones. The same assumption is retained for other vehicles in relative terms.

4.3.2. Carbon capture and storage

The CO_2 storage capacity is significant in Switzerland. A report of the Institute of Geological Science [9] evaluates the geological potential for this option within Switzerland, based on a literature review, at 2680 millions tonnes of CO_2. Figure 5 maps this potential.

While CCS is expected to play an important role in climate policies, its deployment is subject to technical, social and legislative uncertainties. Several studies have analyzed the role of CCS for the European energy transition under different assumptions concerning these uncertainties. The "EU Reference scenario 2013" elaborated with the PRIMES model and published by the European Commission



Map of Switzerland showing the potential for CO_2 sequestration within deep saline aquifers, estimated from data in the literature. The areas of high potentials (green) do not guarantee the feasibility of CO_2 sequestration. Rather, they serve as guides to areas that warrant more detailed investigation. The portions of the four major aquifers with potentials above 0.6 are estimated to have a theoretical (unproven) storage capacity of approximately 2680 millions of tonnes (Mt) of CO_2.

Figure 5: Swiss CO_2 sequestration potential - Source: [9]

[2] determines the development of the EU energy system under current trends and adopted policies until spring 2012 and those that are or will be implemented over the next years. The scenario assumes the implementation of an ETS with a price of 100 € per ton of CO_2 in 2050. CCS develops mainly after 2030 reaching 7% of electricity generation by 2050 and representing a thermal capacity of 38 GWe. Another study performed with the POLES model [11] gives a similar capacity for CCS deployment (i.e. 34 GWe) but for the year 2030 within a scenario that assumes a faster commercial availability of CCS in the power sector. In the Roadmap dedicated to CCS [3], IEA finds a more optimistic deployment where the European CCS capacity reaches 68 GWe in 2050.

IEA in [13] evaluates the cost of CO_2 capture on average at 80 $ per ton of CO_2 for natural gas-fired power plants. The costs per ton of transported CO_2 vary from 2 $ to 6 $ for 2 Mt transported over 100 km according to another publication from IEA [1]. The same publication estimates the cost of CO_2 storage in deep saline aquifers for Europe from 1.90 $ per ton of CO_2 to 6.20 $.

In this analysis we suppose that CCS will begin to be implemented in Switzerland in 2025 at a cost of 100 $ per ton of CO_2.

5. Simulations results

5.1. The reference scenario

Table 10 gives the CO_2 prices and the levy charged on fuels used for transportation. In 2020, one notices that the levy is very low, i.e. around 2 Swiss cents per liter. CO_2 emissions from the road transportation sector are thus not affected by the levy and all CO_2 abatement is provided by other sectors. The 60 CHF tax level defined for the year 2014 is sufficient to reach the 20% abatement target by 2020. In that context the ETS price reaches 40 CHF in 2020, which is mainly driven by the deployment of gas turbines in electricity generation with 4 TWh of electricity generated in 2020. After 2020, prices remain constant following the rules presented in Section 3.

Table 10: CO_2 prices and other levy in CHF_{2013} - Reference scenario

	2020	2030	2040	2050
CO_2 tax	60	60	60	60
CO_2 ETS price	40	40	40	40
Levy on fuel transport	0.02	0.02	0.02	0.02

Figure 6 displays CO_2 emissions by sectors. In 2050, the Swiss CO_2 emissions (including international aviation) are about 29.2 Mt of CO_2, that is 22.5% lower than 2020 levels. Without considering emissions from international aviation, this represents 2.5 tons of CO_2 per capita. We observe that all sectors contribute to the decline of CO_2 emissions except ETS sectors for which emissions increase by 14% between 2007 and 2050 following the deployment of electricity from natural gas. Over the same period, the CO_2 emissions decrease by 31% in the road transportation sector due to the electrification of vehicles while emissions from the residential sector decrease by 56% due to the cumulative effects of the buildings retrofit program.

The electricity generation mix is presented in Figure 7. We observe that nuclear production is gradually substituted by natural gas and renewable productions. Swiss electricity generation reaches 78 TWh in 2050. Electricity consumption increases by 0.3% per year over the period of simulation. This increase is mainly driven by the deployment of electric cars and the substitution of fossil energy by electricity in heating systems (e.g. heat pumps).

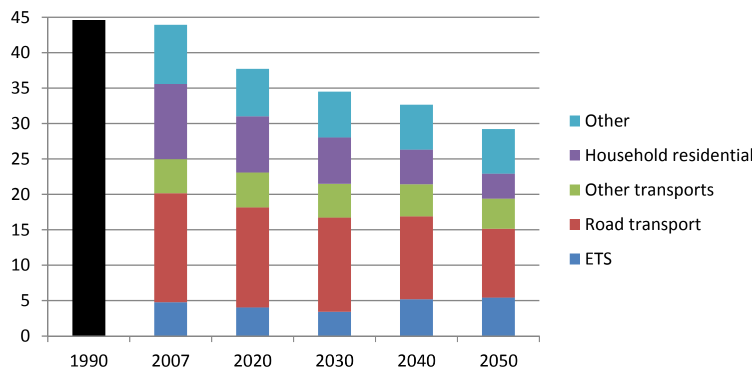


Figure 6: Swiss CO_2 emissions in Mt CO_2 - Reference scenario

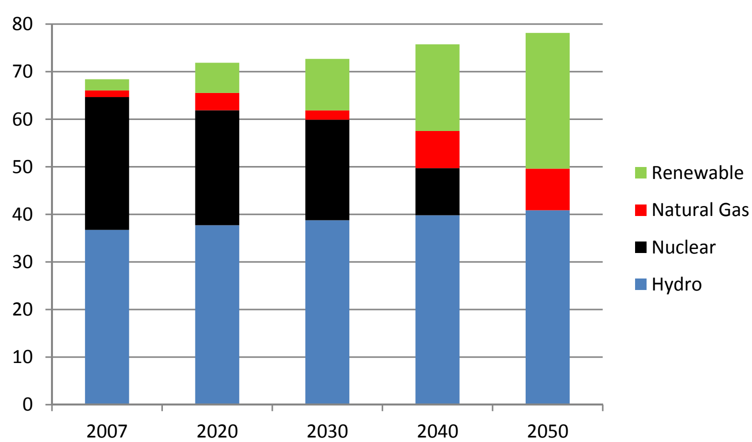


Figure 7: Swiss electricity generation in TWh - Reference scenario

5.2. The DDP scenario

We now suppose that after 2020 a uniform CO_2 price is implemented in Switzerland and gradually increased to reach the objective of 1 ton of CO_2 per capita in 2050. To achieve this goal, carbon emissions must be taxed at 1556 CHF per ton of CO_2 in 2050. As can be seen in Table 14, in the last decade, the CO_2 price is multiplied by a factor two showing the stringency of the target in 2050. A similar result is found with models used to analyse the European strategy in the EMF28 exercice [15]. The welfare cost in percentage of household consumption is shown in Figure 23, it is equivalent to a decrease by 1.7% of household consumption in 2050.

Table 11: CO_2 prices and other levy in CHF_{2013} - DDP scenario

	2020	2030	2040	2050
CO_2 tax	60			
CO_2 ETS price	40			
Levy on fuel transport	0.02			
Uniform CO_2 tax		257	654	1556

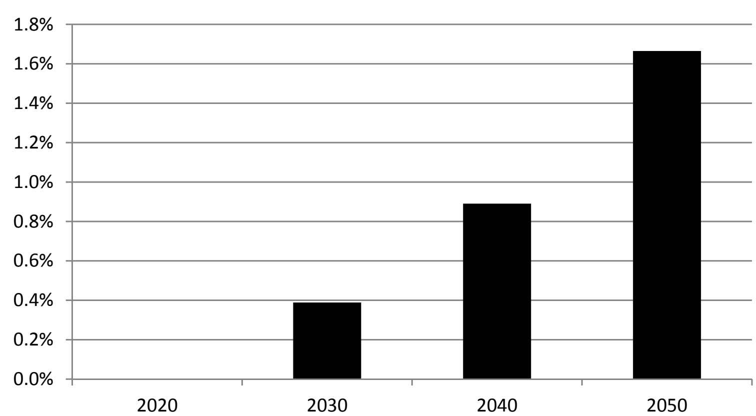


Figure 8: Annual welfare cost in % of household consumption compared to reference scenario - DDP scenario

Figures 9 and 10 show the associated CO_2 emissions by sectors. They decrease linearly from 2007 to 2050, and the 2020 committed target appears to be consistent with the DDP target. All sectors contribute to the abatement except international aviation, which is not taxed in the DDP scenario.

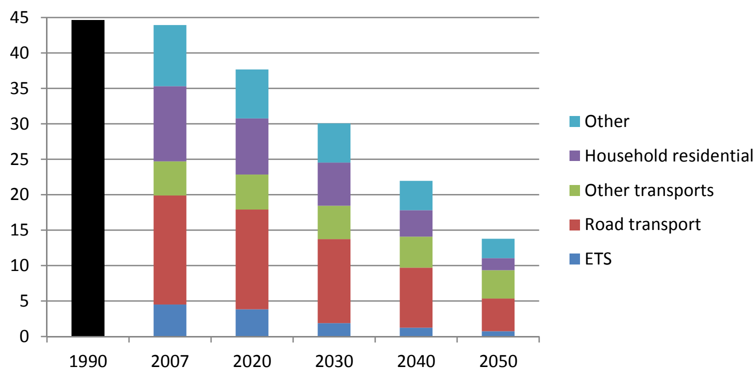


Figure 9: Swiss CO_2 emissions in Mt CO_2 - DDP scenario

By assumption all emissions from natural gas power plants are sequestered after 2025. Over the whole period (2025-2050) this represents 77 Mt of CO_2 and 3% of the Swiss sequestration capacity. The decarbonization of the Swiss economy is thus partly realized through the use of more electricity (see Figures 11 and 12) combined with CCS allowing to produce electricity with natural gas free of CO_2, and through the use of new renewables whose potential is fully used in 2050. In 2050, 90 TWh of electricity are produced, which represents a 15% increase with respect to the reference scenario. Electricity generation from natural gas is equal to 21 TWh.

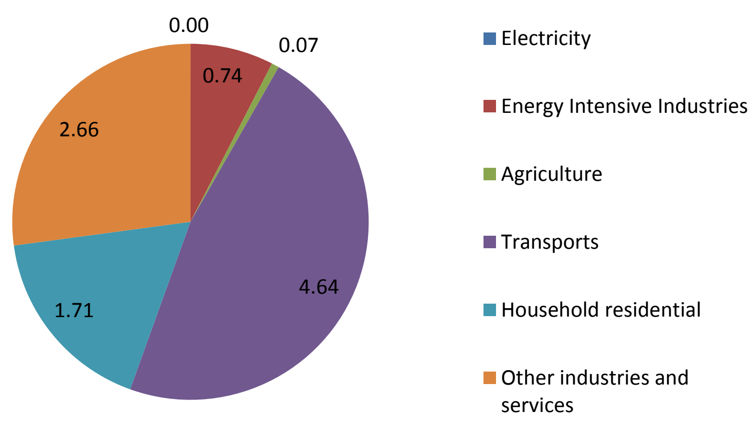


Figure 10: Swiss CO_2 emissions in Mt CO_2 in 2050 (excluding international aviation) - DDPP scenario

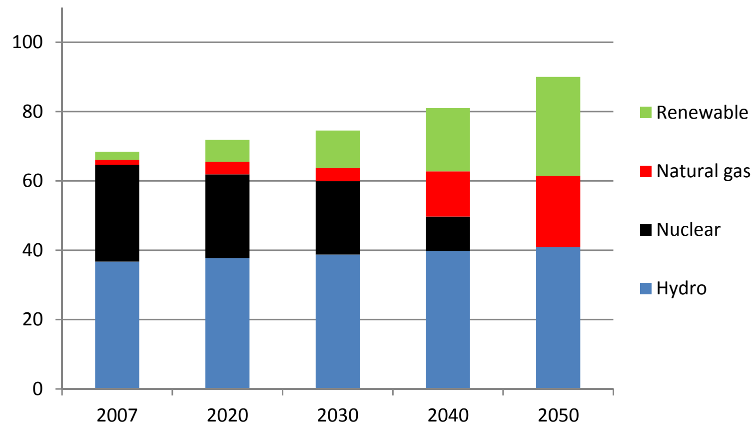


Figure 11: Swiss electricity generation in TWh - DDP scenario

Figure 12 displays the electricity consumption in its main uses. We remark that electric mobility consumption (excluding railways) represents 15 TWh in 2050.

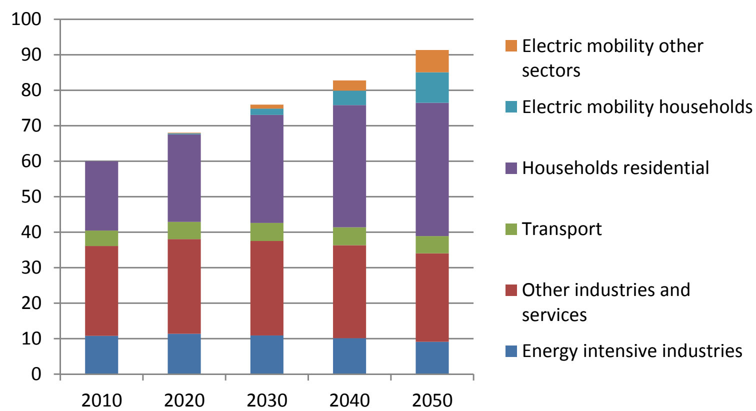


Figure 12: Swiss electricity consumption in TWh - DDP scenario

5.3. The DDP scenario without CCS

We observed in the previous DDP scenario that CCS represents an important contribution to CO_2 abatement. However CCS is surrounded by several uncertainties related mainly to technological issues. The social acceptability of this technology is also highly uncertain, especially in Switzerland where geological conditions are most favorable in regions close to population centers. Therefore, we have simulated a scenario in which we supposed that CCS would no be implemented in electricity generation. In this case, CO_2 emissions from gas power plant are taxed like other carbon emissions.

Because in 2050 all Swiss renewable potentials are used for electricity generation, the remaining part of electricity generation can only be produced from natural gas power plants. This induces carbon emissions, so that a significantly higher CO_2 tax is needed to achieve the target of 1 ton of CO_2 per capita in 2050. In Table 12 one can see that the carbon price jumps to 2650 CHF in 2050 and the welfare loss reaches 1.9% of households consumption (see Figure 13).

Table 12: CO_2 prices and other levy in CHF_{2013} - DDP scenario without CCS

	2020	2030	2040	2050
CO_2 tax	60			
CO_2 ETS price	40			
Levy on fuel transport	0.02			
Uniform CO_2 tax		324	1040	2652

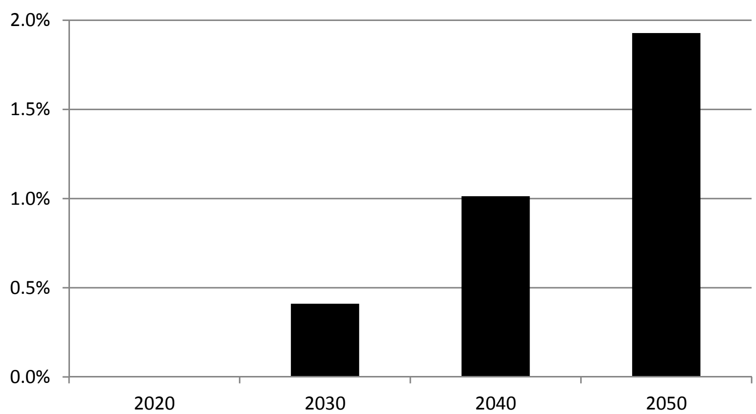


Figure 13: Annual welfare cost in % of household consumption compared to reference scenario - DDP scenario without CCS

The carbon taxation of power plants using natural gas increases the electricity price, limiting the substitution of fossil fuels by electricity. As shown in Figure 15, electricity generation reaches 78 TWh, 12 TWh below the scenario with CCS. Regarding CO_2 emissions, the share of these emissions coming from ETS sectors (that includes those from electricity generation) increases, which of course requires more abatement from the other sectors (see Figures 15 and 16).

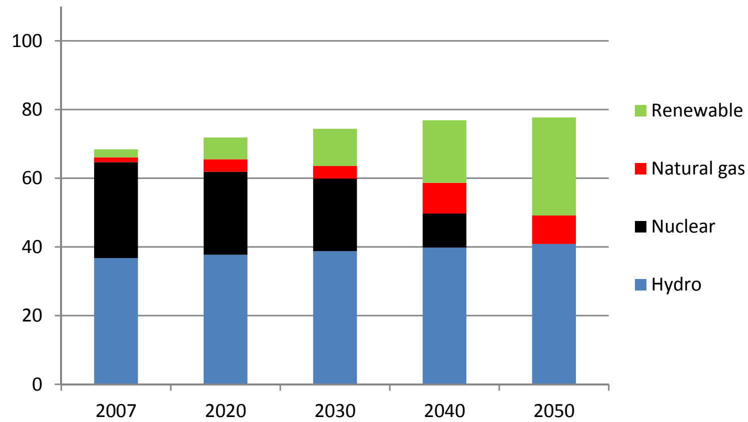


Figure 14: Swiss electricity generation in TWh - DDP scenario without CCS

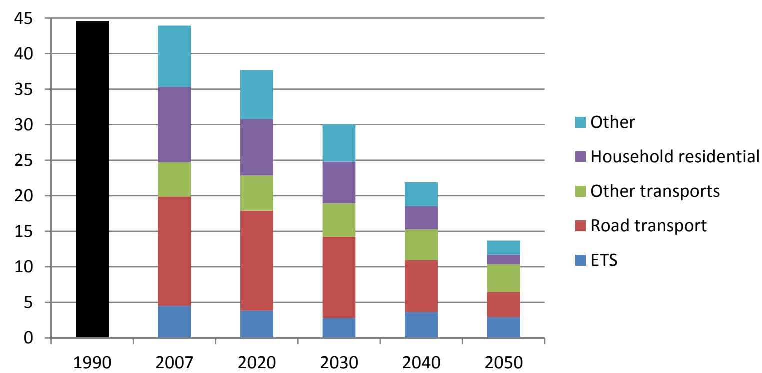


Figure 15: Swiss CO_2 emissions in Mt CO_2 - DDP scenario without CCS

Figure 16 gives for the year 2050 the CO_2 emissions levels by sectors. Emissions coming from electricity generation are equal to 2.4 Mt CO_2 which represents 25% of Swiss emissions (excluding international aviation) .

5.4. The DDP scenario with a constraint on electricity consumption

One of the main conclusions of the DDP scenario analysis is that decarbonization of the Swiss economy comes with an increase in electricity generation partly produced from natural gas. This result is not without rising several issues. First this

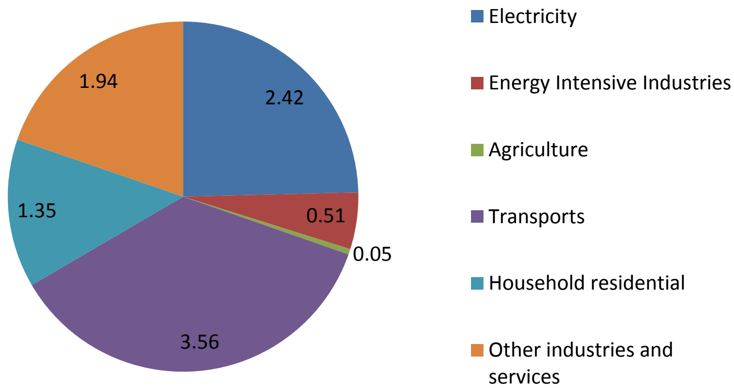


Figure 16: Swiss CO_2 emissions in Mt CO_2 in 2050 (excluding international aviation) - DDP scenario without CCS

option is cost effective only with CCS implementation, which is at the same time highly uncertain. Secondly, the significant induced imports of natural gas stand in contradiction with the Swiss energy strategy that promotes energy security goals.

In order to avoid this undesirable effect of natural gas imports, we consider a new scenario with a constraint on long-term electricity consumption. Indeed we rely on the planned amendment of the Swiss Energy Act that defines a target for electricity consumption per capita that has to decrease by 3% in 2020 and by 13% in 2035 with respect to 2000 levels. We extend this target to a 18% reduction in 2050. Therefore, in 2050 electricity consumption would be equal to 63 TWh. The scenario assumes that this target is implemented through additional indirect taxation of electricity consumption for all uses (intermediate and final).

As can be seen in Figure 17, Swiss electricity consumption would remain flat during the simulation period, and electricity is generated by hydro and other renewables without any natural gas contribution.

Results are reported in Table 13. The required carbon price increases by 26% in 2050 with respect to the DDP scenario without constraint and reaches 1963 CHF. The ceiling on electricity consumption leads to a large increase of electricity taxation with an indirect tax rate equal to 88% in 2050. Combining a carbon tax and a tax on electricity consumption slightly decreases the welfare cost with respect to the DDP scenario to 1.5% in 2050 (see Figure 19). This can be partly explained, by a consumption reduction of natural gas which is totally imported in Switzerland. With the constraint of balanced trade assumed, this creates a trade revenue surplus, i.e. less exports are required to equalize the import costs and the consumption level could increase. A similar result is found with the GENESwIS model [16].

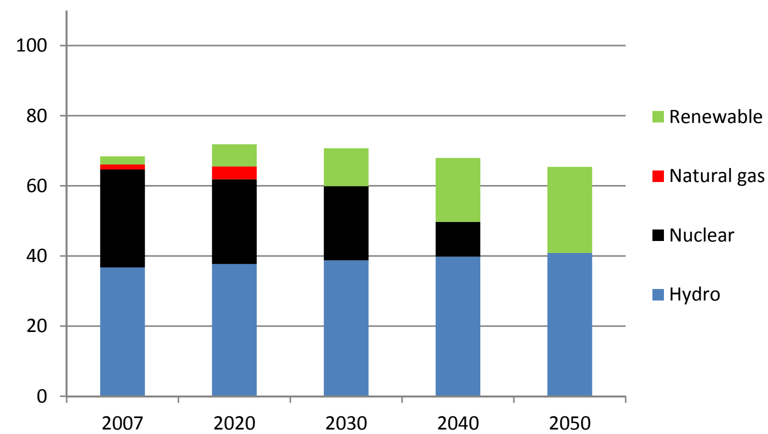


Figure 17: Swiss electricity generation in TWh - DDP scenario with a constraint on electricity consumption

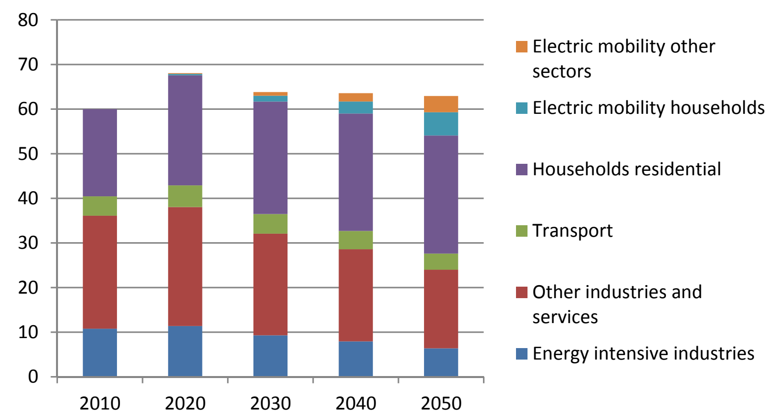


Figure 18: Swiss electricity consumption in TWh - DDP scenario with a constraint on electricity consumption

Table 13: CO_2 prices and other levy in CHF_{2013} - DDP scenario with a constraint on electricity consumption

	2020	2030	2040	2050
CO_2 tax	60			
CO_2 ETS price	40			
Levy on fuel transport	0.02			
Uniform CO_2 tax		299	787	1963
Electricity tax		18%	41%	88%

Figures 19 and 20 give the CO_2 emissions related to this scenario.

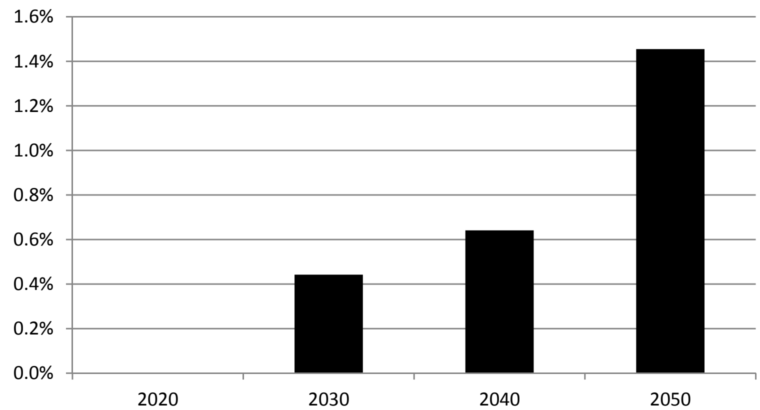


Figure 19: Annual welfare cost in % of household consumption compared to reference scenario - DDP scenario with a constraint on electricity consumption

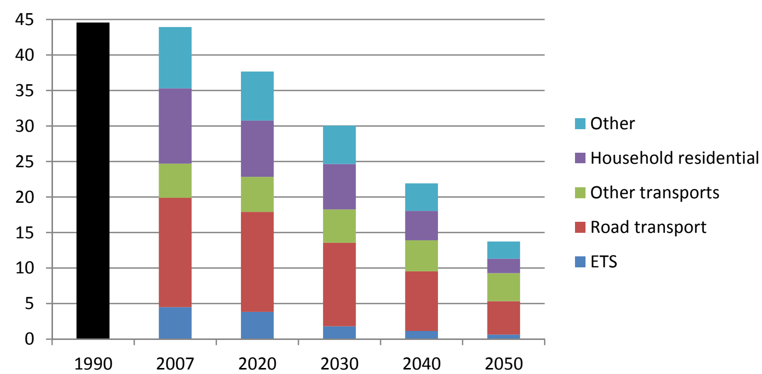


Figure 20: Swiss CO_2 emissions in Mt CO_2 - DDP scenario with a constraint on electricity consumption

5.5. The DDP scenario with earlier decommissioning of nuclear power plants

In the previous scenarios, we assumed a 60 years lifetime for nuclear power plants, an assumption that could be considered as optimistic. In order to analyze the sensitivity of earlier decommissioning on DPP trajectories, we simulate here a scenario that assumes a lifetime of 50 years instead of 60 years for Swiss nuclear

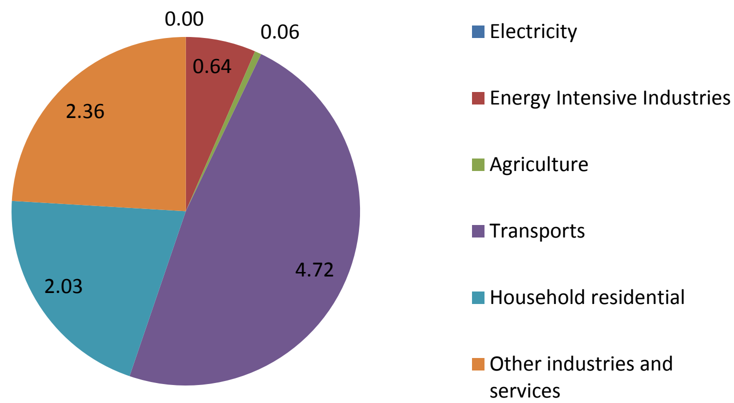


Figure 21: Swiss CO_2 emissions in Mt CO_2 in 2050 (excluding international aviation) - DDDP scenario with a constraint on electricity consumption

power plants, except for the Mühleberg power plant for which the decommissioning date is already fixed by its owner. Note that this required to run a new reference case where the lifetime of nuclear power plant is also fixed to 50 years. An earlier decommissioning of nuclear power plants would impact only the transition period towards a nuclear free electricity generation system, i.e. 2019-2040 (a complete denuclearization of electricity generation is achieved in 2034). During this transition period, we observe that gas power plants increase their contribution to electricity generation inducing higher electricity prices and thus higher CO_2 prices with respect to the DDP scenario with a 60 years lifetime assumption. Globally the welfare cost is also higher, but by 2050, carbon price and welfare cost converge to the ones computed with a 60 years lifetime. We compute the difference of the cumulative cost related to the implementation of the DDP target between the 60 years and 50 years lifetimes. It is equal to 22.5 billions of CHF_{2013}. This gives an upper bound value on the refurbishment expenditures that can be invested in the four Swiss nuclear power plants to extend by 10 years their lifetime. Per KWh that is equal to 9 Swiss cents.

Table 14: CO_2 prices and other levy in CHF_{2013} - DDP scenario with earlier decommissioning of nuclear power plants

	2020	2030	2040	2050
CO2 tax	60			
ETS price	124			
Levy on fuel transport	0.02			
Uniform CO2 tax		267	663	1559

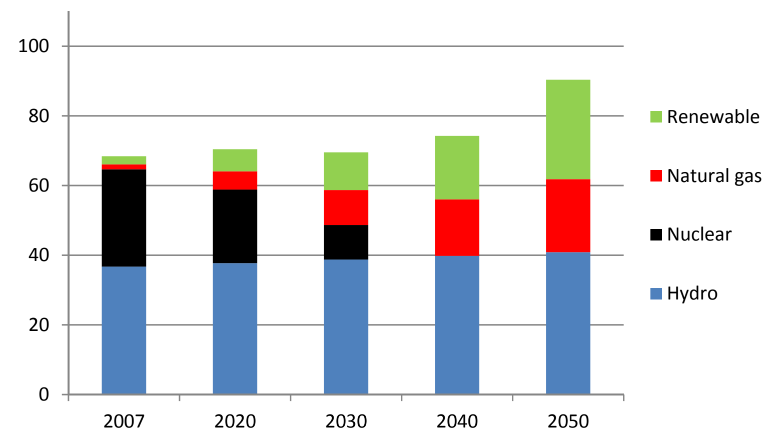


Figure 22: Swiss electricity generation in TWh - DDP scenario with earlier decommissioning of nuclear power plants

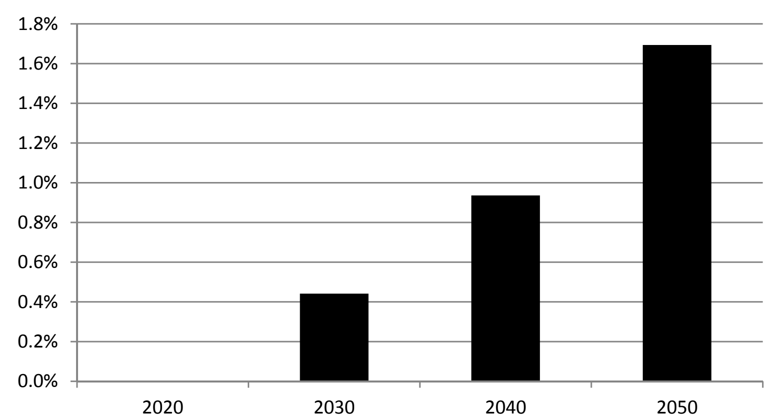


Figure 23: Annual welfare cost in % of household consumption compared to reference scenario - DDP scenario with earlier decommissioning of nuclear power plants

6. Conclusion

This analysis aimed at simulating scenarios of a decarbonization pathway for Switzerland. To do this analysis we used the GEMINI-E3 model adapted to account for the existing Swiss policies.

These simulations provide several insights. First, the objective of 1 ton of CO_2 per capita in the next 35 years appears to be quite challenging, especially with the nuclear phase-out decision by 2044. Nevertheless, it is possible to design a feasible pathway. Assuming CCS deployment, it results in a cumulative welfare loss[6] of 1% of household consumption. In 2050 the welfare loss represents 1.7% of household consumption, which is much lower than the estimates of the FP7 AMPERE project [10] that range from 2% to 9.5% GDP reduction for the European Union. At the end of the period, the CO_2 tax is equal to 1556 CHF. This price is high in comparison with those found in the EMF28 exercice [15] for European countries where the median value is 521 €/tCO_2 with a range of [240 - 1127 €/tCO_2] by 2050. But it is consistent with previous analyses on Switzerland [7]. The main reason is that Switzerland lacks the classical sectors where CO_2 can be mitigated at moderate cost (e.g. coal fired electricity generation, heavy industry). In that context the decarbonization of the Swiss economy is achieved through energy efficiency improvements but also through the substitution of fossil energy by carbon-free electricity. However, as the Swiss renewable potential is not sufficient to satisfy electricity demand, the model shows the deployment of CCS technology associated with combined cycle gas turbines. This penetration of CCS technologies is consistent with other EU studies [10, 15], in which CCS is combined with a growing share of European electricity supply.

Assuming that CCS will no be implemented in Switzerland raises the cost of the DDP scenario, but this increase is limited by gains coming from reduced imports of natural gas for power generation. The welfare cost reaches 1.9% in 2050.

Finally we simulate a scenario that combines targets on carbon emissions and on electricity consumption. In this case Swiss electricity generation remains free of carbon and based on hydro and other renewables. The welfare cost is comparable to the one computed in the DDP scenario but would result in a less energy intensive economy that does not rely on imports of natural gas.

[6] without discounting.

References

[1] *CO_2 capture and storage A key carbon abatement option*. International Energy Agency, 2008.

[2] *EU Energy, Transport and GHG Emissions, Trends to 2050, Reference Scenario 2013*. European Commission, 2013.

[3] International Energy Agency. *Technology Roadmap Carbon Capture and Storage*. 2013.

[4] Auto-Suisse. Rapport annuel sur la réduction de la consommation normalisée de carburant des voitures de tourisme dans le cadre de l'Ordonnance sur l'énergie. Technical report, 2012.

[5] Badri Narayanan, Angel Aguiar, and Robert McDougall, editors. *Global Trade, Assistance, and Production: The GTAP 8 Data Base*. Center for Global Trade Analysis, Purdue University, 2012.

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

[7] Christoph Böhringer and André Müller. Environmental Tax Reforms in Switzerland A Computable General Equilibrium Impacst Analysis. *Swiss Journal of Economics and Statistics*, 150(1):1–21, 2014.

[8] Office Fédérale de la Statistique. Les scénarios de l'évolution de la population de la Suisse 2010-2060. Technical report, 2010.

[9] Larryn W. Diamond, Werner Leu, and Gabriel Chevalier. Potential for geological sequestration of CO_2 in Switzerland. Technical report, Bundesamt für Energie BFE, 2010.

[10] E3MLab and ICCS. Ampere Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates. Technical report, 2013.

[11] Enerdata. Cost and benefits to EU Member States of 2030 Climate and Energy targets. Technical report, 2014.

[12] Conseil fédéral. Potentiel des énergies renouvelables dans la production d'électricité. Technical report, Office fédéral de l'énergie OFEN, 2012.

[13] Matthias Finkenrath. Cost and performance of carbon dioxide capture from power generation. Technical report, International Energy Agency, 2011.

[14] International Energy Agency. *World Energy Outlook 2013*. 2013.

[15] Weyant J, Knopf B., de Cian E., Keppo I., and van Vuuren D. Introduction to the EMF28 Study on scenarios for transforming the European energy system. *Climate Change Economics*, 4, 2013.

[16] Sophie Maire, Rajesh Pattupara, Kannan Ramachandran, Marc Vielle, and Frank Vöhringer. Electricity markets and trade in Switzerland and its neighbouring countries (ELECTRA). Technical report, Econability, PSI, EPFL, 2015.

[17] C. Nathani, D. Sutter, R. van Nieuwkoop, M. Peter, S. Kraner, M. Holzhey, H. Rtter, and R. Zandonella. Energy related disaggregation of the Swiss Input-Output Table. Technical report, SFOE, EWG Publication, Bern, 2011.

[18] Prognos. Die Energieperspektiven für die Schweiz bis 2050 - Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050. Technical report, Study commissioned by the Swiss Federal Office of Energy, Basel, 2012.

[19] Swiss Confederation. *Switzerland's Sixth National Communication and First Biennial Report under the UNFCCC*. 2013.

[20] Department of Economic United Nations and Population Division Social Affairs. World Population Prospects: The 2010 Revision. Technical report, 2011.

[21] Ian Sue Wing. The synthesis of bottom-up and top-down approaches to climate policy: Electric power technologies and the cost of limiting US CO_2 emissions. *Energy Policy*, 34:3847–3869, 2006.