Swiss Energy Strategies under Global Climate Change and Nuclear Policy Uncertainty

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1. Introduction

Increasing global population, rising affluence, shortages of natural resources, and climate change are some of the current global challenges that policy makers face when deciding energy strategies. Many of these challenges and the way countries would respond to them are significantly uncertain, leading to a broad set of possible regional policies and technological pathways. Small countries or countries with limited supplies of natural resources are more likely to be affected by these global uncertainties. This is the case for Switzerland, which depends highly on imported fossil fuels to supply its heating and transport demand.

The nuclear accident in Fukushima, Japan, in March 2011 has increased worldwide the uncertainty regarding nuclear policy. Different policy responses may lead to different pathways of energy system development. In Switzerland, the federal cabinet decided in May 2011 to gradually decommission all Swiss nuclear power plants to reach a complete phase out by 2034 (SWISS FEDERAL COUNCIL, 2011). In addition, Switzerland has an ambitious domestic target of reducing greenhouse gas emissions by 60% in 2050 (compared to 1990 levels); this target is consistent with a global target of 2°C mean temperature increase (compared

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to pre-industrial levels) (OcCC, 2007). Since nuclear power accounts for around 60% of current Swiss electricity generation, the cabinet decision raises important questions concerning alternative technologies and energy saving measures needed to achieve these targets. Furthermore, available strategies for Switzerland are likely to be affected by global or regional energy-related decisions. In this work, we seek to analyze Swiss energy technology options for climate change mitigation; and the possible effect of changed technology preferences (both globally and domestically) after the recent nuclear accident in Fukushima, Japan.

We present a scenario analysis of global and regional technology preferences and climate change mitigation policies using an extended MERGE-ETL model. MERGE (Model for Estimating the Regional and Global Effects of greenhouse gas reductions) is an intertemporal general equilibrium model that can be used to analyze the cost of mitigating greenhouse gas emissions (Manne, Mendelsohn, and Richels, 1995). MERGE is an appropriate analytical framework to analyze global challenges affecting energy, economy and climate; and appropriate responses to them because it represents global energy and economic systems including such features as trade, resources, technology deployment, capital stocks and economic growth. Furthermore, MERGE-ETL (Magne, Kypreos, and Turton, 2010) includes global endogenous technology learning (ETL) that enables the analysis of possible technological change that may improve the long-term competitiveness of technologies that are currently less mature.

This paper is organized as follows: in the first section we present a brief description of the MERGE-ETL model; in the second section we present the key scenario and model assumptions; in the third section we describe the developed scenarios and present the results; finally we discuss some policy implications and conclusions of the analysis.

2. MERGE-ETL

MERGE-ETL is an enhanced version of the MERGE model, including endogenous technological learning (ETL). It is a well-established model for analyzing the economic impact of GHG policies and the role of technologies to fulfill climate targets. MERGE combines a top-down model of the economy and a bottom-up description of the energy sector to determine optimal technological choices to provide energy services (Manne, Mendelsohn, and Richels, 1995). The combination of the two approaches adds a value to MERGE compared to bottom-up or top-down models. Unlike bottom-up models, MERGE is able to account for linkages between economic activity and energy demand in its intertemporal general equilibrium submodel and thus determine endogenously energy demands and prices as well as the economic output (realized GDP). Compared to top-down models, the role of technological change can be analyzed in more detail in MERGE's bottom-up energy sector submodel, which includes a detailed description of electric and non-electric technologies. MERGE-ETL integrates four submodels governing: economic production; the energy sector; climate and emissions; and damage assessment.

Unlike a conventional energy-system approach to analyze individual regions, this application of MERGE enables us to account simultaneously for a range of global uncertainties in an integrated and endogenous way. We reorganized the regional structure of MERGE-ETL around 10 world regions, including: the European Union-plus; Switzerland; Russia; the Middle East; India; China; Japan; the USA; Canada, Australia and New Zealand; and the Rest of the World. This new definition of the regions represents important political-economic groups, which allow us the analysis of trading among the regions and global depletion of scarce energy carriers such as natural gas, petroleum and uranium. In addition, we can study the effect of global challenges on individual regions; in this case we focus on technology pathways in Switzerland. Importantly, we have included bilateral trade of electricity between the European Union and Switzerland, to better represent the Swiss energy system.

The model is calibrated for the years 2000 and 2005 and the projection periods correspond to the years 2010 to 2100 in steps of 10 years.

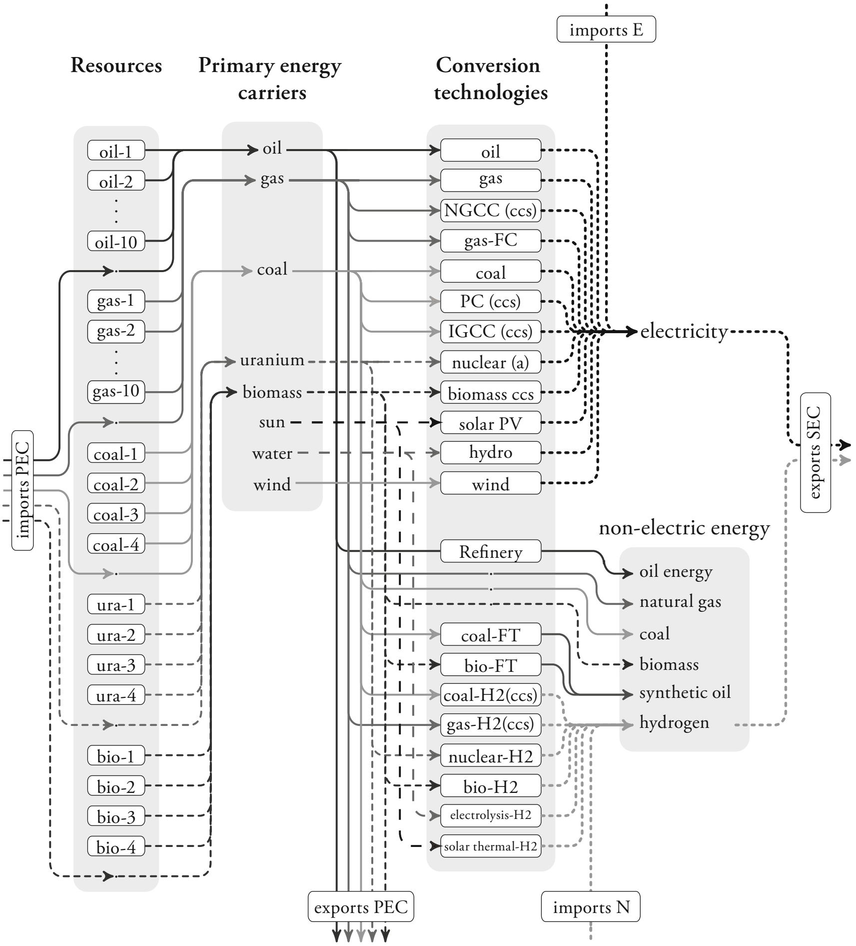
2.1 *Energy Submodel*

The energy submodel supplies electric and non-electric energy inputs to the rest of the economy. The submodel determines the optimal combination of technologies for energy supply. Each region is modeled by a reference energy system such as the one presented in Figure 1.

In the first step, primary resources (PEC) are either extracted in the region or imported from another region. The resource technologies cover the extraction of oil, gas, coal, uranium and biomass at different resources categories representing different costs of extraction (e.g. coal-1, coal-2, etc.). The primary energy carriers are then processed by the conversion technologies, which produce the final energy carriers, comprising electricity and non-electric fuels such as oil products (including synthetic fuels), natural gas, coal, biomass and hydrogen.

The electricity conversion technologies considered in the model comprise the existing stock of generation capacity, along with capacity additions of natural gas combined cycle (NGCC), gas fuel cells, pulverized coal, integrated gasification

Figure 1: Reference Energy System



combined cycle (IGCC) coal, light water nuclear reactors (Nuclear), fast breeder reactors (FBR), biomass, solar, hydropower and wind.

The conversion technologies for producing non-electric energy carriers comprise oil refining, synthetic oil production from coal (coal to liquids) and biomass (bio-FT), and hydrogen synthesis (from coal, natural gas, biomass, electrolysis, and thermochemical nuclear and solar processes).

2.2 Endogenous Technology Learning

Some of the conversion technologies have the potential to improve via endogenous technology learning (ETL). As mentioned above, ETL captures the possibility for relatively immature and expensive technologies to improve with the accumulation of experience and knowledge to achieve long-term competitiveness. This is represented by means of a two-factor learning curve, developed originally by Manne and Barreto (2004) and further developed in Barreto and Kypreos (2004), Kypreos (2005), and Kypreos and Bahn (2003).

The first factor corresponds to the so called "learning-by doing", describing the investment cost as a function of the cumulative capacity, which is used as a proxy for the cumulative experience with the technology (Kypreos and Bahn, 2003). For this factor, the investment cost for the y-technology declines with the installed capacity until it reaches a floor cost, thus,

$$inv_y = \begin{cases} a_y \cdot CC_y^{-b_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases}$$

where a_y is a constant calibrated with the initial cost and capacity; CC_y is the cumulative capacity; b_y is the learning index, which reflects the effectiveness of the learning process for the y-technology; and l_y is the floor cost of the y-technology.

The second factor of the learning curve accounts for the fact that knowledge is also accumulated through investments in research and development. This factor corresponds to the so-called "learning-by-searching". Thus, the investment cost of the y-technology declines proportionally to both cumulative capacity and cumulative research and development expenditures (CRD),

$$inv_y = \begin{cases} a_y \cdot CC_y^{-b_y} CRD_y^{-c_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases} \tag{1}$$

where c_y is the learning-by-searching index. The cumulative R&D expenditures are endogenously estimated.

In MERGE-ETL technology learning is assumed to occur as a collective evolutionary process, following the paradigm of technology clusters described in Seebregts et al. (2000). This approach, developed by Magne, Kypreos, and Turton (2010), is based on the idea that a number of key components (e.g. gasifier, gas turbines, carbon capture technologies, etc.) are often used across different technologies. Thus, the learning process for the *y*-technology benefits the other technologies that share key components with *y*. Accordingly, the two factor learning process, presented in Equation (1), is applied at the key component level.

2.3 Nuclear Cycle

As mentioned in the introduction, nuclear electricity generation has the potential to play an important role in the future to respond to energy challenges. To properly represent this potential and some of the limits of this technology, MERGE-ETL includes some of the features of the nuclear fuel cycle to give a more accurate representation of the actual generation process and resource availability. This is also important given that the recent accident at Fukushima may result in policy changes that will limit the available options for nuclear generation and close off parts of the nuclear cycle. The nuclear cycle in MERGE-ETL models the flows of the different types of uranium, plutonium and wastes, based on Chakravorty, Magne, and Moreaux (2009).

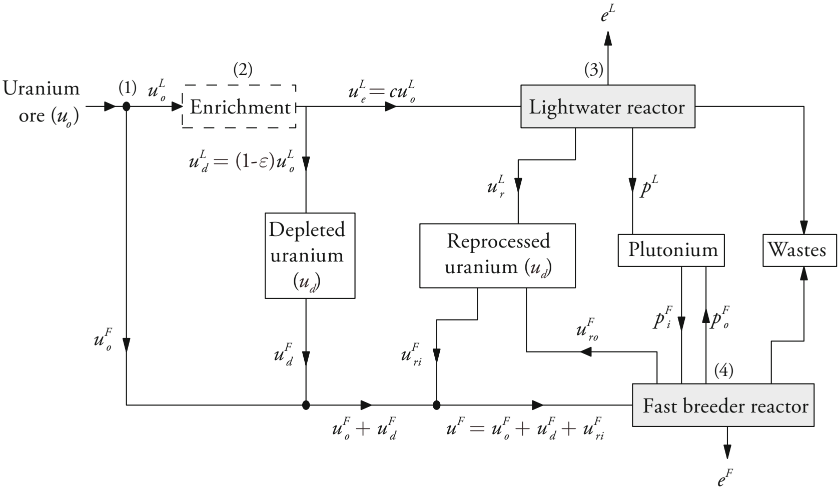
The fuel cycle presented in Figure 2 includes two types of technologies: a light water reactor (LWR) and a fast breeder reactor (FBR). The LWR is modeled based on the European Pressurized reactor. It uses enriched uranium (u_e^L) to produce electricity (e^L), reprocessed uranium (u_r^L), plutonium (p^L) and wastes. The FBR uses a combination of plutonium (p_i^F) and uranium coming from uranium ore (u_o^F), depleted uranium from the enrichment process (u_d^F), and reprocessed uranium coming for both reactors (u_{ri}^F). It produces electricity (e^F), reprocessed uranium (u_{ro}^F), plutonium (u_o^F) and wastes. For further detail see Marcucci and Turton (2011).

3. Key Scenario Modelling Assumptions

3.1 Population and Economic Development

The scenarios analyzed in this paper are based on the IIASA B2 scenario (IIASA, 2009). In this scenario, population follows a medium growth path, with a "strong convergence in fertility levels toward replacement levels, ultimately yielding a stabilization of world population levels" (Riahi, Grübler, and Nakicenovic, 2007). The global population is assumed to be 8.95 Billion by 2050 and 10.4 Billion by 2100. Although global population stabilizes to around 10 Billion people after 2070, this global picture hides some important regional differences. For instance, China and Eastern Europe continue to have low fertility rates or

Figure 2: Nuclear Cycle



further declines in fertility, which lead to a declining population in the second half of the century. Globally, this is offset with high population growth in the ROW region, mainly Africa, driven by high fertility and reduced mortality rates (Lutz, Sanderson, and Scherbov, 2008).

In Switzerland, the population is estimated until 2050 based on the medium growth scenario from the BFS (2010). It uses a medium fertility scenario with around 1.5 births per woman and an average childbearing age of 31.5; a slight increase in life expectancy from 84 to 90 years for women and 80 to 86 for men; and a decrease in net migration from 98000 people per year in 2008 to 22500 in 2030 and constant afterwards. After 2050, Swiss population is estimated using the IIASA B2 scenario, which assumes decreasing fertility rates. Based on the BFS assumption, the net migration is kept constant after 2050. With these assumptions Swiss population rises from 7.2 million in 2000, reaches 8.15 million by 2050 and then declines, returning to 7.2 million by the end of the projection period.

The economic growth, represented by GDP growth, is a key factor affecting energy demand. As an input to the model we apply a potential (or reference) GDP pathway representing productivity improvements and economic output at constant energy prices. However in MERGE, due the energy-economic interactions, this reference GDP does not exclusively determine the realized GDP. A climate policy, for example, will lead to an increase in energy costs which will reduce the economic output (Manne, Mendelsohn, and Richels, 1995). Potential (or reference) GDP is based on the IIASA B2 scenario (IIASA, 2009) and the projections from the Federal Department of Finance for Switzerland until 2050 (EFD, 2008). The IIASA B2 scenario is a medium growth scenario. It assumes that growth in per capita productivity is higher in low-income regions; and that in lagging regions (e.g., Africa) the economic catch-up is delayed (Riahi, Grübler, and Nakicenovic, 2007). With this projection, global potential GDP grows 3.74 times (up to 89.7 trillion USD 2000) between 2000 and 2050 and economies in transition, such as China and ROW are responsible for most of the global economic growth. Switzerland has a yearly growth rate of potential GDP of 0.7% for the period 2020 to 2050, slowing to an average of 0.4% after 2050.

3.2 Technology Costs and Learning

The technology cost assumptions used in this scenario analysis are presented in Table 1 (Magne, Kypreos, and Turton, 2010). As mentioned in Section 2.1, MERGE-ETL represents different resources categories with different extraction costs. The estimates in Table 1 are based on the cheapest resource category so the actual costs, endogenous to the model, will vary. The estimates in Table 1 for the nuclear technologies are based on the unit costs of the nuclear cycle presented in Section 2.3. We assume that all the uranium used in the FBR is natural uranium; that the plutonium produced in the LWR is stored indefinitely; and that the plutonium produced in the FBR is completely used by the reactor. We use a 5% discount rate.

For some of the technologies, these levelized costs change with the technology learning. In Table 1 we present the initial investment costs. The impact of technology learning depends on the deployment of the key components. In most of the technologies the key components represent 45% to 60% of the initial investment cost, except for wind and solar technologies where the key component accounts for 100% of the initial investment cost. Carbon capture, fuel cells and solar components have a learning rate of 10%; while wind, gasifiers and gas turbines have a learning rate of 5%. As mentioned in Section 2.2, all the learning components have a floor cost, which corresponds to 20% to 50% of the initial investment cost.

Table 1: Conversion Technologies Levelized Costs

	Technology	Total levelized cost [cents$/kWh]
Electricity	oil	6.28
	gas	4.93
	NGCC	3.07
	NGCC (ccs)	4.89
	gas-FC	5.66
	coal	3.68
	PC	4.26
	PC (ccs)	6.39
	IGCC	3.43
	IGCC(ccs)	4.63
	LWR	2.17
	FBR	2.69
	bio (ccs)	8.02
	solar	16.12
	hydro	5.26
	wind	4.48

	Technology	Total levelized cost [$/GJ/a]
Non-electric energy	coal-lquids	9.34
	bio-liquids	14.85
	coal-H2	10.42
	coal-H2 (ccs)	10.93
	gas-H2	9.20
	gas-H2 (ccs)	9.61
	nuc-H2	10.87
	bio-H2	12.64
	electrolysis-H2	5.93
	solar-thermal-H2	41.28

4. Case Studies

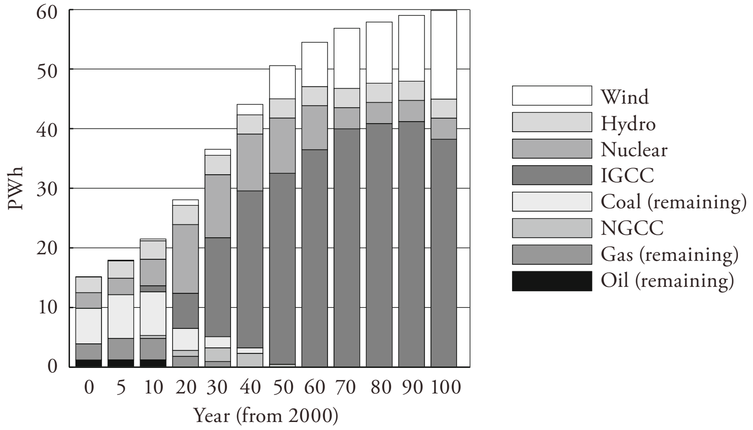
We develop different scenarios including a baseline and a number of additional scenarios accounting for measures aimed at addressing global challenges. The baseline is a business-as-usual scenario (BAU) assuming no climate policies. The other scenarios explore the challenge of climate change mitigation and the feasibility of climate stabilization with different availability of nuclear technologies worldwide and in Switzerland.

4.1 Business as Usual Scenario

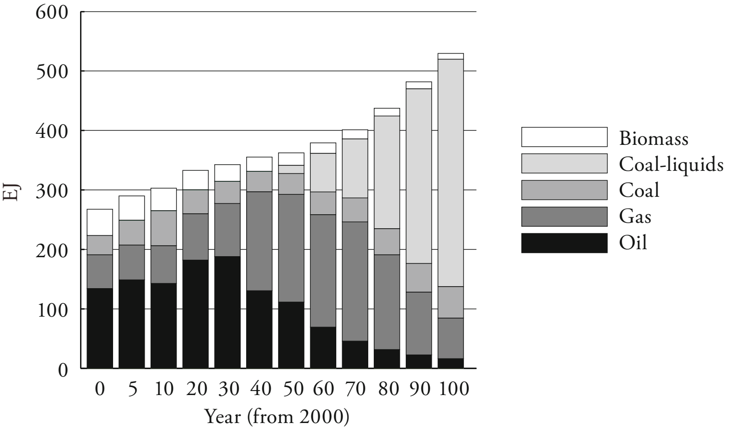
The baseline scenario (see Figure 3) exhibits an increasing demand for both electricity and non-electric energy globally, driven primarily by the emerging economies. In this scenario, coal is the main primary energy carrier used in the production of electricity and non-electric energy carriers. This is because, in the absence of a climate policy, coal is attractive due to its abundance and low price of reserves compared to other fossil fuels.

Figure 3: Business as Usual Scenario: Global Energy Production

(a) Electricity production



(b) Non-electric production



The results for the electricity sector for this scenario (see Figure 3a) show, in the first half of the century, a replacement of the existing stock of generation capacity mainly with coal IGCC and nuclear generation. Later in the century, the share of IGCC reaches 63% of the electricity generation by 2050 and 70% by 2090[1]. This IGCC technology is deployed extensively in almost all regions. The exceptions are Japan and Switzerland, where electricity is based on nuclear, and nuclear and hydro generation, respectively. Nuclear energy slowly declines later in the century as uranium resources begin to be exhausted (noting that the fast breeder reactor option in Section 2.3 is assumed not to be available in this baseline scenario). Another important result is the increasing share of wind in electricity production. This considerable increase is driven by the technology learning that reduces the levelized electricity cost for this technology to competitive levels compared to the fossil fuel technologies.

For the non-electric energy supply (see Figure 3b), as the oil and gas reserves are depleted, synthetic oil production from coal (coal to liquids) starts playing an important role and becomes a major source of fuels by 2100. The global demand of non-electric energy increases over the projection period, although at a much slower rate than electricity demand. This is due to the larger relative change in price of the the non-electric energy compared to the electricity, because of the depletion of cheap oil and gas. The growth in global non-electric energy demand is driven by developing regions, predominantly China, India, the Middle East and the Rest of the World, while most of the other regions have declining demand.

The energy production for the baseline scenario in Switzerland is presented in Figure 4. Electricity production in this scenario is dominated throughout the scenario timeframe by nuclear and hydropower, as it is currently the case. The share of wind increases over time due to the global technology learning (i.e., illustrating a global influence that appears to have the potential to affect technology choices in Switzerland), but the overall potential for wind is assumed to be small. Solar generation remains uncompetitive. Nuclear generation declines later in the century as the availability of uranium decreases, and it is replaced by IGCC (rather than natural gas, which is expensive due to depletion over the century). There is also bilateral electricity trade with the European Union (a negative value in Figure 4 indicates exports to the EU and a positive value indicates imports). In 2020, Switzerland exports 23.3 TWh to the EU; and in 2040, 2050 and 2100 Switzerland imports 2.7, 1.6 and 1.8 TWh, respectively. The relatively large exports of electricity in 2020 are a relocation of electricity supply from the

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[1] In this scenario IGCC is preferred over the Pulverized Coal technology due to the assumed initial levelized cost (see Table 1) and the technology learning.

EU to Switzerland, decided from the perspective of a global planer with perfect foresight, along with the vintaging of technologies[2].

Figure 4b presents the non-electric energy production results for the baseline scenario in Switzerland. It shows a reduction in demand from 670 PJ to around 300 PJ by 2100. This decline is driven partly by the decreasing population (after 2050) and efficiency improvements; but it is accelerated by increasing prices of non-electric energy carriers, particularly oil, which leads to additional efficiency and substitution by electricity. Although electricity production is also declining, the substitution of non-electric energy by electricity is reflected in the increasing relative share of electricity in the energy bundle. Furthermore, the depletion of oil and gas resources, primarily by countries other than Switzerland, leads to a substitution of oil by gas in the first half of the century and after 2050 with coal-to-liquids. This illustrates another mechanism by which options for the Swiss energy system are affected by global factors, including the available oil and gas resources, and the rates of energy demand growth in other regions (which is driven in turn by economic growth and technological developments).

4.2 Climate Stabilization Scenarios

In the business as usual scenario, the global energy-related CO_2 emissions increase to 25.8 Gt CO_2 by 2100, and atmospheric CO_2 concentration reaches 763 ppm. This considerable increase in the energy related emissions is due to large use of coal in electricity and non-electric energy production. This CO_2 concentration will most likely lead to undesirable climate change. In this sense, climate policies are required to mitigate climate change and low-carbon technologies are needed. We analyze a long-term global target for atmospheric CO_2 concentration of 400 ppm[3]. According to the Intergovernmental Panel In Climate Change (IPCC) (2007), this greenhouse gas mitigation target corresponds to

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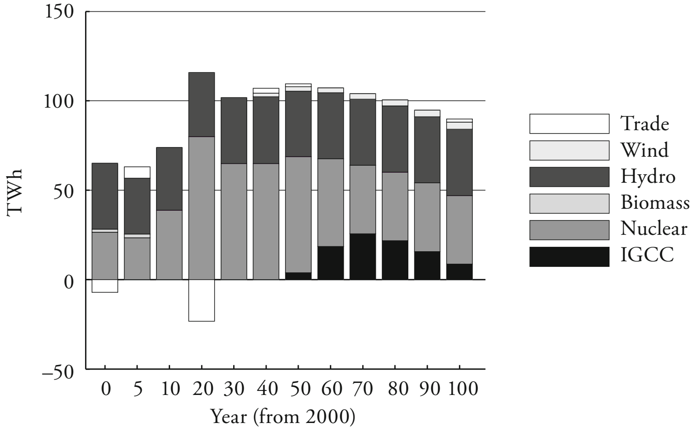
[2] Over the longer term, the preferred source of electricity supply in the EU is IGCC. However, this can only be expanded relatively slowly and in the meantime (2020) an alternative supply is needed. In Switzerland, nuclear energy is the preferred long-term option rather than IGCC. Thus, from a global perspective it is attractive to bring forward the construction of nuclear capacity in Switzerland and export the excess generation to the EU while it builds up its IGCC capacity. The alternative of building new long-lived nuclear capacity in the EU is less attractive because these plants are assumed to be operated for the rest of their 50-year life.

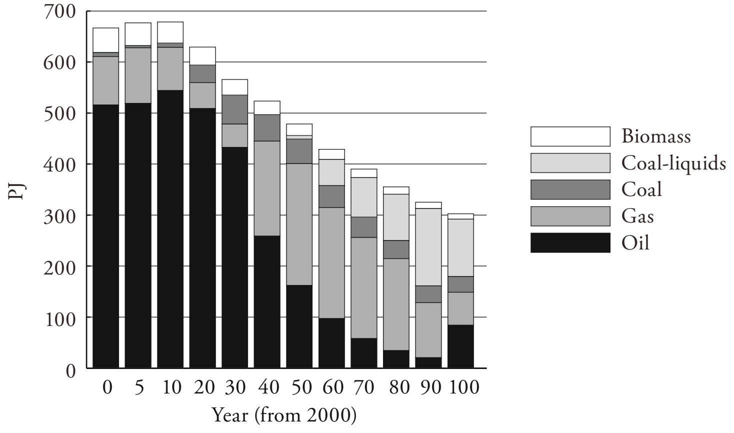
[3] Note that the target is imposed just on carbon dioxide concentration and not on the other greenhouse gases. According to the Intergovernmental Panel In Climate Change (IPCC) (2007),, this CO_2 concentration target corresponds approximately to a 490 ppm CO_2e target.

Figure 4: Swiss Energy Production

(a) Electricity production



(a) Non-electric energy production



a global mean temperature increase between 1.8°C and 3.8°C (2.5°C using the "best estimate" climate sensitivity of 3°C) compared to pre-industrial levels. In 2009 the global concentration of CO_2 was around 387 ppm, and therefore, a concentration of 400pm represents a stringent realistically feasible target that would require immediate global action.

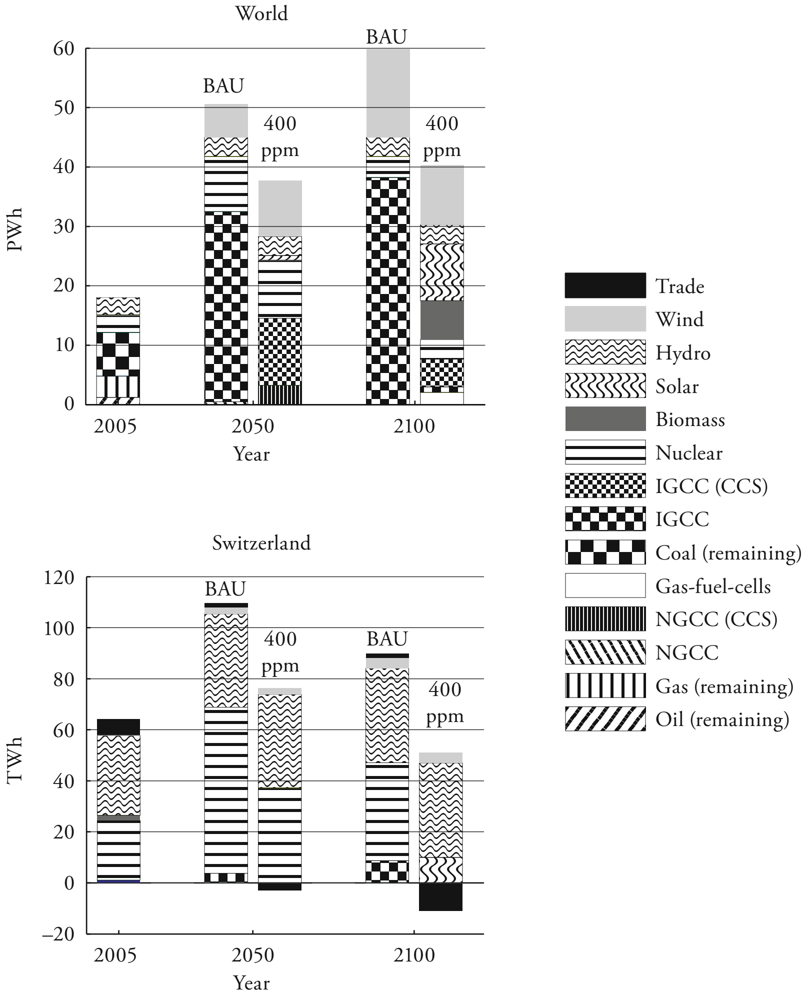
The 400 ppm concentration target is imposed as a cap on the global concentration of CO_2. Thus, MERGE-ETL determines the optimal technology combination from a global social planer perspective that maximizes global welfare, that is, it determines "when", "where" and "how" abatement is undertaken to achieve the global target.

Figure 5 presents the global and Swiss electricity production in 2050 and 2100 in the business as usual and the 400ppm scenarios. The climate stabilization scenario exhibits a slower increase in global electricity demand and a considerable deployment of renewable and nuclear technologies. Compared to the BAU scenario, coal generation (IGCC) is not anymore the preferred technology. Instead, coal and natural gas generation with carbon capture are used in 2050 (IGCC(CCS) and NGCC(CCS), respectively); and solar, biomass and IGCC(CCS) in 2100. Nuclear generation continues to play an important role, representing around 25% of the total electricity generation by 2050 and 8% by 2100. This decrease in the share of nuclear generation is related to the global depletion of natural uranium. One technology option that has the potential to overcome this depletion is the Fast Breeder Reactor, which can use besides natural uranium, depleted and reprocessed uranium as well as plutonium. We discuss the potential role of such a technology, assuming it is publicly acceptable, further below. By 2100 solar electricity generation represents a large share of the total.

The reduction in electricity production in the 400ppm scenario in the Swiss region implies substantial efficiency improvements on the demand side, that is, in end-use technologies in the residential, industrial, services and transport sectors; and some reduction in economic activity (see Section 4.5). We assume that for security reasons hydropower generation in Switzerland is maintained up to the potential of 37 TWh/a by 2100 (based on LAUFER et al., 2004). Due to the higher prices of uranium, coming from depletion and demand in other world regions, such as India, China and the USA, nuclear generation is replaced by solar photovoltaic generation after 2070. In this scenario, Switzerland exports 2.9 and 11 TWh to the EU in 2050 and 2100, respectively.

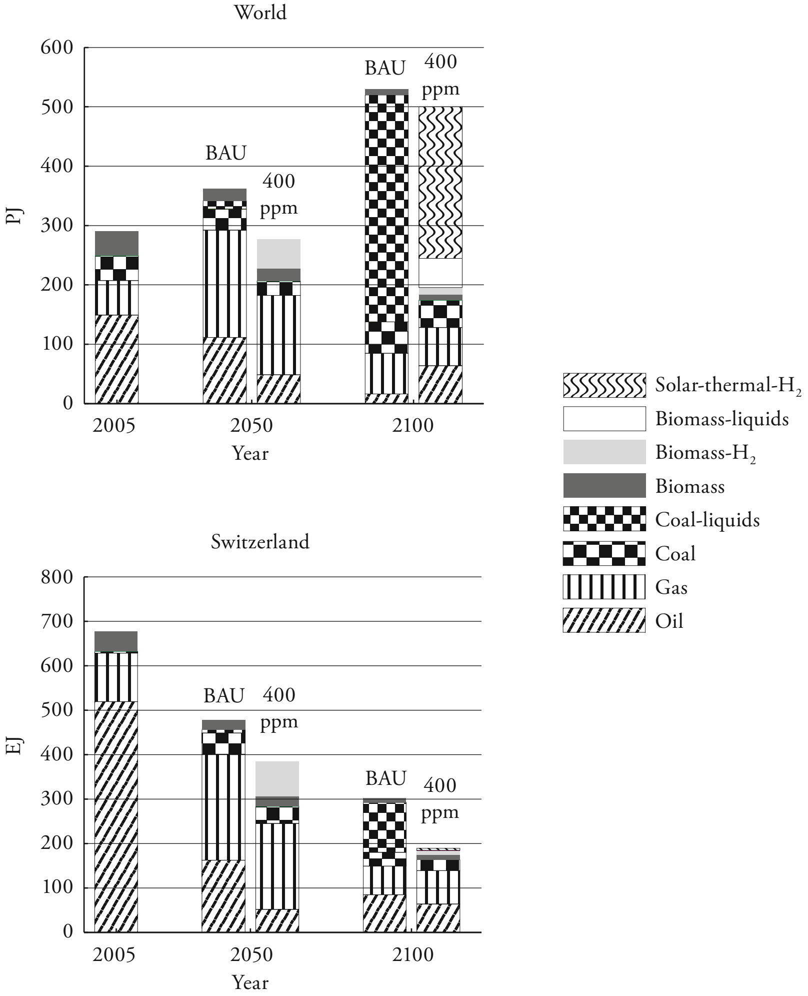
In this scenario, we see important spillovers from global developments to Switzerland. On one hand, the deployment of wind generation in Switzerland is supported by reductions in investment costs due to global technology learning. This global learning-by-doing is driven by the global climate policy and arises due to technology experience gained mainly by other world regions, such as the EU, China and USA. On the other hand, electricity and non-electric energy production are affected by the availability of the resources, in particular depletion of oil, gas and uranium, determined by economic growth and strong climate policies (particularly in the case of uranium) in other world regions.

Figure 5: Electricity Production in the Climate Stabilization Scenario



Regarding the non-electric energy production (see Figure 6), in this scenario we see an important shift from fossil fuels to production with renewables, mainly biomass-to-hydrogen in 2050 and solar thermal hydrogen by 2100. Globally, in 2100 the non-electric energy demand remains relatively unchanged compared to the business-as-usual scenario due to the large global potential of solar thermal hydrogen. Contrary to the global results, in Switzerland we see a decrease in the non-electric energy demand due to the relatively low potential of this technology[4].

Figure 6: Non-Electric Energy Production in the Climate Stabilization Scenario



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[4] The sth-h2 potentials were estimated, based on the potential published by the SATW (2007) for solar thermal heating, to 3.35 and 4.75 PJ for 2050 and 2100, respectively.

4.3 The FBR as an Option for the Climate Stabilization Objective

In the previous Section we showed that in a scenario with a stringent climate mitigation target the use of nuclear generation is reduced by the end of the projection period due to limited global uranium resources. This depletion could be avoided or delayed through the deployment of fast breeder reactors (FBRs), which can generate electricity using depleted and reprocessed uranium; and plutonium. Demonstration and prototype fast breeder reactors, with electrical power output from 250 to 1200 MW, have been developed since the 1960's (IAEA, 2011). Currently, the research on fast reactors is developed by the Generation IV International Forum and the IAEA (International project on Innovative Nuclear and Fuel Cycles – INPRO); as well as different national incentives, including countries such as Russia, China and India. We analyze the case in which the FBR is available from 2040, which is an ambitious but still possible starting date assuming some of the technical limitations of the technology are overcame[5].

In Figure 7 we present global and Swiss electricity generation for the climate stabilization scenarios with and without FBRs. We see that all the regions deploy the FBR at the fastest feasible rate. By providing a source of baseload low-carbon electricity, without significant resource constraints, the FBR avoids the need for large electricity demand reductions to achieve the 400ppm scenario. However, realizing the FBR scenario would require considerable support to nuclear research and development and efforts to address the security issues of the reprocessing of spent fuel.

The non-electric energy production (see Figure 8) remains relatively unchanged in 2050. By 2100 hydrogen continues to play an important role but its production changes from the solar-thermal technique to electrolysis, due to high availability and low price of electricity. For Switzerland, we see an increase in the non-electric energy production in 2100 due to larger potential of electrolysis to produce hydrogen compared to the assumed potential of the solar thermal option.

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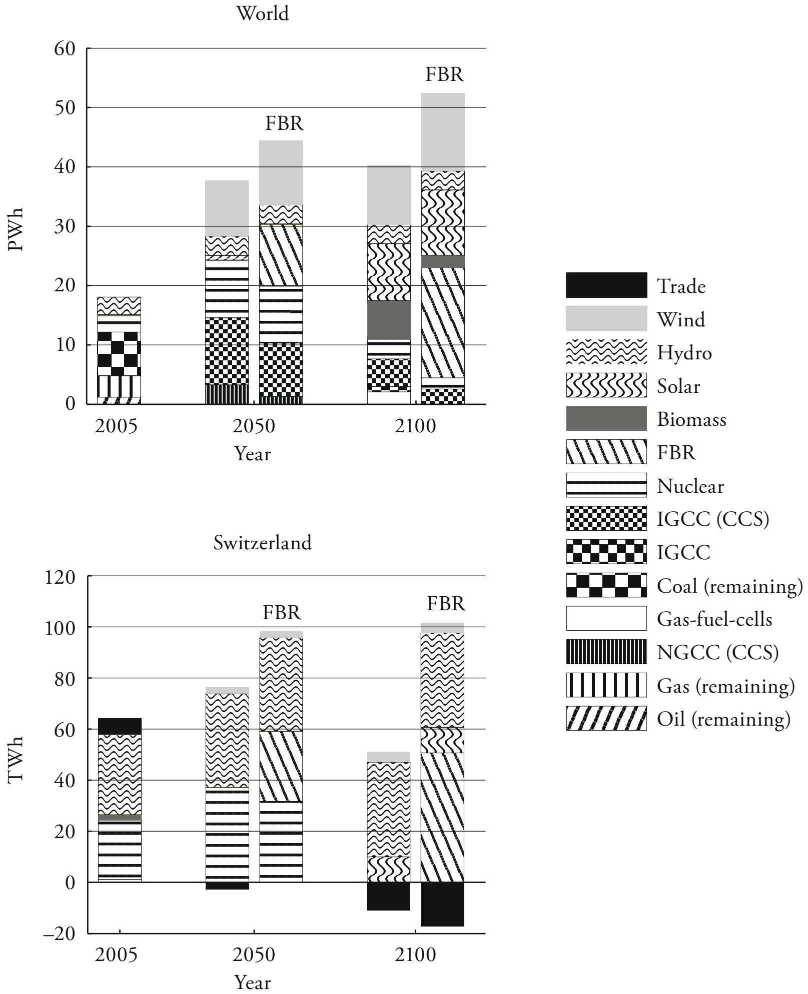
[5] Note that some of the research aims to have a Generation IV demonstration reactor in operation by around 2030 (IAEA, 2011).

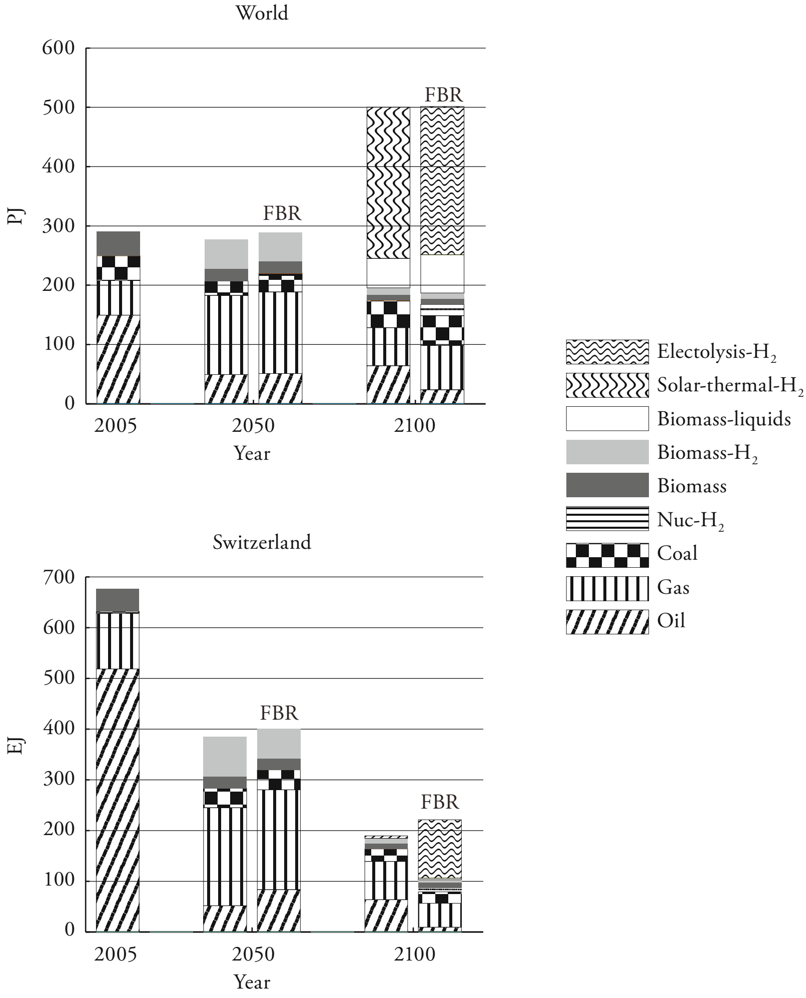
Figure 7: Electricity Production in the Climate Stabilization Scenario with FBR



4.4 Scenarios Without Nuclear Development

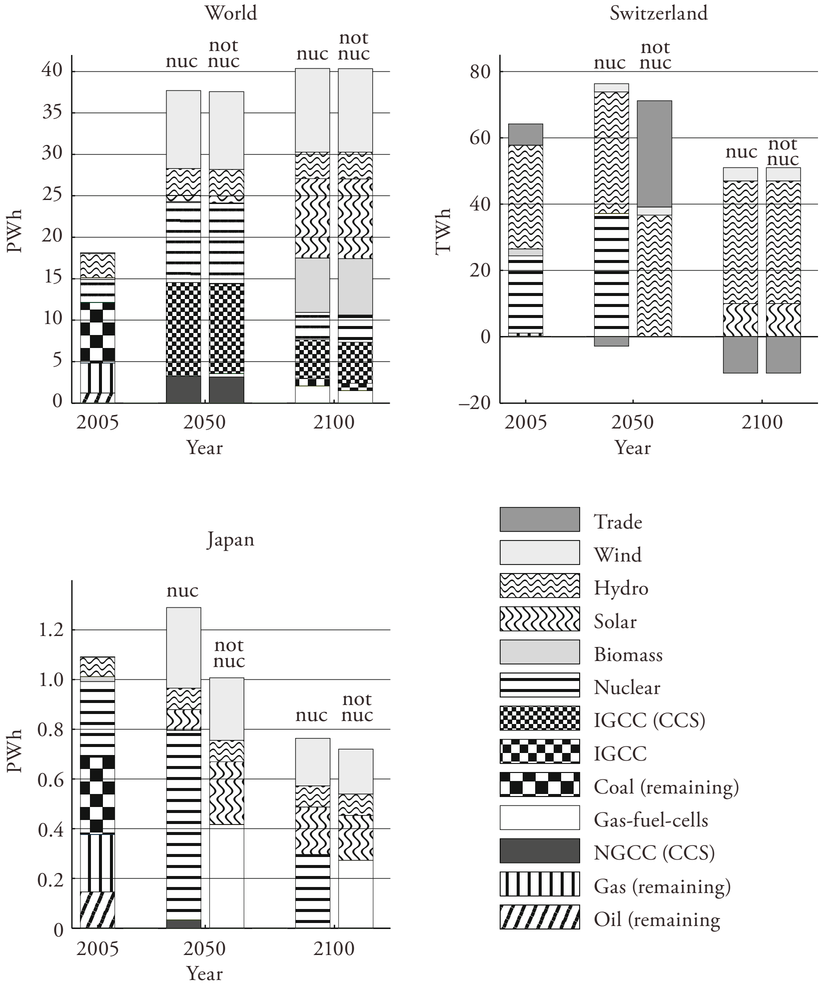
One of the possible outcomes from the accident in Fukushima is a phase-out of nuclear power plants (assumed to have a 50 years lifetime) in some of the regions with large shares of nuclear generation. This scenario analyses the case in which both Switzerland and Japan opt for this policy. Figure 9 presents the electricity

Figure 8: Non-Electric Energy Production in the Climate Stabilization Scenario with FBR



production in 2050 and 2100 for the world, Switzerland and Japan. Globally, there is a small reduction in the demand, arising from demand reductions in Japan. We can see an important difference between the Swiss and the Japanese regions. In this scenario, Swiss electricity demand decreases only slightly in 2050 due to the ability to replace nuclear generation with electricity imports from the

Figure 9: Electricity Production: 400ppm Scenario With and Without Nuclear Development in Switzerland and Japan



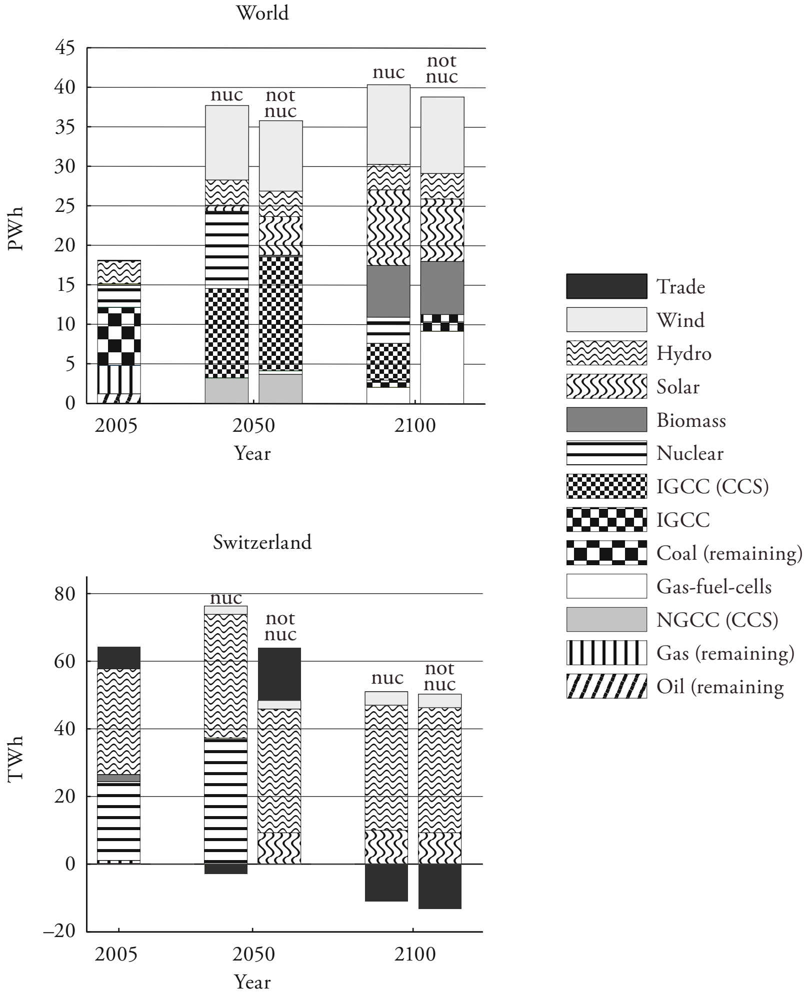
EU (it is also worth noting that global nuclear output is largely unchanged, thus the implication is that the Swiss reactors merely relocate to the EU). This illustrates an important potential trade-off between a domestic phase-out of nuclear energy, maintaining self sufficiency in electricity supply, and achieving ambitious climate targets.

Unlike Switzerland, the electricity demand in Japan is reduced by around 290 TWh in 2050 and 40 TWh by 2100, and imports are assumed not to be available. Carbon capture technologies are not an option for the Japanese electricity sector due to the limited storage capacity. Thus, besides additional efficiency (and reduced demand due to lower economic activity), nuclear generation is replaced by gas fuel cells because they are the lowest-carbon fossil technology without carbon capture.

Another possible consequence of the Japanese accident is a global nuclear phase-out, that is, no replacement of the current nuclear power plants (assumed to have 50 years lifetime). Figure 10 presents the 400ppm scenario with and without nuclear deployment globally. We can see a slight reduction in global electricity demand in the case in which no new nuclear power plants are built. This implies additional efficiency improvements and, to some extent, reduced demand due to lower economic activity. Additionally, in the middle of the projection period the contribution of IGCC with carbon capture increases to partially replace nuclear generation, but due to the limits on the global carbon storage capacity, IGCC (CCS) is replaced by gas fuel cells (as mentioned above, the lowest-carbon fossil technology without CCS) by the end of the projection period. By 2100 renewable technologies, i.e. wind, solar and biomass, represent 70% of the total global generation when no nuclear technologies are available. This implies an increase in the share of renewable technologies compared to the 400ppm scenario with nuclear, where they accounted for around 60% of the total global generation. In the no-nuclear case the intermittent sources, i.e. wind and solar, represent 45% of the total. This large share of intermittent renewables is likely to create major challenges and trade-offs related to electricity supply reliability and security.

For Switzerland, the picture is different to the case presented in Figure 9, where only Switzerland and Japan adopted a no-nuclear policy. In the global no-nuclear case, Switzerland does not import as much electricity from the European Union since this region also adopts a nuclear moratorium. Instead, Switzerland implements additional efficiency measures and deploys solar generation earlier, starting in 2050. Another important difference in the Swiss region (not shown in Figure 10) is the use of NGCC with carbon capture as a transition technology before efficiency measures and technology learning for solar are realized. It accounts in 2030 and 2040 for half of the Swiss electricity production. Unlike Switzerland, the Japanese electricity production is very similar to the case presented in Figure 9.

Figure 10: Electricity Production: 400ppm Scenario With and Without Nuclear Development

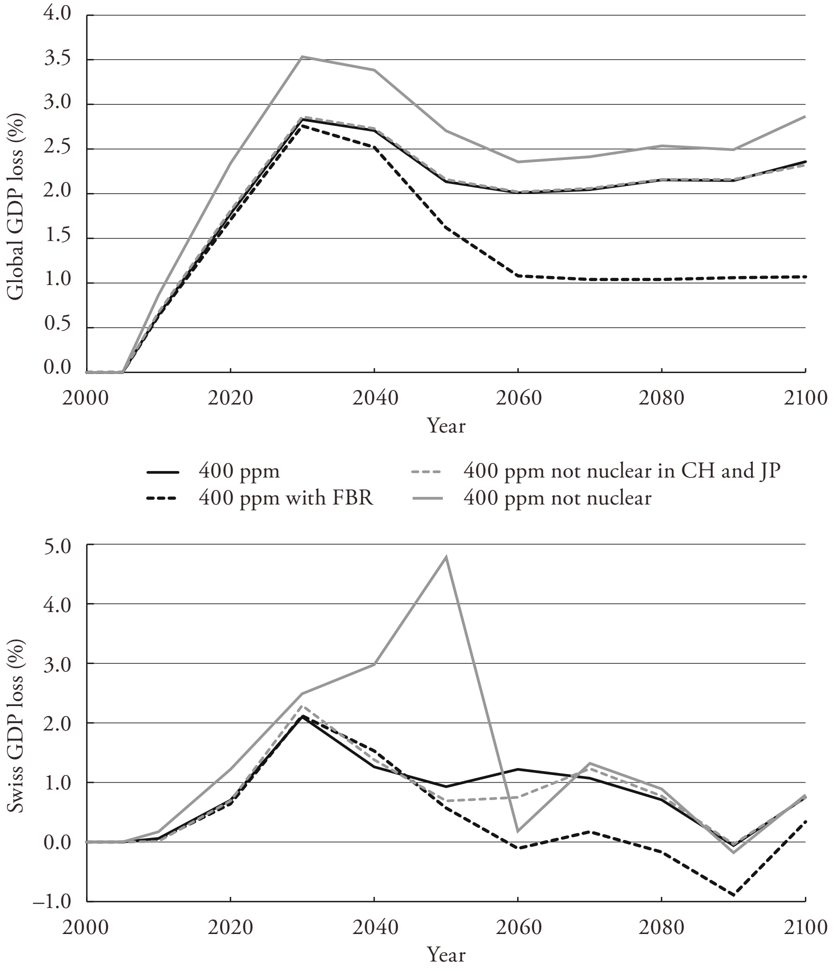


4.5 Economics Implications: GDP Losses

Figure 11 presents the GDP losses for the 400ppm scenario with and without nuclear deployment. The global GDP losses in the 400ppm scenario compared to the baseline scenario reach a maximum of 2.8% by 2030 and decrease to 2.4% by the end of the projection period. Russia and Middle East are the regions with the greatest GDP losses due to reduced revenue from exports of fossil fuels. On the other hand, the regions with the lower GDP losses are Switzerland and Japan; since these are the countries with a shortage of own resources and in which electricity generation is relatively carbon-free in the business-as-usual scenario.

The no-nuclear policy leads to an additional reduction in global GDP compared to the 400ppm case with nuclear, with losses around 0.7 percentage points higher in 2030 and 0.5 percentage points higher in 2100.

Figure 11: GDP Losses in the 400ppm Scenarios



Swiss GDP losses are generally lower than global GDP losses because the electricity sector is already decarbonized in the BAU scenario. Swiss GDP losses in the no-nuclear scenario, like global GDP losses, increase substantially in the period 2040–2050, driven by earlier investment in solar technologies and additional measures to reduce demand. However, as mentioned above, if only Switzerland and Japan forgo nuclear, while the rest of the world continues to use this technology, then the Swiss GDP losses are substantially lower (although reliance on imports is greatly increased). After 2070, Swiss electricity in the 400ppm scenario is produced mainly with hydropower, solar and wind generation, due to high prices of uranium driven by global depletion. For this reason, Swiss GDP losses after 2070 are similar in the 400ppm and the two no-nuclear scenarios.

The GDP losses when the FBR is deployed are lower in every period compared to the 400ppm scenario. By the end of the projection period the global GDP losses correspond to 1% (1.2 percentage points less than in the 400ppm scenario). The FBR replaces the most expensive technologies (e.g. biomass, solar and gas-fuel-cells and solar-thermal to hydrogen for non-electric energy) leading to lower energy costs and, therefore, lower GDP losses. As in the global case, Swiss GDP losses are lower compared to the losses in the 400ppm scenario (and even compared to the BAU scenario in 2090). It is important to notice that these GDP losses are measured relative to the BAU scenario, where the FBR was not available. Larger GDP losses could be expected when comparing the climate scenario to a BAU scenario with FBR.

5. Discussion and Policy Implications

A worldwide climate policy that aims to achieve a global CO_2 concentration level of 400ppm requires major changes to the energy system, including reductions in global energy and electricity demand and substantial efficiency measures in all the regions. In addition, major deployment of low-carbon energy sources is required. The cost of the efficiency measures and investments in low-carbon technologies is likely to result in a reduction in global GDP (although some of the economic costs of climate change will be avoided, which is not modeled in this analysis). A similar pattern is seen in Switzerland, although the large contribution from hydro and nuclear technologies helps to limit the extent of GDP losses in Switzerland under stringent climate policy, since the electricity sector is already decarbonized in the BAU scenario.

Among the low-carbon energy sources, nuclear energy has the potential to play a major role in the future energy system, but whether this potential can be realized has become highly uncertain given recent events. Further, if nuclear light-water reactors are acceptable to global policymakers, conventional natural uranium resources are likely to be depleted during the course of the 21st century, thus limiting the long-term potential of nuclear technologies to contribute to climate change mitigation. However, more advanced nuclear technologies, such as fast breeder reactors, may have the potential to overcome this resource depletion assuming the closed fuel cycle (as the one presented in Section 2.3), already proved to be feasible in demonstration reactors, works for large scale commercial reactors. Furthermore, the deployment of fast breeders reactors would require high support to nuclear energy research, while the reprocessing of spent fuel may potentially require additional safety measures and efforts to ameliorate proliferation risks.

After the accident in Fukushima, there has been a lot of discussion on the future of nuclear generation. This analysis has explored some of the implications for the global energy system of possible policy consequences arising from the recent accident, including moratoria on the construction of new nuclear power plants, both light water and fast breeder reactors. The consequences of such a policy include the need for additional electricity efficiency measures and the integration of a large share of intermittent renewables, which is likely to create major challenges for electricity system reliability, requiring improved grid integration and management, and demand-side management options. The technical feasibility of such a large-scale integration of intermittent sources requires further analysis (building on some existing studies as PRICEWATERHOUSECOOPERS, 2010). Moreover a moratorium of the deployment of nuclear technologies would increase the cost of achieving global climate change mitigation targets. This negative effect may be more severe in Switzerland, where the electricity sector has a high reliance on nuclear generation, for the BAU and the climate stabilization scenarios.

Analysis of nuclear phase-outs in only Switzerland and Japan reveal somewhat divergent results. While both countries have very limited natural resources (including carbon storage potentials), Switzerland has more ready access to imported electricity. Assuming that a large reliance on imports is acceptable to Swiss policymakers, nuclear energy could be largely replaced by imports, producing only minimal economic effects (in effect, the Swiss reactors shift to the EU). However, should the rest of the world implement the same policy, access to cheap low-carbon electricity imports becomes limited, requiring more drastic action in Switzerland. For Japan, access to electricity imports is limited in all cases, so a domestic phase-out of nuclear requires significant changes to the energy system, while a global phase-out of nuclear has relatively little increment effect.

Weidmann, Ramachandran, and Turton (2012) analyzed the implications of a nuclear phase out in Switzerland using two bottom-up models, the Swiss MARKAL energy system model (SMM) and Swiss TIMES electricity sector model (STM). These represent different modeling approaches to MERGE-ETL and, therefore, the results are not expected to be identical but rather complementary. SMM and STM are Swiss national models with a highly detailed energy sector and do not include the linkages between economic activity and energy demand, i.e. energy costs and energy service demands are exogenous inputs. Thus, Weidmann, Ramachandran, and Turton (2012) analyze from a domestic perspective the consequences of the nuclear phase out policy on the Swiss end use sectors and electricity generation schedules. In contrast, MERGE-ETL is a global integrated assessment model that allows us to analyze the effect of the nuclear phase out policy in Switzerland from a global perspective, including the effects of resources depletion, trading, technology learning and endogenous energy prices and demands.

It should be noted that Weidmann, Ramachandran, and Turton (2012) apply some different scenario driving forces (GDP, population), but the broad results can still be compared for similar scenarios. We focus in particular on the climate policy scenarios with a nuclear phase-out.

In the nuclear phase out analyses, both studies show that achieving stringent climate targets without nuclear generation results in higher energy costs and requires further energy demand reductions, which imply additional energy efficiency measures. In both studies hydropower is deployed to its maximum potential of 37–38 TWh. Weidmann, Ramachandran, and Turton (2012) found that dam hydro facilities contribute to supply security through their storage capability, which allows imports of cheap electricity during the night and their dispatch during the day. By 2050 solar and wind generation play an important role in both studies. In SMM and STM the remaining electricity is produced with biomass and gas while in our study it is imported from the EU. This difference is driven by two factors. First, in MERGE-ETL global depletion of gas resources leads to high gas prices such that gas generation is uncompetitive for Switzerland. This also means that gas is less attractive in the non-electric sector, and thus biomass resources are used here rather than for electricity production. Second, Weidmann, Ramachandran, and Turton (2012) did not consider cases with a large reliance on electricity imports, and placed a higher emphasis on self sufficiency.

It is important to note some of the limitations of the scenario modeling analysis presented in this paper. For instance, energy efficiency measures were identified as an important element in the global climate mitigation scenarios. However, MERGE does not model efficiency technologies explicitly, but instead accounts for an elasticity of substitution between energy and capital. Thus, complementary analyses regarding these efficiency technologies is needed to further understand the feasibility of the combination of supply and demand-side changes presented in these scenarios. In addition, for this work we have considered only conventional resources for all the energy carriers, given the high levels of uncertainty regarding the availability of unconventional sources. However, analysis of additional scenarios with unconventional resources, such as for oil, gas and uranium would likely provide additional insights about the range of conditions under which different technologies may be more attractive. Similarly, a range of possible economic development scenarios, and scenarios of technology performance, learning and cost may be worth exploring. For example, the nuclear accident in Japan itself may impact the investment cost for nuclear technologies or lead to more rigorous regulations for nuclear waste disposal, among many others. Despite this uncertainty, the analysis here provides an initial basis for understanding some of the trade-offs and implications of different technology options using an integrated approach.

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SUMMARY

Domestic strategies for the Swiss energy system are likely to be affected by a range of uncertain global challenges, such as natural resource availability and depletion, international climate change policies, and global technology policies. We analyze technological choices for Switzerland under a stringent global climate policy with modest global energy resources; and the possible consequences of different global or regional policies in response to the recent nuclear accident in Fukushima, Japan. We use MERGE, an integrated assessment model, with a division of the world in 10 regions, including Switzerland and Japan. We find that nuclear energy, including light water reactors or more advanced technologies have the potential to play a major role in the future energy system. The consequences of a moratorium on the construction of new nuclear power plants include the need for additional electricity efficiency measures and the integration of a large share of intermittent renewables, raising additional challenges.