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Costs of meeting international climate targets without nuclear power

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Abstract

This paper assesses the impact of a global phase-out of nuclear energy on the costs of meeting international climate policy targets for 2020. The analyses are based on simulations with a global energy systems model. The phase-out of nuclear power increases greenhouse gas emissions by 2% globally, and 7% for Annex I countries. The price of certificates increases by 24% and total compliance costs of Annex I countries rise by 28%. Compliance costs increase the most for Japan (+58%) and the USA (+28%). China, India and Russia benefit from a global nuclear phase-out because revenues from higher trading volumes of certificates outweigh the costs of losing nuclear power as a mitigation option. Even for countries that face a relatively large increase in compliance costs, such as Japan, the nuclear phase-out implies a relatively small overall economic burden. When trading of certificates is available only to countries that committed to a second Kyoto period, the nuclear phase-out results in a larger increase in the compliance costs for the group of Annex I countries (but not for the EU and Australia). Results from sensitivity analyses suggest that our findings are fairly robust to alternative burden-sharing schemes and emission target levels

Keywords: nuclear power; phase out; climate policy; Post-Kyoto; Copenhagen pledges

Table of Contents

1 Introduction

For many countries, nuclear power has long been considered a key ingredient to meeting electricity demand and achieving greenhouse gas (GHG) emission targets. According to Joskow and Parsons (2012) the main nuclear electricity producing countries, i.e. the USA, Japan and France, had already extended or were planning to extend the licenses and operating lives of most existing power plants prior to the Fukushima accident. New power plants were under construction in Finland and France, and planned in Japan, the UK, the USA, Russia, India, South Korea, Taiwan, Egypt, Israel, Saudi Arabia, or Turkey. China, in particular, had announced to increase its share of nuclear power generation by 2020 from 1% to 6%.

Scenarios developed by the International Energy Agency (IEA 2010a,b), the US Energy Information Administration (EIA 2009), and the Energy Modelling Forum (Clarke et al. 2009), had included a remarkable increase in the share of nuclear energy over the next decades. Accordingly, 20 to 30 new nuclear power plants were envisaged every year for the next four decades, in particular in Asia and in Eastern Europe. For example, in the BLUE Map scenario (IEA 2010a), which was designed to meet global climate targets, the share of nuclear in electricity generation rises from around 14% (< 400 GW) in 2007 to 24% (i.e. 1 250 GW) in 2020 - despite problems related to skills shortage, the storage of nuclear waste, concerns about nuclear accidents, security issues (e.g. terrorist attacks) and the proliferation of nuclear weapons.

Since the Fukushima Daiichi accident in March 2011, support for nuclear, has declined in many countries. A global shift in opinion could be observed — at least initially (WIN-Gallup 2011). As an immediate reaction, several countries, including India, Pakistan, Russia, Spain, the USA and the EU, announced stress tests for existing nuclear power plants. Italy renounced a planned return to nuclear power via referendum, and China declared a memorandum for permits for new power plants. Arguably, the strongest initial reactions could be observed in Germany, Belgium and Switzerland, where governments decided to phase-out nuclear by 2022, 2025 and 2034, respectively (see also Skea et al. 2013). In Japan, which is the leading builder of nuclear power plants, all 50 existing reactors had been closed by May 2012 for maintenance and safety checks and in September 2012, the (former) Japanese government announced plans to phase-out nuclear energy by 2040.

Countries like Indonesia, Malaysia and the Philippines, which had planned to build nuclear reactors for the first time, are delaying or revising deployment. But other countries like Belarus, France, Indonesia, and Turkey have not altered plans to build new power stations (e.g. IEA 2012b, pp. 69; Schneider et al. 2011). Recent developments also suggest that the impact of the Fukushima accident on the future of nuclear energy may be less severe than initially thought (e.g. China). Similarly, although nuclear energy contributes substantially less to global power generation than before Fukushima in the latest studies by the IEA (2012a,b), it continues to be a major power generation technology.

In addition to the lack of social and political acceptance in some regions, nuclear energy faces severe economic challenges resulting from high capital costs (to meet, among others, more stringent safety standards) and competition from other fuels, such as unconventional gas in the USA (e.g. Davis 2011). Hence, the future role of nuclear energy in power generation and, consequently, as an option to achieve climate policy targets, is highly uncertain.

To limit the increase in global surface temperature to 2°C compared to pre-industrial levels carbon dioxide emissions must be reduced by 50-85% in 2050 compared to 2000 and global emissions must peak before 2020 (Gupta et al. 2007). For 2020, Gupta et al. (2007) suggest intermediate emission reduction targets of 25-40% compared to 1990 levels for Annex I countries. For non-Annex I countries Den Elzen and Höhne (2008) advocate reductions of 15-30% below baseline emissions in 2020. According to a concrete proposal by the European Commission (2009a), Annex I countries should collectively reduce emissions by 30% in 2020 compared to 1990 levels, and economically more-advanced non-Annex I countries need to decrease emissions by 15-30% below business as usual.

While the climate summits in Copenhagen and Cancun in 2009 and 2010 did not lead to an international agreement involving binding GHG emissions targets for the Post-Kyoto era, most Annex I countries pledged quantifiable emission targets under the Copenhagen Accord and the Cancun Agreement (UNFCCC, 2009, UNFCCC, 2010). In addition, several non-Annex I countries submitted nationally appropriate mitigation actions (NAMAs). The implied emission targets, however, are unlikely to be consistent with a path towards reaching the 2°C target (e.g. Den Elzen et al. 2010a, 2010b; Rogelj et al., 2010; Höhne et al. 2012).

At the UNFCCC climate conference in Doha in 2012, some Annex I countries committed to a second commitment period under the Kyoto Protocol (second Kyoto Period), transforming their pledges for 2020 into binding reduction targets under an international agreement. Since large Annex I emitters like Japan and Russia refused to sign, the amendment to the Kyoto Protocol regulates only about 15% of global GHG emissions. At this time though, no country-specific targets are being debated at the international level for beyond 2020.

In this paper, we assess the impact of a potential global nuclear phase-out on the costs of meeting international climate policy targets for 2020. Methodologically, our analyses rely on simulations with a global partial equilibrium model, which allows for a wide range of electricity generation technologies and for a differentiated assessment of impacts for numerous countries. The simulations take into account that a phase-out of nuclear may alter countries' baseline emissions and restrict their options to mitigate GHG emissions. Our policy scenario involves a uniform 30% reduction target for Annex I countries. For non-Annex I countries the targets are derived from NAMAs they submitted under the Copenhagen Accord/Cancun Agreements. We also allow for the trading of emission certificates across countries to assess the impact of the phase-out of nuclear power on certificate prices, countries' revenues from certificate trading, and on domestic mitigation efforts.

The remainder of this paper is organized as follows: Section 2 briefly reviews the literature. Section 3 describes the baselines for the reference and the nuclear phase-out scenarios. Section 4 introduces our climate policy scenario. Section 5 presents the results of the modelling analyses for the climate policy scenario. Section 6 briefly summarizes the main findings from additional policy scenarios involving alternative trading rules, burden sharing rules among Annex I countries and a more ambitious reduction target for the group of Annex I countries. Section 7 reviews the main findings and concludes.

2 Literature review

Den Elzen et al. (2011), McKibbin et al. (2011), Peterson et al. (2011), Saveyn et al. (2011), Dellink et al. (2011) and Ciscar et al. (2013) analyzed the economic implications of the Copenhagen/Cancun pledges prior to the Fukushima accident. Their findings suggest that the economic costs in terms of lower GDP, consumption or welfare compared to baseline levels, are rather low at the global level and for most individual countries. Economic costs are typically below 1%, particularly if the trading of emission certificates is allowed. McKibbin et al. (2011) find significantly higher costs, mainly because emissions are assumed to grow rather strongly in the baseline. Methodologically, these studies typically rely on “top-down” dynamic computable general equilibrium models, which account for macroeconomic effects resulting from changes in prices, income, or exports and imports. Thus, top down modelling typically does not allow for a specific treatment of generation processes such as nuclear energy technology. Only Den Elzen et al. (2010a, 2010b) use a “bottom-up” partial equilibrium model. While “bottom-up” models typically include a rather detailed representation of technologies, they can hardly capture macroeconomic effects.

Only a few studies focus on the role of nuclear power in global emission mitigation scenarios such as Kurosawa (2000), Vaillancourt et al. (2008), Rafaj and Kypreos (2008), Remme and Blesl (2008) and Bauer et al. (2012). Assuming rather modest targets in Annex I countries for 2030 of 92% and 108% of 1990 emission levels, Kurosawa (2000) finds that the cost of a global phase-out of nuclear energy amounts to 0.36% lower consumption. Vaillancourt et al. (2008) find nuclear power to be the dominant power technology, having a share in the power mix of more than 50% in 2100 under various emission reduction scenarios. Rafaj and Kypros (2008) conclude that as a result of a nuclear phase-out, global CO_2e emissions in 2050 are 15% higher (a reduction below 2000 levels of 42% instead of 49%). According to Remme and Blesl (2008), annual costs of reaching the 2°C targets may be lowered by 9%, if nuclear energy was allowed to increase by two thirds compared to the base case and account for a share of 35% of global electricity generation compared to 21% in the base case. Comparing harmonized long-term low-carbon stabilization scenarios with five models[1], Edenhofer et al. (2010) conclude that when investment in nuclear power stops after 2000 the additional aggregated global mitigation costs (measured as a percentage of GDP in 2100) increase by up to 0.7 percentage points. Only the study by Bauer et al. (2012) is motivated by the Fukushima accident. Linking a long-term, top-down growth model with a bottom-up model, Bauer et al. (2012) analyse the global impact of decommissioning existing nuclear power plants and restricting future investments in new nuclear power capacity under long-term emissions caps, which are consistent with the 2°C target. The near-term effect of a nuclear phase-out on GDP is rather small (loss of less than 0.1% in

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[1] This comparison also includes a long-term scenario carried out with the POLES model (Kitous et al., 2010).

2020), and somewhat larger in the long-term (loss of 0.2% in 2050). For 2020, ambitious climate policy leads to a loss in global GDP of around 1.2%.

In sum, most existing studies rely on bottom-up type models to explore the role of nuclear in meeting climate policy targets. Most (but not all) studies find the additional costs of a nuclear phase-out to be low, and to amount to less than 1% of global GDP[2]. Further, existing studies exhibit only a weak link to actual climate policy and do not allow for certificate trading. Finally, since most modelling analyses tend to be rather aggregate at the country and regional level, they often do not allow for a country-specific representation of technologies or policy impacts.

3 Methodology and baselines

For the baseline and policy simulations we employ POLES, which is a world simulation model for the energy sector. POLES is a techno-economic model with endogenous projection of energy prices, a complete accounting of demand and supply of energy carriers and associated technologies.

Since POLES is a partial equilibrium model, GDP for each region is exogenously given (together with population) – unlike in CGE models, for example.[3] Hence, POLES does not model all economic linkages within an economy, such as income effects, or price effects and does not allow energy or climate policy to affect GDP, employment, consumption or other measures of economic welfare.[4]

In this study, POLES has been employed to generate a *reference baseline* and a *nuclear phase-out baseline*. While our policy analyses focus on 2020, the assumed phase out of nuclear energy in the *phase-out baseline* is embedded in a longer-run phase out path until 2050.[5] Our baselines abstract from the fact that

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[2] These studies do not take into account that climate policy also reduces climate change damages and thus curb potential GDP losses.

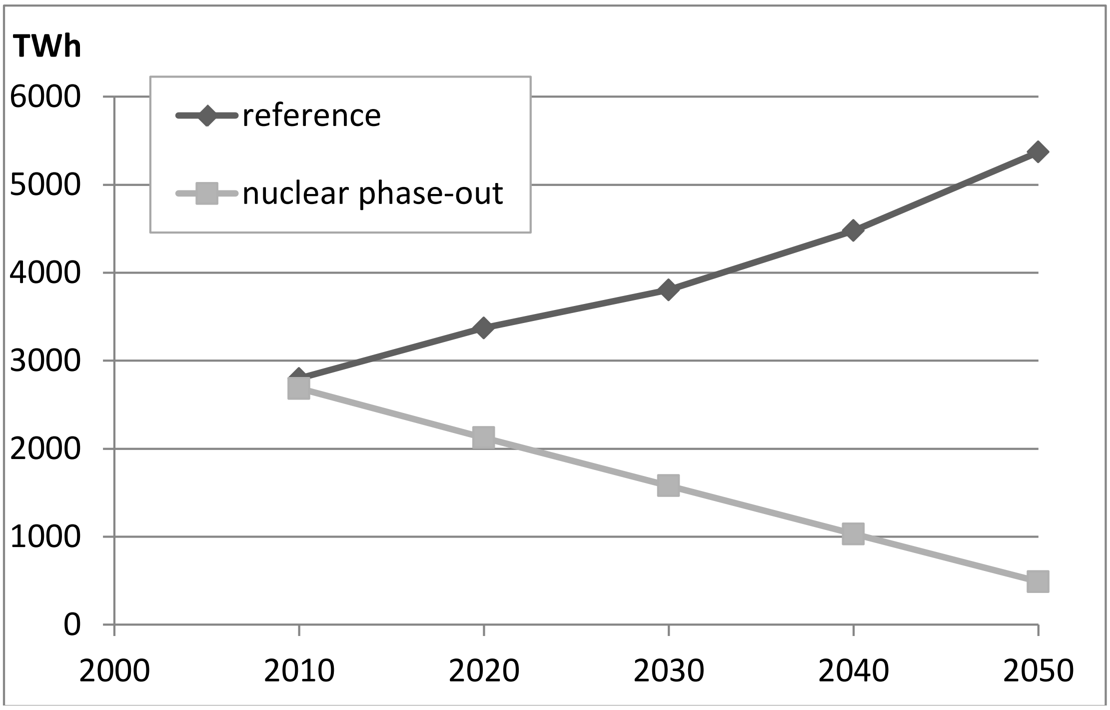
[3] A more detailed description of POLES is presented in Appendix A. For further details about the POLES model see also Kitous et al. (2010).

[4] Similarly, POLES cannot reflect that adequately designed policies may lead to a more resource-efficient economy without compromising economic growth (OECD 2011, Hallegatte et al. 2012). This view about the effectiveness of “Green Growth”, however, is controversially discussed (e.g. Toman 2011).

[5] Our analyses abstract though from lower external costs (e.g. waste deposit, health risks, proliferation) associated with a nuclear phase out.

climate change may affect economic development or energy demand (e.g. heating and cooling needs) and energy supply (e.g. availability of hydropower, biomass).

Figure 1: Development of nuclear power generation in reference and nuclear phase-out baselines

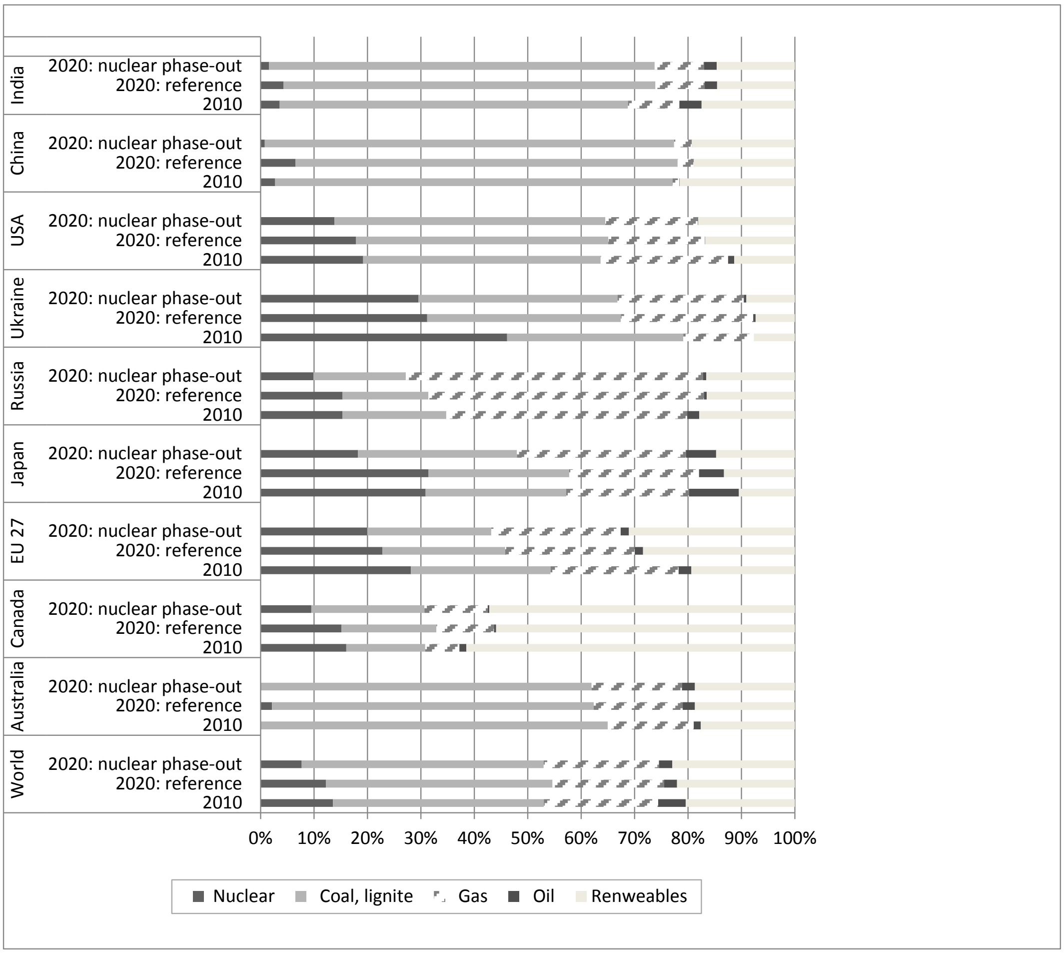


Both baselines rely on the same macroeconomic assumptions: world population is expected to reach 7.6 billion (i.e. 7600 million) in 2020 (UN, 2009) and global GDP growth is expected to evolve at an average rate of 4% between 2010 and 2020.

The *reference baseline* has been calibrated on the energy balances of the 'Current Policies' scenario in the *World Energy Outlook* 2010 (IEA 2010b). This reference case represents a world in which no additional climate policies are implemented. Global power generation is assumed to grow by 3% and nuclear energy by 1.9% per year between 2010 and 2020 to meet a rising energy demand, in particular in developing countries (see Figure 1). Between 2010 and 2020 global electricity generation in the *reference baseline* is assumed to increase by 34% (from 20 700 TWh to 27 700 TWh). Fossil fuels remain the dominant source of power generation in 2010 and 2020 (share of 65%), with a key role played by coal (about 40%). Between 2010 and 2020, global coal-based power generation increases by more than 40%. This above-average growth is mostly driven by the demand in emerging economies. The second-most important fuel in 2010 is natural gas (21%), which grows by 32% until 2020, and keeps its share in the global power mix about constant. The share of renewables in global electricity generation rises from 20% in 2010 to 22% in 2020, which corresponds to an increase in generation by 45% over this ten year span. Finally, the share of nuclear power decreases from 13.5% in 2010 to 12% in 2020, while absolute generation increases by 20%, and installed nuclear capacity by 23%. This growth in nuclear energy is mainly driven by emerging economies and, in particular, in China, with a strong increase from 14 GW to 58 GW installed capacity. India almost doubles its installed capacity between 2010 and 2020 (from 6 GW to 11 GW).

Moreover, nuclear power generation is concentrated in only a few countries: the USA, China, France and Japan account for more than 60% of global nuclear power production. South Korea, Russia and Canada produce another combined 15%. The share of nuclear power in the national power mix differs substantially and ranges from 72% in France to 36% in South Korea, 31% in Japan, 18% in the USA, 15% in Russia and Canada, and 7% in China. In contrast to most other countries, nuclear power production in Germany will decrease between 2010 and 2020 even in the *reference baseline*, since Germany had decided to phase-out nuclear prior to the Fukushima accident (but at a somewhat slower rate, see e.g. Lechtenböhmer and Samadi (2012) for details). This also translates into a small decrease in nuclear power generation for the EU in the *reference baseline*. In India, nuclear power accounts for a rather small share in the power mix, i.e.3.5% in 2010 and 4.2% in 2020. As a consequence, our country-specific analyses often disregard India.

Figure 2: Power generation by fuel and country in 2010 and 2020 in both base-line scenarios



In the *nuclear phase-out baseline* no new nuclear capacities will be built, and existing nuclear capacities are progressively decommissioned over the next four decades. The speed of the phase-out is determined on a country-by-country level, based on the average age of the nuclear power plants. Although by 2050 not all nuclear power plants are phased-out, the production of electricity from nuclear power plants is reduced to about 1% (i.e. 500 TWh) of global power generation, compared to 11% in the *reference baseline*. In the medium term, nuclear power accounts for about 11% (3°350 TWh) of global power generation in the *WEO baseline* by 2020, but only 8% (2 100 TWh) in the *nuclear phase-out baseline*.

The decrease in nuclear power generation in 2020 by 1 250 TWh in the *nuclear phase-out baseline* corresponds to about 5% of global power generation and is mostly compensated by a stronger deployment of fossil fuels (see Figure 2).

The shares of coal and natural gas in global power generation increase from 42% to 45% for coal and from 21% to 22% for natural gas. In comparison, the share of renewables increases from 22% to 23%. The higher generation costs of the power mix lead to higher electricity prices and a decrease in global power production by 60 TWh (0.2%).

In the *nuclear phase-out baseline*, global GHG emissions in 2020 are about 2.2%, i.e. 800 million metric tons (Mt) CO_2e, higher compared to *reference baseline*. For most countries, the nuclear phase-out leaves baseline GHG emissions almost unchanged, because nuclear energy is not an important part of their national power mix. As expected, countries with a high dependency on nuclear power generation in the *reference baseline* tend to experience a significant increase in GHG emissions, in particular Japan, Canada and Russia (see Figure 3). In Japan, where two-thirds of power generated from nuclear plants is replaced by natural gas (and not by coal), the phase-out increases GHG emissions by 7% (80 Mt CO_2e) in 2020. Due to a lower share of nuclear energy in their national power mix, GHG emissions rise less in China (3%) and the USA (+2%), although nuclear power production is mainly replaced by coal. In absolute terms, however, the increase in emissions is largest in China (+300 Mt CO_2e) and the USA (+100 Mt CO_2e).

Interestingly, GHG emissions for a small number of countries are lower in the *nuclear phase-out baseline* than in the *reference baseline* in 2020. For example, in Finland, France or Sweden, where nuclear energy plays a key role and where strong renewable support policies are deployed, the power mix in the *reference baseline* largely relies on a mix of nuclear and renewable energy. A nuclear phase-out then leads to an offset of nuclear power by renewable energy in those countries[6]. Moreover, energy prices increase (compared to the *reference baseline*) and lead to lower energy demand and also to lower CO_2e emissions compared to the *reference baseline*.[7] Because the phase-out of nuclear power results in higher CO_2e emissions of comparable magnitude in other EU Member States, total emissions in the EU in the *nuclear phase-out* baseline are about the same as in the *reference* baseline.

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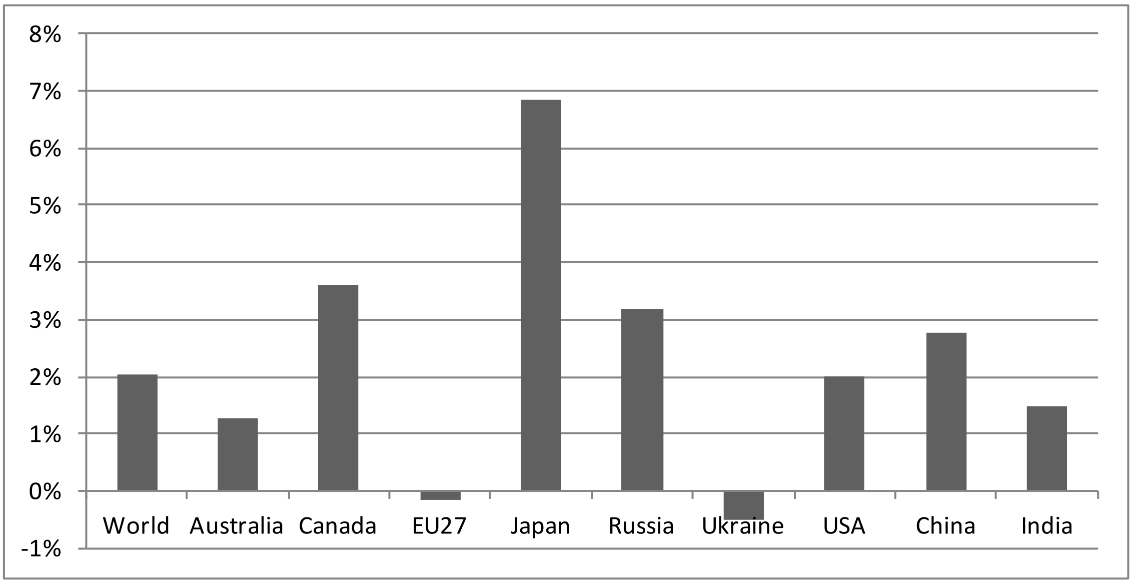
[6] For Germany, this is already the case in the *reference baseline* (see also Lechtenböhmer and Samadi, 2012).

[7] For France, hardly any existing nuclear capacity will actually be decommissioned before 2020 but nuclear capacity, which had already been under construction for several years (e.g. the EPR in Flamanville) will be put into operation (as was announced by the French government in the wake of the Fukushima accident).

Figure 3: Percentage changes in the GHG emissions in 2020 in nuclear phase-out versus reference baseline



4 Climate policy scenario

Our climate policy scenario includes GHG emission targets for Annex I and non-Annex I countries for 2020 that are deemed consistent with meeting the 2°C target.

4.1 Emission targets for 2020

The aggregate emission target for Annex I countries for 2020 is taken from the proposal by the European Commission (2009a), which assumes emission reductions of 30% below 1990 levels. Following Peterson et al. (2011), this scenario may be interpreted as an illustrative example for possible Post-Kyoto climate targets, which are consistent with the 2°C target. While, in principle, there are numerous ways of splitting the 30% reduction target between Annex I countries, we chose the simplest type of burden-sharing rule: each Annex I country faces a uniform reduction rate of 30% below 1990 levels.[8]

For non-Annex I countries the targets are derived from their NAMAs submitted under the Copenhagen Accord/Cancun Agreements, i.e. only non-Annex I

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[8] See Ciscar et al. (2013) for a recent analysis of the economic implications of alternative burden-sharing rules.

countries which submitted a NAMA (NAMA-NAI) face emission targets in our climate policy analyses. Several NAMAs define the emission target as a target rate below baseline emissions and not as an absolute emission target derived from emission levels in a historic base year. As most NAMA submissions do not provide quantitative reduction targets, these submissions had to be translated into quantitative reduction targets. In case of China and India, which provided CO_2e emission intensity targets, the targets are calculated using emissions and real (2005) GDP based on market exchange rates.[9] For non-Annex I countries that submitted specific measures rather than general emission reduction targets, the associated emission reductions had to be calculated. To do so, we assumed that these reductions correspond to a threshold price of 10 €/t CO_2e in 2020. In other words, NAMA-NAI countries are expected to implement the cheapest reduction measures available in the countries as NAMAs, where the cost of the most expensive measure implemented as a NAMA is 10 €/t CO_2e. The emission reductions that can be realized at this price are between 5% below baseline in Jordan and 20% below baseline in several African countries. We employ the marginal abatement cost curves of the *reference baseline* to derive these emission reductions[10]. Unlike Annex I countries' reduction targets, non-Annex I countries' reduction targets expressed in absolute levels vary between the *reference* and the *nuclear phase-out climate policy scenario* as they depend on the baseline emissions in 2020.

Table 1 shows the emission reduction targets as percentage of baseline emissions for the *reference* and the *nuclear phase-out baseline*. At the global level, the climate policy scenario implies GHG emission reductions of 12% compared to baseline emissions in 2020 in both scenarios. Emissions for Annex I countries are, on average, 28% below emissions in the *reference climate policy scenario*, and 30% below emissions in the *nuclear phase-out climate policy scenario*. Thus, on average, the nuclear phase-out increases required emission reductions by about 7% since baseline emissions are 2% higher compared to the *reference climate policy scenario*. In comparison, for non-Annex I countries the policy targets translate into GHG emissions which are 3% below baseline emissions in both scenarios.

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[9] Compared to other interpretations of the NAMAs the applied targets for China and India are rather lenient (see e.g. climateactiontracker.org for updated interpretations of countries' pledges).

[10] See Appendix B for a detailed description of how the marginal abatement costs curves are derived.

In both scenarios Australia, Canada, Japan and the USA face more ambitious emission targets than the group of Annex I countries on average. Japan and the USA are most affected by the phase-out of nuclear energy. The differences in emission targets below baseline increase by 4 percentage points for Japan and 2 percentage points for the USA. This corresponds to an increase in total emission reductions of 13% for Japan and 5% for the USA. For Russia, the uniform 30% reduction target implies rather modest reductions compared to baseline emissions. Because baseline emissions in Russia are higher in the *nuclear phase-out baseline*, required emission reductions increase from 7% to 9% below baseline compared to the *reference climate policy scenario*. For the Ukraine the uniform reduction rate means, that GHG emissions may exceed baseline emissions by 36% and 37% in 2020.

As NAMAs for NAI countries are calculated below baseline emissions, percentage figures do not change for the two scenarios. Among the NAI countries listed in Table 1, South Africa, South Korea, and Mexico face the most ambitious reduction targets relative to both baseline scenarios. For China and India, the efficiency targets pledged under the Copenhagen Accord / Cancun Agreement translate into emission reduction targets for 2020 that correspond to the baseline emissions.[11]

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[11] For China, this finding is consistent with, among others, Wang et al. (2009) and Carraro and Massetti (2011).

Table 1: Baseline emissions (Mt CO2e) and reduction targets (% compared to baseline emissions) in 2020

	1990 emissions***	Baseline emissions		Climate policy reduction targets (compared to baselines)	
		Reference	Nuclear phase-out	Reference	Nuclear phase-out
Australia*	418	591	599	- 50%	- 51%
Canada	592	825	845	- 50%	- 51%
EU 27*	5567	4990	4978	- 22%	- 22%
Japan	1269	1274	1342	- 30%	- 34%
Russia	3322	2493	2557	- 7%	- 9%
Ukraine**	928	476	474	+ 36%	+ 37%
USA	6112	6835	6962	- 37%	- 39%
Brazil		1533	1545	- 14%	- 14%
China		14810	15154	0%	0%
India		3609	3657	0%	0%
Mexico		723	732	- 21%	- 21%
South Africa		457	462	- 34%	- 34%
South Korea		671	732	- 30%	- 30%
Annex I	18733	18337	18620	- 28%	- 30%
Non-Annex I		33894	34432	- 3%	- 3%
Global		52231	53053	- 12%	- 12%

4.2 Certificates trading

All Annex I countries are allowed to trade emission certificates among each other, i.e. they may exchange Assigned Amount Units (AAUs). Non-Annex I countries may sell offsetting credits (CERs) to any Annex I country, but trading of CERs is assumed to be governed by three restrictions. First, to avoid double counting, NAMA-NAI countries can only generate and sell CERs for emission reductions that go beyond their domestic NAMA targets. Second, the non-Annex I countries can realize only 20% of their mitigation potential via CERs. This share is consistent with Castro (2010) who finds that only a small amount of a country's mitigation potential is realized under the CDM (see also Duscha and Schleich 2013). Third, the Annex I countries face a limit in the use of CERs to fulfil their reduction targets as has been debated among Annex I countries during the discussions of the Copenhagen Accord. This CER-quota is set to 20% of the emission reductions below baseline and applies to all Annex I countries.

The Annex I countries allowed to trade in either scenario need to fulfil at least 50% of the required emission reductions below baseline domestically (domestic compliance quota). Since the domestic compliance quota may prevent perfect arbitrage, the costs of domestic mitigation efforts in countries where the domestic compliance quota is binding, will exceed the market price of AAUs. While the CER-quota and the domestic compliance quota reflect features of actual climate policy discussions, they prevent the globally cost-efficient outcome to be achieved via the trading mechanism.

5 Results of climate policy scenario

For all countries and regions included in the model, sets of marginal abatement cost curves are generated from the *reference* and *nuclear phase-out baselines* by progressively introducing a range of carbon-prices, following a similar approach as Anger (2008), Den Elzen et al. (2011) or Duscha and Schleich (2013). Higher CO_2e prices not only increase the deployment of nuclear power to reduce the CO_2e emissions in the *reference scenario*, but also spur other mitigation options such as energy efficiency improvements, fuel switch from coal to gas, or the deployment of renewables.

Based on the two sets of marginal abatement cost curves, the impact of the nuclear phase-out on certificate prices, domestic mitigation effort, certificate trading, power generation, and compliance costs may be evaluated for the climate policy scenario.

5.1 Certificate prices

Table 2 displays the prices of AAUs and the prices of CERs in 2020 compared to the *reference* and the *nuclear phase-out* baselines.

Table 2: Certificate prices in 2020

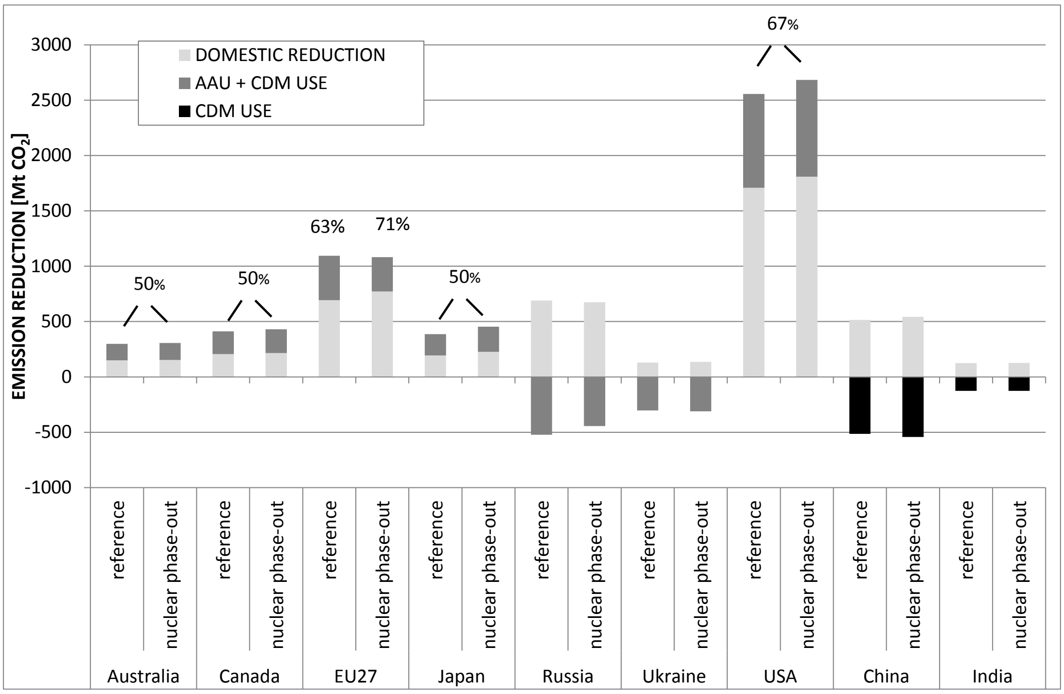
	Reference [2005€/tCO_2e]	Nuclear phase-out [2005€/tCO_2e]
AAUs	61	76
CERs	26	30

Since trading between Annex I countries is not limited, they face equal marginal abatement costs of 61 €/tCO_2e in the *reference climate policy scenario,* unless their domestic compliance quota is binding. The nuclear phase-out results in an increase in the price of AAUs of about 24% compared to the *reference climate policy scenario*. This increase reflects the (small) increase in required GHG emission reductions in the *nuclear phase-out climate policy scenario* compared to the *reference climate policy scenario* (baseline effect) and the fact that nuclear power plants are no longer available as a mitigation option (mitigation cost effect). Similarly, the price of CERs is about 19% higher in the *nuclear phase-out climate policy scenario* compared to the *reference climate policy scenario*. Since the CER-quota of 20% is binding in both cases in some Annex I countries, the price of CERs is below the price of AAUs. The vast majority of CERs are generated in China and India, reflecting both rather lenient emission targets (equal to baseline emissions) and large potentials of low-cost mitigation options in these countries.

5.2 Emission reductions and pattern of compliance

For most countries the increase in prices for emission certificates between the *reference* and the *nuclear phase-out climate policy scenarios* is associated with changes in emission reductions and with changes in the pattern of compliance — i.e. whether countries meet their emission targets via domestic mitigation or via purchasing certificates from abroad (see Figure 4).

Figure 4: Emission reduction and pattern of compliance in climate policy scenar-ios versus reference and nuclear phase-out baselines in 2020



Typically for Annex I countries, the nuclear phase-out not only means that the emission targets become more ambitious (because of the baseline effect); it also leads to a change in the share of domestic mitigation efforts in total required compliance efforts (domestic compliance share) compared to the *reference climate policy scenario*. Figure 4 shows that the domestic compliance share ranges from a minimum of 50% in countries with particularly high mitigation costs like Australia, Canada or Japan (i.e. the use of certificates is limited by the domestic compliance quota of 50%) up to 71% in the EU.

For countries that employ nuclear power, the impact of the nuclear phase-out on the domestic compliance share is governed by two countervailing effects. First, the mitigation cost effect results in a lower domestic compliance share, ceteris paribus. Second, higher prices for AAUs render additional domestic mitigation options profitable, leading to a higher domestic compliance share, ceteris paribus. For countries that do not rely on nuclear power, only the second effect matters. As a consequence, for most countries the nuclear phase-out is associated with a higher domestic compliance share.

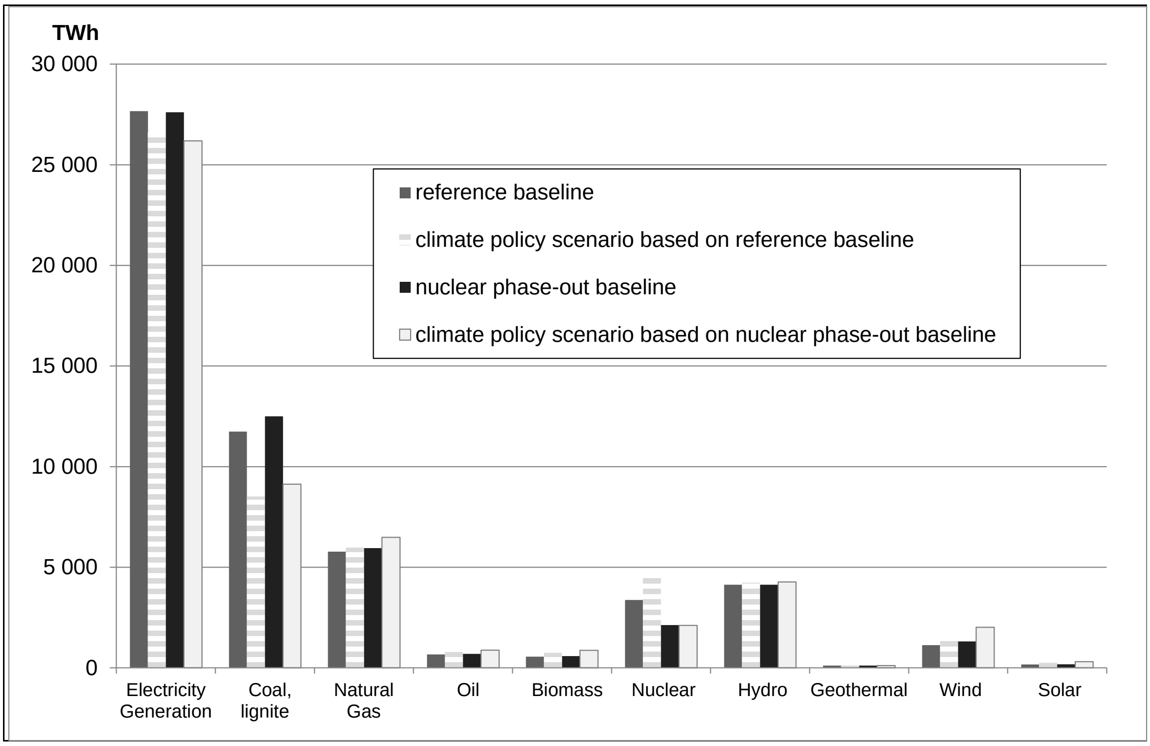
In Russia domestic emission reductions are lower in the *nuclear phase-out* than in the *reference climate policy scenario*. Russia not only faces higher baseline emissions in the *nuclear phase-out climate policy scenario* but also loses nuclear as a mitigation option. Both effects lower Russia's supply of AAUs (despite higher certificate prices) by about 80 million AAUs.

For China and the Ukraine, which are net sellers of certificates, the trading volume is noticeably higher in the *nuclear phase-out* than in the *reference climate policy scenario*. In contrast to Russia, countries such as India and the Ukraine, where the share of nuclear power in the reference baseline is rather low, benefit from the higher certificate prices without losing a significant share of their mitigation potential. For China, where emissions are substantially higher in the *nuclear phase-out baseline* (by 350 Mt CO_2e), certificates sales increase by around 30 Mt CO_2e.

5.3 Power sector

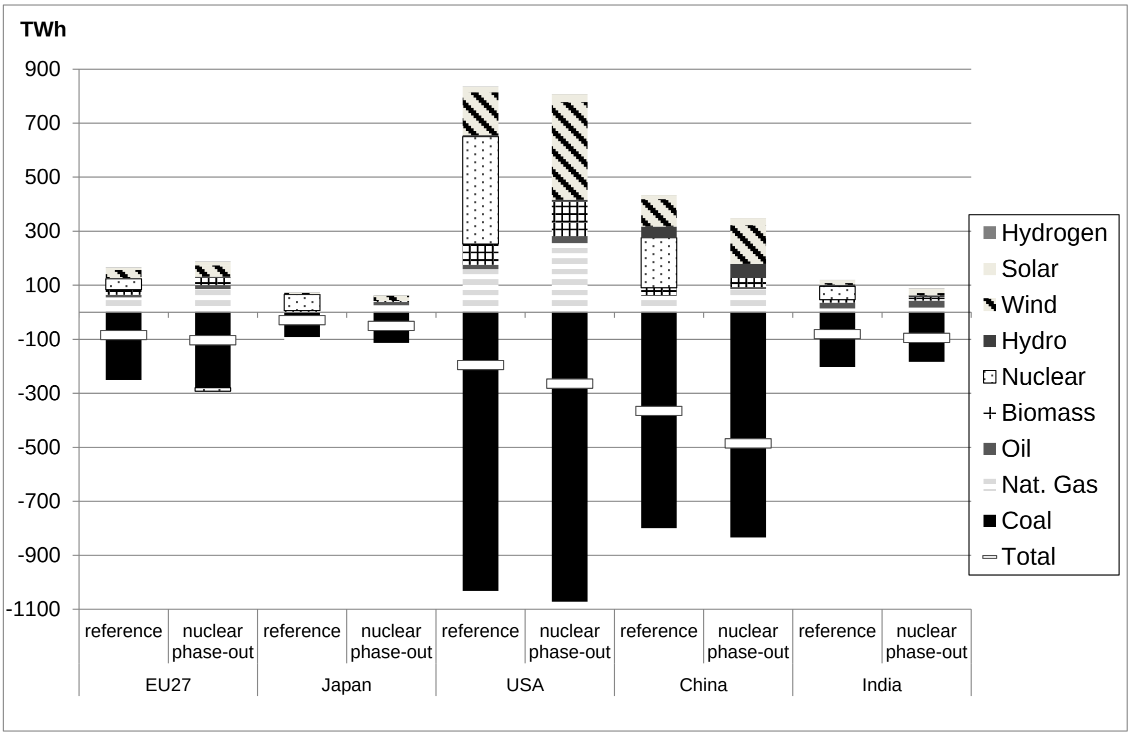
A phase-out of nuclear power substantially affects the fuel mix in the baseline, as described in Section 3. Meeting ambitious climate policy targets leads to additional adjustments in the power sector (Figure 5 and Figure 6). In both policy scenarios, the generation of coal-fired power is lower than in the baseline scenarios. While in the *reference climate policy scenario* nuclear power generation increases especially, in the *nuclear phase-out climate policy scenario* natural gas and wind increase the most. In particular, the power generation from natural gas, solar and wind increases by 9%, 21%, and 34% in the *nuclear phase-out* compared to the *reference climate policy scenario.* These developments go together with a 4% reduction in global and Annex I electricity demand in the *reference climate policy scenario* and – because of the fairly stronger deployment of more expensive low-carbon technologies – with a 5% reduction in the *nuclear phase-out climate policy scenario*.

Figure 5: Global electricity generation by fuel in 2020 for baseline and climate policy scenarios



A comparison across countries reveals that the pattern of adjustment in the power mix is quite similar in most countries and in line with the overall global pattern. Figure 6 shows the extent to which the effects differ across countries/regions with a high share of nuclear power. For example, the USA which heavily relies on the expansion of nuclear power to meet their climate policy target show a much stronger increase in electricity generated by wind (+65%), biomass (+28%) and natural gas (+6%) in the *nuclear phase-out* than in the *reference climate policy scenario*. In the USA and China, the effects are of an order of magnitude larger than in other “high nuclear” countries. For France, the effects are small, because only a relatively small share of the nuclear capacity is phased-out prior to 2020 in the *nuclear phase-out baseline.*

Figure 6: Changes in electricity generation in 2020 for countries with high share of nuclear energy (policy scenarios versus reference and nuclear phase-out baselines)



Consequently, all Annex I countries but the EU experience an increase in CO_2e emissions in the power sector in the *nuclear phase-out climate policy scenario* compared to the *reference climate policy scenario*. Hence, those Annex I countries need to realize additional mitigation efforts in other domestic sectors or purchase certificates abroad.

In all Annex I countries though, the power sector hosts a substantial share of domestic mitigation efforts in both policy scenarios, covering between 28% (Ukraine, *nuclear phase-out*) and 54% (US, *reference*) of total emission reductions. The share of the power sector in domestic mitigation efforts is lower in the *nuclear phase-out* than in the *reference climate policy scenario* in all countries but Canada. This difference is particularly large in Japan and Russia, where the power sector's share of domestic mitigation efforts decreases from 41% to 32% and from 33% to 28%, respectively. The main increases in other sectors' contributions can be found in industry (Japan: +5 percentage points) and residential & services (Japan and Russia: +2 percentage points).

5.4 Compliance costs

Compliance costs reflect a country's costs for meeting its emission target. They are measured as the sum of the mitigation costs for domestic efforts in the energy system (domestic mitigation costs) plus the net costs of purchasing and selling certificates (trade costs). The compliance costs in 2020 for the policy scenario for both the *reference* and the *nuclear phase-out climate policy scenario* are shown in Figure 7. The compliance costs of each country are disaggregated into domestic mitigation costs and trading costs. Accordingly, the phase-out of nuclear power increases compliance costs in the group of Annex I countries by 28%, but effects vary significantly across countries.

As expected, the USA and the EU, where the uniform 30% reduction target implies the largest required emission reductions below baseline of all Annex I countries, also carry the highest compliance costs in both policy scenarios. The USA also faces the largest increase in absolute compliance costs due to the nuclear phase-out (+21 billion €). In comparison, Japan faces the highest relative increase in compliance costs (+58%), followed by the USA (+28%). In contrast, the Ukraine and Russia, who are net sellers of AAUs, as well as India and China, who are net sellers of CERs, benefit from the increase in certificate prices. At the same time, though, the nuclear phase-out also leads to higher domestic mitigation costs for these countries. Taking both effects into account, India and China are better off in the *nuclear phase-out climate policy scenario*. Russia and the Ukraine also benefits from the phase-out of nuclear energy, even though it sells fewer certificates in the *nuclear phase-out* compared to the *reference climate policy scenario*, but at a higher price.

In general, the nuclear phase-out tends to increase a country's domestic mitigation costs combined with either an increase in trade costs if it is a net-buyer of certificates or with an increase in trade revenues if it is a net-seller. A deviation from this pattern can be found in the EU, where the increase in the price of AAUs leads to additional domestic mitigation efforts, and hence reduces the amount of AAUs purchased from abroad.

Figure 7: Compliance costs in 2020

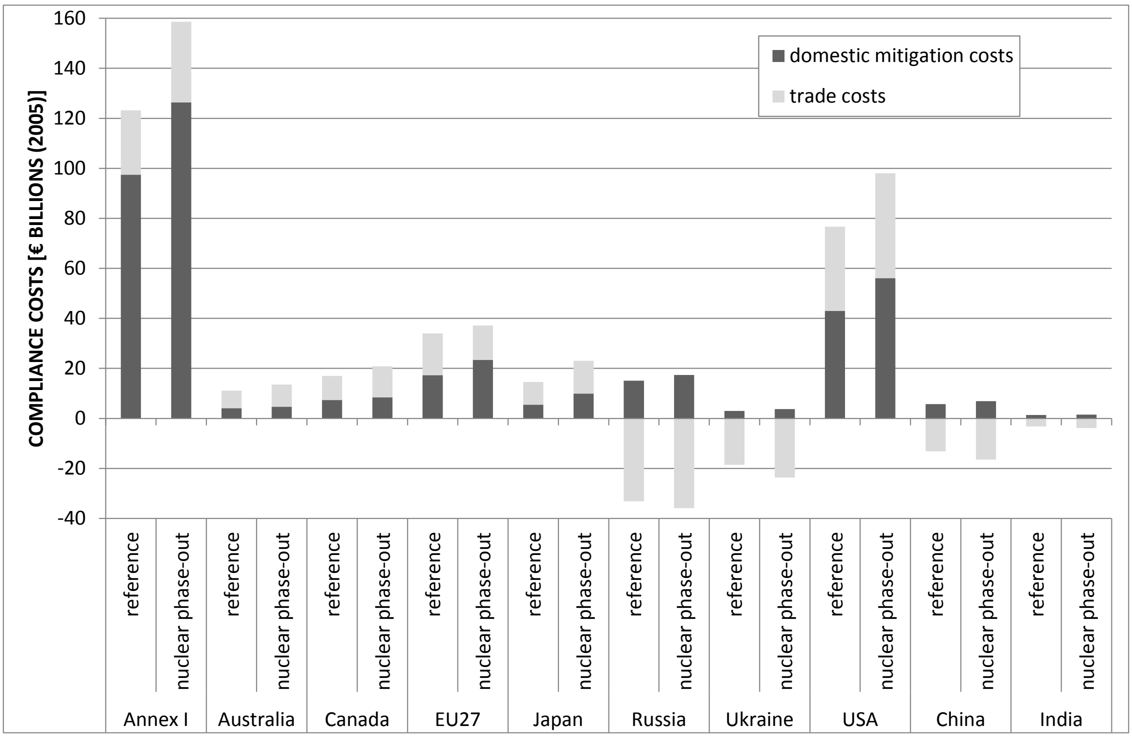


Figure 8: Change in compliance costs induced by nuclear phase-out

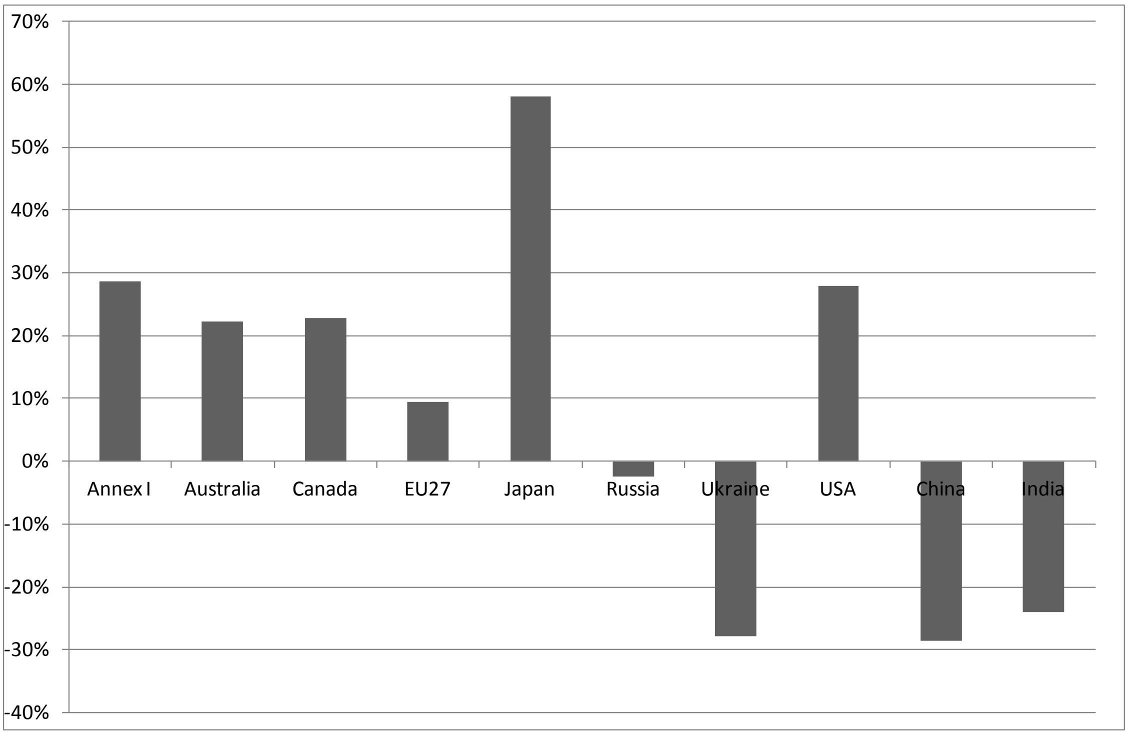


Figure 9: Compliance costs as share of GDP

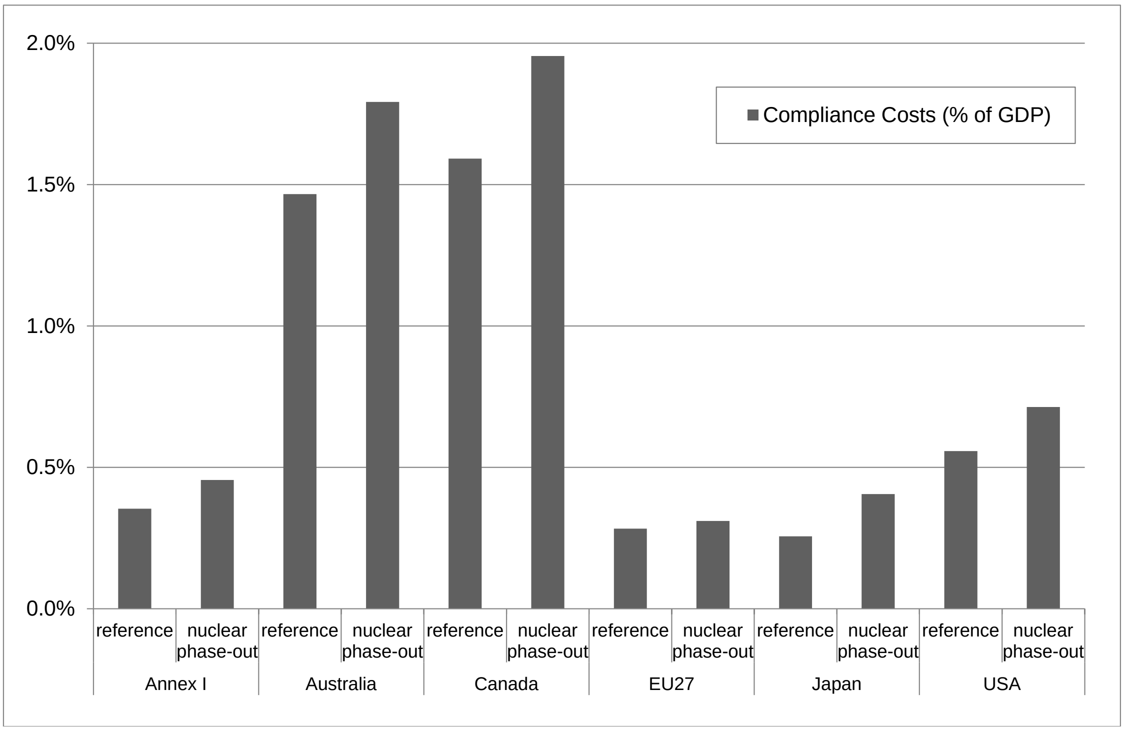


Figure 9 displays the compliance costs as a share of GDP for the group of Annex I countries and for Annex I countries with positive compliance costs. Compliance costs for the entire group of Annex I are around 0.4% of GDP. That is, in general, costs to meet the 30% reduction targets are low, but differences exist across countries. These differences generally depend on the strictness of the targets and the countries' mitigation potential and mitigation costs. Total compliance costs are by far highest in the USA, followed by the EU. Compliance costs are quite modest if they are measured as a share of GDP, i.e. they are below 1% for the USA and 0.5% for the EU. In contrast, while absolute compliance costs for Australia and Canada are significantly lower compared to those of the USA and the EU, they account for a significantly larger amount of GDP (between 1.5 and 2% of GDP). Thus, a 30% reduction target has a more significant economic impact on these two countries than it has on the USA or the EU.

Likewise, the nuclear phase-out increases the compliance costs as a share of GDP in Annex I countries by only 0.1 percentage points, i.e. is rather small when measured for the group of Annex I countries. For Australia and Canada this share increases by 0.3 and 0.4 percentage points, and less for the USA (0.15 percentage points), the EU (0.03 percentage points),) and Japan (0.14 percentage points). Thus, for Japan, where the nuclear phase-out leads to the largest increase in total compliance costs of any country (see Figure 10), this increase still amounts to a relatively small overall economic burden even though nuclear is an important technology in their power production. In contrast, because of the resulting increase in prices on the carbon market, the global nuclear phase-out results in a more pronounced increase in costs in Australia and Canada, measured as share of GDP, even though these countries do not rely on nuclear power.

5.5 Decomposition of changes in compliance costs in baseline effect and mitigation cost effect

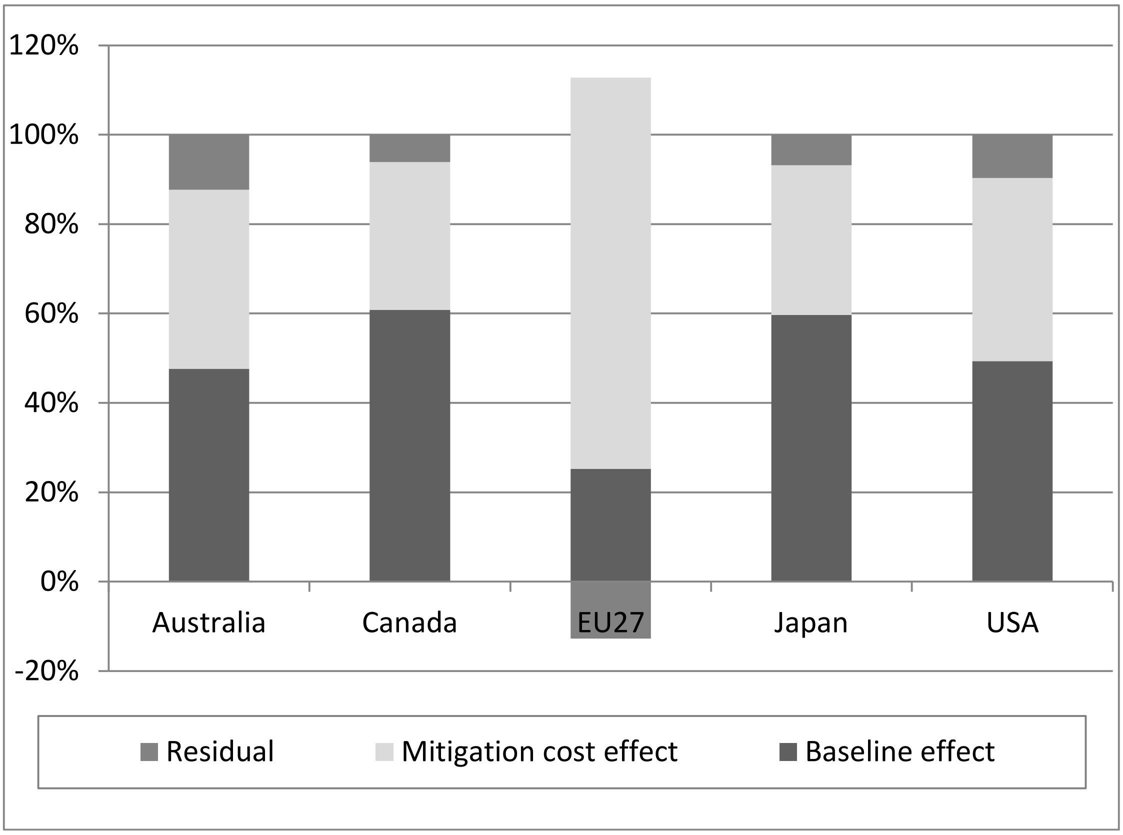
Figure 7 illustrates that the effects of a nuclear phase-out differ across countries depending on the share of nuclear in the power mix and on the importance of nuclear compared to other domestic mitigation options. To gain additional insights into the factors underlying the differences in countries' compliance costs in response to a nuclear phase-out, we decompose compliance costs changes into two effects. The first effect reflects the difference in compliance costs due to the global increase in baseline emissions in the *nuclear phase-out* compared to *reference baseline* (baseline effect). The second effect captures the additional compliance costs from losing nuclear power as a mitigation option (mitigation cost effect).

To quantify the baseline effect we recalculate each country's compliance costs, assuming the baseline emissions from the *nuclear phase-out baseline*, but employing the mitigation cost curves derived under the *reference scenario* (adapted baseline policy scenario). That is, countries where the phase-out of nuclear energy leads to higher (lower) baseline emissions must reduce more (less) emissions in the adapted baseline policy scenario than in the *reference climate policy scenario*. The baseline effect is then calculated as the differences in compliance costs between the adapted baseline policy scenario and the *reference climate policy scenario*. Note that, since the phase-out of nuclear energy leads to higher global baseline emissions than in the *reference baseline*, certificate prices are also higher in the adapted baseline policy scenario.

To quantify the mitigation cost effect, we recalculate each country's compliance costs, employing the mitigation cost curves from the *nuclear phase-out scenario*, but assuming the baseline emissions from the *reference baseline* (adapted mitigation cost policy scenario). Now, countries where the phase-out of nuclear energy leads to higher (lower) baseline emissions must reduce less (more) emissions in the adapted mitigation cost policy scenario than in the *nuclear phase-out climate policy scenario.* The mitigation cost effect is then calculated as the differences in compliance costs between the adapted mitigation cost policy scenario and the *reference climate policy scenario*.

Any difference in costs between the *nuclear phase-out* and the *reference climate policy scenario* which cannot be explained by the sum of the baseline effect and the mitigation costs effect is captured by a residual. This residual reflects the interaction of baseline and mitigation effects and may be positive or negative depending on whether the effects amplify or weaken each other. The results of this decomposition analysis are shown in Figure 10. Note that for all five countries, the residual is only around 10%.

Figure 10: Baseline effect and mitigation cost effect in 2020



Note: Russia, Ukraine, China and India are not included in the decomposition analysis because they are net-seller of certificates

For all countries but the EU, at least half the increase in compliance costs is attributable to the baseline effect. For Japan, the high share of the baseline effect reflects the large increase in baseline emissions (+7%) due to the phase-out of nuclear energy. The mitigation cost effect only explains about 30% of the compliance cost increase, i.e. the loss of nuclear power as a mitigation option in Japan only accounts for 30% of the overall compliance cost increase. For the

USA, the increase in baseline emissions explains about 50% of the overall compliance cost increase, while losing nuclear as a mitigation option accounts for 40% of the increase in compliance costs. Unlike in Japan and the USA, the nuclear phase-out does not directly affect the baseline emissions or mitigation options of Australia and Canada. Instead, the increase in compliance costs reflects an indirect effect, i.e. the rise in certificate prices in the *nuclear phase-out* climate policy *scenario*.

In contrast, in the EU the mitigation cost effect explains the lion's share of the increase in compliance costs. Two factors drive this result. First, the EU does not experience an increase in baseline emissions. Second, due to relatively low additional domestic mitigation costs, the EU may alleviate the effects of higher certificate prices by increasing domestic reductions in the *nuclear phase-out climate policy scenario*. Hence, for the baseline effect, there is an indirect effect (i.e. certificate price increase), but no direct effect. For the EU the indirect effect is softened by higher domestic emission reductions compared to the *reference climate policy scenario*. For the mitigation costs effect, there is a direct impact (i.e. losing nuclear as a mitigation option), and also an indirect effect.

6 Results of alternative policy scenarios

To gain further insights into the interaction of a nuclear phase-out and climate policy we conducted additional scenario analyses. Because of space limitations we only present the main findings of these additional scenarios.[12]

6.1 Restricted trading scenario (KP2)

The first additional scenario (*KP2*) differs from the *climate policy scenario* in only one aspect: trading of AAUs is limited to those Annex I countries which have committed to a second Kyoto period, i.e. Australia, Belarus, Croatia, the EU, Iceland, Kazakhstan, Liechtenstein, Monaco, New Zealand[13], Norway, Switzerland and the Ukraine. At the time the analyses were conducted, Canada, Japan and Russia stated that they would not participate in a second Kyoto period. Also, the USA will continue to abstain from the Kyoto Protocol. Hence, Can-

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[12] A more detailed presentation of these findings is available upon request from the authors.

[13] Since the time when the analyses were conducted, New Zealand decided against participation in the second Kyoto period.

ada, Japan, and the USA can no longer rely on certificate trading for compliance and must intensify their domestic mitigation efforts, while Russia can no longer enjoy revenues from selling certificates.

Compared to the *climate policy scenario* (with full Annex I trading), prices of AAUs (CERs) are 19% (8%) lower. Further, compliance costs of Annex I countries in the restricted trading scenario are about 28% higher than in the *reference policy scenario*, and 29% higher than in the *nuclear phase-out policy scenario*. On the one hand, these figures reflect the savings in overall compliance costs, which may be realized via emissions trading. On the other hand, they also illustrate that the nuclear phase-out is more costly when certificate trading is restricted. Most prominently, in Japan, the nuclear phase-out now leads to a 200% increase in compliance costs (compared to 120% in the *climate policy scenario*). But in the USA, additional compliance costs due to the nuclear phase-out do not differ much relative to the *climate policy scenario* because the USA may substitute the purchase of certificates with domestic reductions at rather modest additional domestic compliance costs. In contrast to the *climate policy scenario*, the nuclear phase-out makes Russia worse off in *KP2* because Russia no longer enjoys revenues from selling AAUs. The lower certificate prices make net sellers (e.g. China, India, Ukraine) worse off compared to the *climate policy scenario*. At the same time, countries which face stringent emission targets but may purchase certificates (i.e. Australia, EU) benefit from lower certificate prices. Compared to the *climate policy scenario,* the additional compliance costs due to a nuclear phase-out are almost 60% lower for the EU and about 50% lower for Australia. In sum, net additional compliance costs of a nuclear phase-out for the group of Annex I countries are 35% higher in the *KP2 trade scenario* than in the *climate policy scenario*.

6.2 Alternative target scenarios

The second set of additional scenarios involves alternatives to our *climate policy scenario* with respect to (i) the assumed uniform allocation of the reduction target for the group of Annex I countries; and (ii) the reduction target of 30% for the group of Annex I countries. These assumptions are varied in two additional target scenarios, while keeping the targets for non-Annex I countries as in the *climate policy scenario*.

In principle, an infinite number of possible burden-sharing schemes exist. We compare our uniform reduction target of 30% to the indicator-based burden-sharing scheme developed by the European Commission (2009b).[14] Accordingly, the 30%-reduction target among Annex I countries in this *EC30% scenario* is allocated across regions based on four equally-weighted indicators: GDP per capita (in 2005) - reflecting a country's ability to pay; GHG per GDP (in 2005) - recognizing domestic emission reduction potential; population trend (1990 to 2005) - accounting for "needs"; and GDP trends (1990 to 2005) - reflecting domestic "early action".[15]

To test the sensitivity of our findings with respect to target stringency, we also compare our policy scenario to a scenario involving a more stringent 40% (instead of a 30%) uniform reduction target for the group of Annex I countries (*Uniform40% scenario*). Table A-2 in Appendix C provides an overview of the emission reduction targets for Annex I countries applied within the alternative target scenarios.

Figure 11 presents the findings on the change in compliance costs due to a nuclear phase-out for the alternative target scenarios for selected Annex I countries. Since the effects of these scenarios on non-Annex I countries are negligible and involve only indirect effects via changes in CER prices, we focus on the results for Annex I countries. Moreover, to keep changes in positive compliance costs separate from changes in negative costs, Figure 11 does not show results for Russia and Ukraine.

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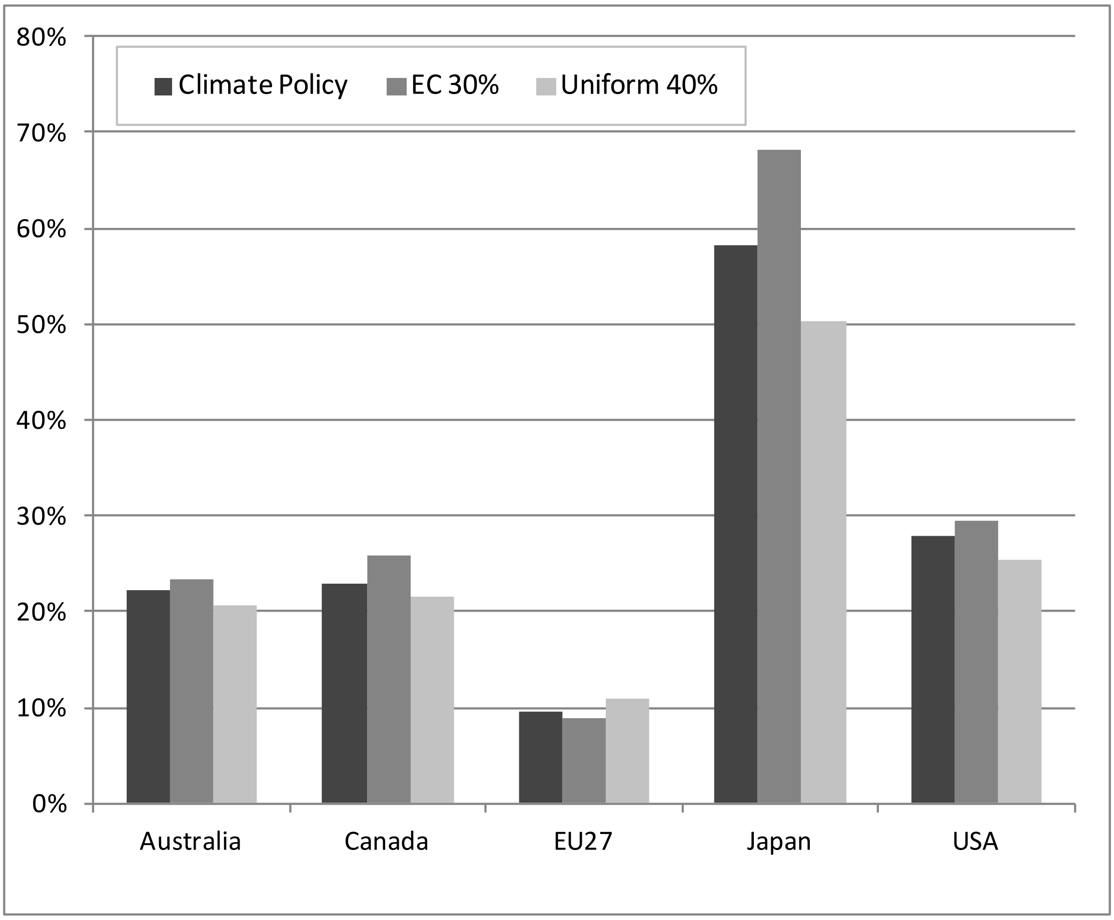
[14] See Kartha et al. (2009) or Brouns and Ott (2005) for other burden-sharing schemes.

[15] See also Peterson et al. (2011) for an implementation of EU (2009) indicator-based burden sharing scheme.

Figure 11: Change in compliance costs induced by nuclear phase-out in the alternative target scenarios



Note: Climate Policy refers to the 30% uniform reduction target for Annex I countries assessed in detail in the previous sections of this paper.

The alternative burden sharing scheme (*EC30%*) leaves the US, Canada, Australia, Japan and the US with a lower mitigation target than the uniform 30% scheme. Thus, mitigation costs are lower in these countries. Figure 11 suggests that the phase out of nuclear leads to quite similar effects on percentage changes in compliance costs in Annex I countries in *EC30%* as in our original *climate policy scenario*. For the group of Annex I countries, the nuclear phase-out increases mitigation costs by about 29% in both scenarios. The only noticeable difference can be observed for Japan, which needs to offset a large share of nuclear power in the phase-out scenario. The lower mitigation target helps bring down these additional costs. The relative difference in certificate prices between the *reference* and the *phase-out scenarios* is rather similar in both burden sharing scenarios (see Table A-3 in Appendix C).[16] Russia and Ukraine are net sellers of certificates in the *EC30%* as well as in the *climate policy scenario*, but better off under the *climate policy scenario* since *EC30%* means less hot air for both countries.[17]

Intensifying the reduction target in moving from a 30% to a 40% target increases the level of compliance costs (by around 130% for the group of Annex I countries) and also certificate prices (AAUs: +80%, CERs: +70%). The additional phase out of nuclear, however, leads to quite similar effects on percentage changes in compliance costs of Annex I countries as in the *climate policy scenario, i.e. to an increase of about 26%* for the group of Annex I countries. For Japan, the relative difference is markedly smaller for the more ambitious *uniform40% scenario*. In absolute terms, however, the difference is quite pronounced. The nuclear phase-out increases compliance costs in Japan about twice as much in the *uniform40%* than in the *climate policy scenario*. Russia and Ukraine remain net sellers of certificates in *uniform40%.* Finally, the relative change in certificate prices in response to a nuclear phase-out is similar to the other scenarios (see Table A-3 in Appendix C).

In general, the results of the additional target scenarios suggest that our main findings for the *climate policy scenario* are fairly robust to the variations in burden sharing and target level for Annex I countries considered.

7 Conclusions

In this paper we employ a global energy systems model to analyse the effects of a global phase-out of nuclear power on the costs of meeting climate policy targets in 2020, which are consistent with the 2°C target. In our *climate policy scenario*, Annex I countries face a uniform 30% reduction rate compared to their 1990 GHG emission levels. Non-Annex I countries are assumed to meet their NAMA targets. Simulations of the new baseline suggest that a long-term global phase-out of nuclear power by 2050 lowers the share of nuclear in the global

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[16] The price levels differ slightly between the scenarios because the limits on the use of CERs become binding at different reduction levels, This also explains the (negligible) compliance cost decrease in EU27 and the marginal increase in Australia, Canada and the US in Figure 11.

[17] Note that the domestic reduction potential, which is particularly high in these countries, is one of the burden-sharing indicators in *EC30%.*

power mix from 11% to 8% in 2020. This reduction is almost entirely offset by a stronger deployment of fossil fuels and – in countries with ambitious support for renewable energy (e.g. the EU) – also by renewables. As a result, global GHG emissions in the baseline increase by 2% under a nuclear phase-out and the emission reductions required to meet the climate policy targets increase by 3% globally.

Simulations of the climate policy scenario with unrestricted trading reveal that the nuclear phase-out increases AAU prices by 24% and total compliance costs of Annex I countries by 28%. While Japan (+58%) and the USA (+28%) face the largest relative increase, China, India, Ukraine and Russia benefit because the additional revenues from selling certificates outweigh higher domestic abatement costs. Similar to Edenhofer et al. (2010) or Bauer et al. (2012), we find a modest increase in compliance costs in relation to GDP.

To meet the 30% emission reduction targets for 2020, domestic efforts in Annex I countries involve the power sector, in particular. The share of coal-based power generation declines and the share of natural gas, nuclear power and renewables (in particular wind power) increases in the *reference scenario*. The nuclear phase-out increases the share of natural gas, wind and solar in the power mix of most countries, in particular in those countries which rely strongly on nuclear power (e.g. USA). Somewhat higher electrictiy prices lead to a slightly lower demand than in the *reference scenario*.

Decomposing the overall changes in countries’ compliance costs due to a nuclear phase-out into a baseline effect and a mitigation cost effect we find that the share of the mitigation cost effect is about twice as high in the EU as in Australia, Canada, Japan, or the USA. While the nuclear phase-out hardly affects baseline emissions in the EU until 2020, the loss of nuclear power as a mitigation option weighs rather heavily compared to other regions.

Results from alternative policy scenarios provide additional insights. When trading of AAUs is restricted to those Annex I countries which have committed to a second Kyoto period, compliance costs of Annex I countries in the climate policy scenarios are about 28% higher than in the *reference climate policy scenario*, and 29% higher than in the *nuclear phase-out climate policy scenario*. These figures reflect the savings in overall compliance costs, which may be realized via unlimited emissions trading between Annex I countries. They further illustrate that the nuclear phase-out is more costly when certificate trading is restricted. Also, our general findings on the relative impact of a global nuclear phase-out on global and regional patterns of compliance costs appear to be fairly robust to the considered alternative ways of sharing the burden of emission reductions across Annex I countries and to more ambitous emission targets for the group of Annex I countries.

Our modeling assumptions and findings should be interpreted with caution, though. Arguably, the assumed global phase-out of nuclear may overstate actual long-term reactions to the Fukushima accident. Yet, our *nuclear phase-out scenario* serves as an interesting benchmark, as it reflects what may happen should concerns about the future of nuclear energy increase dramatically, and globally. Also, it should be kept in mind that by focussing on the year 2020, where actual policy targets are available for most countries, our analysis takes on a relatively short-term perspective. For example, the licences of most nuclear units in the USA expire after 2030. In addition, ongoing international climate diplomacy attempts to create binding targets which go beyond 2020. These targets need to be more ambitious than those implemented for 2020 to meet the 2°C target with a high probability. From this perspective a global phase-out of nuclear power is expected to bring about stronger economic and environmental implications in the longer run than analysed for 2020. But in the long run, the energy system will also exhibit higher flexibility and feature learning effects for low-carbon technologies. These factors will lower adjustment costs of banning a major power generation and mitigation option. The findings by Bauer et al. (2012) and Edenhofer et al. (2010) suggest that in the long run, the economic impact of restricting nuclear power is small compared to the impact of ambitious mitigation policies.

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Appendix A: Description of the POLES model

POLES is a techno-economic model with endogenous projection of energy prices, a complete accounting of demand and supply of energy carriers and associated technologies. The model includes, among others, 24 competing power generation technologies for 57 different countries/regions, and accounts for CO_2 and other GHG emissions. This high level of regional disaggregation allows a very large extent of country-specific modelling of technology availability. The model builds on price-driven behavioral equations for final energy demand (by carriers and consumption sectors) and cost-driven behavioral equations for energy supply (by fuels and technologies). Supply and demand are balanced on a yearly basis via recursive simulation.

For the Power Generation sector, POLES forecasts the technology-specific development of capacities based on cost competition accounting for endogenous technological learning (“learning by searching”, “learning by doing”) and of power generation based on a must-run and merit-order approach. Techno-economic parameters are taken from the TECHPOL[18] database, including investment costs, operation & management costs, efficiencies and lifetimes. The model then calculates full and marginal costs taking into account learning effects, fuel costs and CO_2 taxation. Table A-1 displays investment costs per kW (without technology learning) for competing technologies. Regarding nuclear power, the expected lifetime is 40 years (extensions via refurbishment are not modeled). CCS technologies are assumed not to be available before 2020.

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[18] TECHPOL is compiled and maintained by EDDEN (Economie du Développement Durable et de l’Energie, UPMF, Grenoble)

Table Annex 1: Investment costs for major power technologies in the POLES model (in 2005$/kW)

Technologies *(costs are expressed in $05/kW)*	**2005**	**2020**
Pressurised Fluidised Coal	1890	1777
Pressurised Fluidised Coal + CCS	3329	2864
Integrated Coal Gaseification (IGCC)	2634	2126
IGCC + CCS	3470	2775
Lignite Conventional Thermal	1966	1909
Coal Conventional Thermal	1739	1682
Oil Conventional Thermal	1270	1214
Gas Conventional Thermal	1190	1134
Gas-fired Gas Turbine	589	545
Oil-fired Gas turbine	589	545
Gas-fired Gas Turbine + CCS	1374	1225
Gas-fired Gas turbine Combined Cycle	745	689
Biomass Gasification	3822	3233
Biomass Gasification + CCS	5009	4187
Biomass Thermal	2939	2428
Nuclear	3015	2672
New Nuclear Design (Gen.IV)	11162	8796
Combined Heat & Power	1010	956
Hydroelectricity	2657	2657
Wind onshore	1791	1491
Wind offshore	3163	2597
Solar Power Plant (CSP power plant)	4280	3348
Small Hydro	3672	3672
Distributed Photovoltaics	8685	4333

Appendix B: Derivation of marginal abatement cost curves with POLES

The marginal abatement cost curves (MACC) are constructed by introducing a Carbon Value (CV) which is interpreted as a shadow price of CO_2 emissions, i.e. a per unit tax based on the CO_2 content of fossil fuels. The CV affects the competitiveness of the different fuels in the energy system, both in the final consumption sectors and in the energy supply sector. As a consequence, the system becomes less carbon intensive as the CV increases: at any given date, the CV corresponds with the marginal cost of an emission reduction (for each sector and country) compared to a business-as-usual scenario with a CV of zero, for example. It is then possible to quantify annual mitigation costs for specific countries and sectors measuring the area under the MACC. It is important to note that external costs such as climate damages or nuclear waste are not taken into account in the model. To derive the MACC in this paper, for each simulated year, the CV is increased in steps of 10$/tC from 0 to 700 $/tC.[19] Values provided are in constant (2005) US dollars. For the analyses presented in this paper the costs were converted into € of 2005. The targeted CV, i.e. the CV which implements the emission targets, is reached linearly between 2011 and the considered year, i.e. climate policy becomes more and more stringent over time. The MACCs therefore integrate the different levels of flexibility of each country and sector to mitigate their CO_2 emissions such as fuel mix in the baseline, nuclear policy in place, existing potentials for renewable energies.

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[19] 10 $/t C correspond to 2.73 (=10*12/44) $/t CO_2

Appendix C

Table Annex 2: Targets in 2020 compared to 1990 levels for Annex I countries in the climate policy scenario and in the alternative target scenarios

	Climate Policy	EC 30%	Uniform 40%
Australia	-30%	-24%	-40%
EU 27	-30%	-30%	-40%
Canada	-30%	-23%	-40%
Iceland	-30%	-21%	-40%
Japan	-30%	-24%	-40%
New Zealand	-30%	-15%	-40%
Norway	-30%	-28%	-40%
Russia	-30%	-38%	-40%
Switzerland	-30%	-27%	-40%
Ukraine	-30%	-60%	-40%
USA	-30%	-24%	-40%
Annex I	-30%	-30%	-40%

Table Annex 3: Change in certificate prices due to nuclear phase-out in the climate policy scenario and in the alternative target scenarios

	Climate Policy	EC 30%	Uniform 40%
AAUs	24%	26%	23%
CERs	19%	19%	18%

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