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Costs of meeting international climate targets without nuclear power

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Costs of meeting international climate targets without nuclear power

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Policy Relevance

The role of nuclear power as a cost-efficient mitigation option to achieving climate policy targets has long been controversially discussed. The Fukushima accident in March 2011 has led many (but not all) countries to reconsider the future role of nuclear. Lack of social acceptance, but also geo-political and economic factors render the future role of nuclear energy in power generation and as an option to achieve climate policy targets highly uncertain. Our paper looks at the economic effects of a potential global phase-out of nuclear energy on the costs of meeting ambitious climate policy targets in 2020. The targets for developed countries are derived from a proposal by the European Commission, while targets for emerging and developing countries are taken from the pledges they made at recent United Nations climate conferences.

Our calculations with a well-known global energy systems model show that the impact of a global phase-out of nuclear energy on global mitigation costs is quite modest, but there are substantial differences across countries. Total compliance costs increase the most for Japan and the USA, but they are rather marginal, if measured in terms of GDP. China, India and Russia benefit from a nuclear phase out because their additional revenues from selling certificates outweigh the additional costs of losing nuclear power as a mitigation option. Our findings also highlight the importance of certificate trading to achieving climate targets in a cost-efficient way. If Japan or the US were banned from certificate trading with other countries, because they do not participate in a second Kyoto period, their compliance costs increased substantially under a phase-out of nuclear. The EU, however, would benefit, because certificate prices were be lower.

Zusammenfassung

In diesem Bericht werden die Auswirkungen eines globalen Ausstiegs aus der Kernenergie bis zum Jahr 2050 auf die Kosten zur Erreichung internationaler Klimaschutzziele für das Jahr 2020 analysiert. Die Analysen basieren auf Simulationen mit einem globalen Energiesystemmodell. Unsere Analysen zeigen ein Anstieg der globalen Treibhausgasemissionen im Jahr 2020 um 2%, in den Annex I-Ländern um 7% als Resultat des Atomausstiegs. Im Vergleich zum Referenzszenario steigen die Zertifikatpreise für Treibhausgasemissionen um 24%, die Erfüllungskosten der Annex I-Länder um 28% wenn freier Handel mit Zertifikaten zugelassen wird („alltrade"-Szenario). Der größte Anstieg in den Erfüllungskosten ist in Japan (+58%) und der USA (+28%) zu beobachten. China, Indien und Rußland dagegen profitieren von einem globalen Atomausstieg, wobei der Anstieg der Gewinne durch höhere Zertifikathandelsvolumina den Anstieg der Vermeidungskosten durch den Wegfall von Atomenergie übersteigt. Auch für Länder wie Japan, für die ein relativ großer Anstieg der Erfüllungskosten durch den Atomausstieg zu beobachten ist, sind die ökonomischen Auswirkungen begrenzt. Bei einer Einschränkung des Zertifikathandels auf die Länder, die sich an der 2. Verpflichtungsperiode des Kyoto Protokolls beteiligen, führt der globale Atomausstieg zu einem deutlich höheren Anstieg der Erfüllungskosten in den Annex I-Ländern (dies gilt jedoch nicht für die EU und Australien) im Vergleich zu einem Szenario mit uneingeschränktem Zertifikathandel.

Schlagwörter: Nuklearenergie; Ausstieg; Klimaschutzpolitik; Post-Kyoto; Copenhagen pledges

Abstract

This paper assesses the impact of a global phase-out of nuclear energy by 2050 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. Compared to a reference scenario, the price of certificates increases by 24% and total compliance costs of Annex I countries rise by 28%, if trading of emissions certificates is not restricted (all trade scenario) in an international climate policy regime. 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) than in the all trade scenario.

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

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%.

Analyses by the International Energy Agency, for example, had indicated a remarkable increase in the share of nuclear energy (IEA 2010a). 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. 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 more nuclear accidents, security issues (e.g. terrorist attacks) and the proliferation of nuclear weapons. Other seminal analyses by the IEA (2010b), the US Energy Information Administration (EIA 2009), and the Energy Modelling Forum (Clarke et al. 2009) also featured increased deployment rates for nuclear power generation over the next decades.

Since the Fukushima Daiichi accident in March 2011, support for nuclear, has declined in many countries. Results from WIN-Gallup International public opinion polls suggest, that the Fukushima accident has resulted in a global shift in opinion — 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 reaction 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). Responding to the crumbling political and social support for nuclear, Germany-based Siemens, the largest engineering conglomerate in Europe and the builder of all of Germany's 17 nuclear power plants, announced in the Fall of 2011 that it would stop building nuclear power plants anywhere in the world. 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.[1]

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 (2009), 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). At the recent UNFCCC climate conference in Doha, the EU and other 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, but also Canada and New Zealand, 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.

The aim of this study is to assess the impact of a potential global nuclear phase-out on the costs of meeting international climate policy targets for 2020. Methodologically, the 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 power may alter countries' baseline emissions and may restrict their options to mitigate GHG emissions. The simulations allow for 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. Further, the analyses cover the outcomes of a nuclear phase-out when trading of certificates is limited to countries that have committed to a second Kyoto period.

2 Literature review

Studies of the environmental implications of Copenhagen Accord and the Cancun Agreement unequivocally conclude that the targets implied are unlikely to be consistent with a path towards reaching the 2°C target (e.g. 2009; Den Elzen et al. 2010a, 2010b; Rogelj et al., 2010; Höhne et al. 2012). Analyses of the economic implications of the Copenhagen/Cancun pledges were carried out prior to the Fukushima accident and include 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). 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%, in particular 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. Only the study by Bauer et al. (2012) is motivated by the Fukushima accident and it also highlights the interdependence of climate and nuclear power policies. Bauer et al. (2012) analyse the 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 2020), and somewhat larger in the long-term (loss of 0.2% in 2050). Bauer et al. (2012) also point out that the economic impact of introducing an ambitious climate policy is much larger than the impact of restricting the use of nuclear power. For 2020, such a climate policy leads to a loss in global GDP of around 1.2%.

In sum, with the exception of the analysis by Bauer et al. (2012), which links a long-term, top-down growth model with a bottom-up model, existing studies rely on bottom-up type models to explore the role of nuclear in meeting climate policy targets. Most (but not all) of studies find

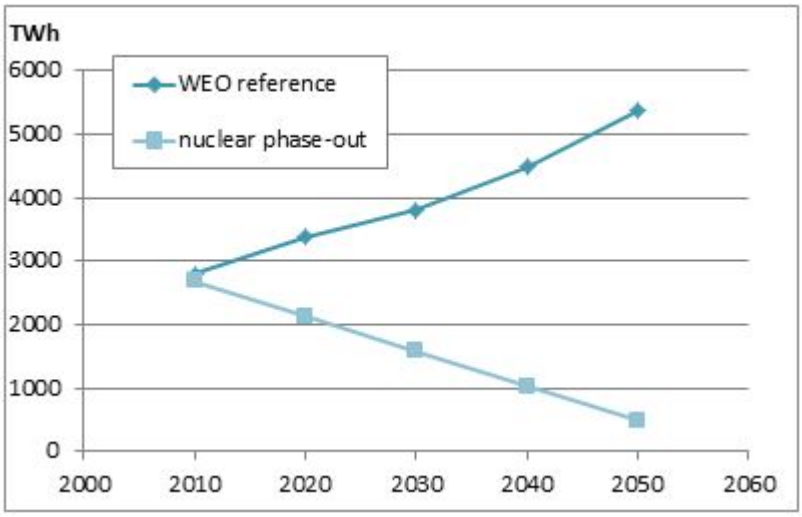
the additional costs of a nuclear phase-out to be low, and to amount to less than 1% of global GDP. Further, existing studies exhibit only a weak link to actual climate policy and do not allow for certificate trading. Finally, since most modelling analyses tend to be rather aggregate at the country and 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. The model includes, among others, 30 different power generation technologies for 57 different countries/regions, and accounts for CO_2 and other GHG emissions. This high level of regional disaggregation allows to a very large extent for a country-specific modelling of technology availability.

POLES has been employed to generate a *reference* baseline and a *nuclear phase-out* baseline. Both baselines rely on the same macroeconomic assumptions: world population is expected to reach 9 billion (i.e. 9000 million) in 2050 (UN, 2009) and global GDP growth is expected to evolve at an average rate of 4% between 2010 and 2020 (and to be more moderate on the long term with a stabilization of around 2% by 2050).

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



The *WEO 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.[1] Global power generation is assumed to grow by 2% and nuclear energy by 1.6% per year between 2010 and 2050 to meet a rising energy demand, in particular in developing countries (see Figure 1).

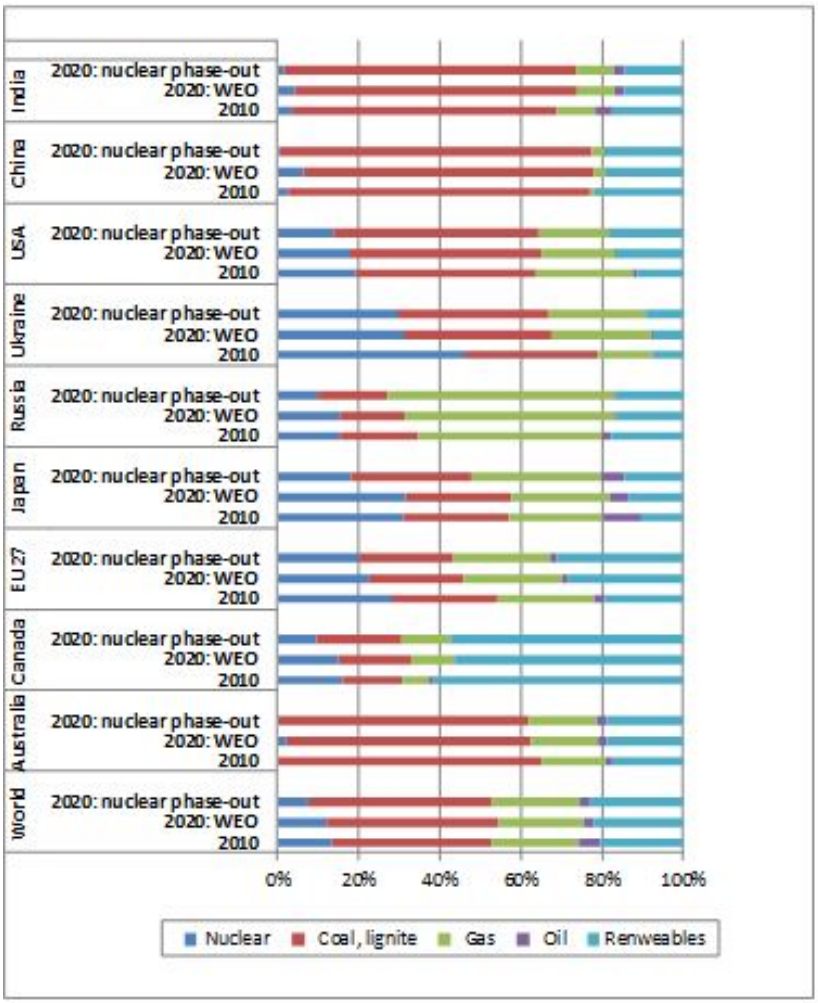
Between 2010 and 2020 global electricity generation in the WEO *reference baseline* is assumed to increase by 34% (from 20 700 TWh to 27 700 TWh). Fossil fuels remain the dominant source of power generation in 2010 and 2020 (share of 65%), with a key role played by coal (about 40%). Between 2010 and 2020, global coal-based power generation increases by more than

[1] In contrast, the New Policies Scenario and the 450ppm Scenario imply additional mitigation policies and measures on different levels of stringency.

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 *WEO reference baseline*, since Germany had decided to phase-out nuclear prior to the Fukushima accident (but at a somewhat slower rate). This also translates into a small decrease in nuclear power generation for the EU in the *WEO 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 (see also Table A1).

Figure 2 Power generation by fuel and country in 2010 and 2020 in both baseline scenarios



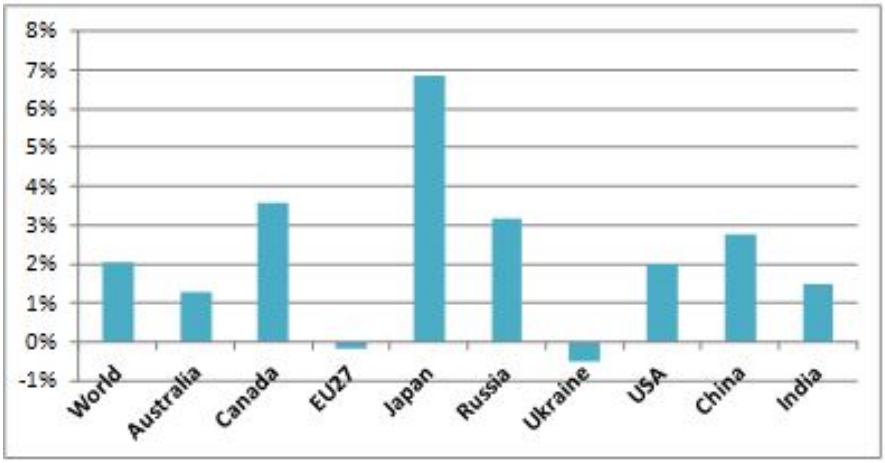
In the *nuclear phase-out baseline* no new nuclear capacities will be built, and existing nuclear capacities are progressively decommissioned over the next four decades. The speed of the phase-out is determined on a country-by-country level, based on the average age of the nuclear power plants. Although by 2050 not all nuclear power plants are phased-out, the production of electricity from nuclear power plants is reduced by that time to about 1% (i.e. 500 TWh) of global power generation, compared to 11% in the *WEO reference baseline*. In the medium term, nuclear power accounts for about 12% (3˚350 TWh) of global power generation in the *WEO reference baseline* by 2020, but only 8% (2 100 TWh) in the *nuclear phase-out baseline* by 2020.

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 2and Table A1). 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 *WEO reference baseline (see also Table A2)*. 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 *WEO reference baseline* tend to experience a significant increase in GHG emissions, in particular Japan, Canada and Russia (see Figure 3). In Japan, the nuclear phase-out increases GHG emissions by 7% (80 Mt CO_2e) in 2020, even though two-thirds of power generated from nuclear plants is replaced by natural gas (and not by coal). 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 *WEO baseline* in 2020. For example, in Finland or Sweden, where nuclear energy plays a key role and where specified renewable support policies are deployed, the power mix in the *WEO reference baseline* largely relies on a mix of nuclear and renewable energy. A nuclear phase-out then leads to a substitution of nuclear power plants by renewable energy technologies and higher energy prices (compared to the *WEO reference baseline*). In turn, higher energy prices lead to lower energy demand and also to lower CO_2e emissions compared to the *WEO reference baseline*.[3] 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 *WEO reference* baseline.

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



4 Policy scenarios

Our policy scenarios include GHG emission targets for Annex I and non-Annex I countries for 2020 that are deemed consistent with meeting the 2°C target. For these GHG emission targets, we consider two certificates trading scenarios.

4.1 Emission targets for 2020

For the policy scenarios the aggregate emission target for Annex I countries for 2020 is taken from the proposal by the European Commission (2009), 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 many 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.[4] 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 countries which submitted a NAMA (NAMA-NAI) face emission targets in our 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. 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 *WEO reference baseline* to derive these emission reductions.

Table 1 shows the emission reduction targets as percentage of baseline emissions for the *WEO reference* baseline and the *nuclear phase-out baseline (absolute targets are given in Table A2 in the Annex)*. At the global level, the 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 *WEO scenario*, and 30% below emissions in the *nuclear phase-out scenario compared to the respective baselines*. Since baseline emissions are 2% higher compared to the *WEO reference scenario (see Figure 3),* higher emissions reduction are needed in the nuclear-phase scenario to meet the target, more specifically, on average, required emission reductions increase by about 7% in Annex I countries in the nuclear phase-out scenario. In comparison, for non-Annex I countries the policy targets translate into GHG emissions which are 3% below baseline emissions in both scenarios.

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 scenario*, required emission reductions increase from 7% to 9% below baseline compared to *the WEO reference 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.[5]

Table 1 Reduction targets in 2020 (% of baseline emissions) in WEO scenario and nuclear phase-out scenario

	WEO	Nuclear phase-out
Australia*	50%	49%
Canada	50%	49%
EU 27*	78%	78%
Japan	70%	66%
Russia	93%	91%
Ukraine**	136%	137%
USA	63%	61%
Brazil	86%	86%
China	100%	100%
India	100%	100%
Mexico	79%	79%
South Africa	66%	66%
South Korea	70%	70%
Annex I	72%	70%
Non-Annex I	97%	97%
Global	88%	88%

* participates in second Kyoto period

** had not decided on participation in second Kyoto period when analyses were conducted]

4.2 Certificates trading scenarios

Our policy analyses distinguish between an *all trade scenario* and a *KP2 trade scenario*. In the *all trade scenario* all Annex I countries are allowed to trade emission certificates among each

other, i.e. they may exchange Assigned Amount Units (AAUs). In the *KP2 trade scenario*, only those Annex I countries are allowed to trade AAUs, which have committed to a second Kyoto period. Those countries are Australia, Belarus, Croatia, the EU, Iceland, Kazakhstan, Liechtenstein, Monaco, New Zealand[6], Norway, Switzerland and the Ukraine[7]. 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. The *KP2 trade scenario* reflects the ongoing debate on whether countries not participating in the second Kyoto period should be allowed to use the flexible mechanisms such as emissions trading and offsetting credits generated under Joint Implementation or the Clean Development Mechanism (CDM) to fulfill their (non-binding) Copenhagen pledges.

In both trading scenarios 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 in both trading scenarios.

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 Model results

For all countries and regions included in the model, sets of marginal abatement cost curves are generated from the *WEO* and *nuclear phase-out baseline scenarios* 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 *WEO 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 *all trade* and the *KP2 trade* climate policy scenarios.

5.1 All trade scenario

5.1.1 Certificate prices

Table 2 displays the prices of AAUs and the prices of CERs in 2020 in the *WEO scenario* and the *nuclear phase-out scenario*.

Table 2 Certificate prices in 2020 (all trade scenario)

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

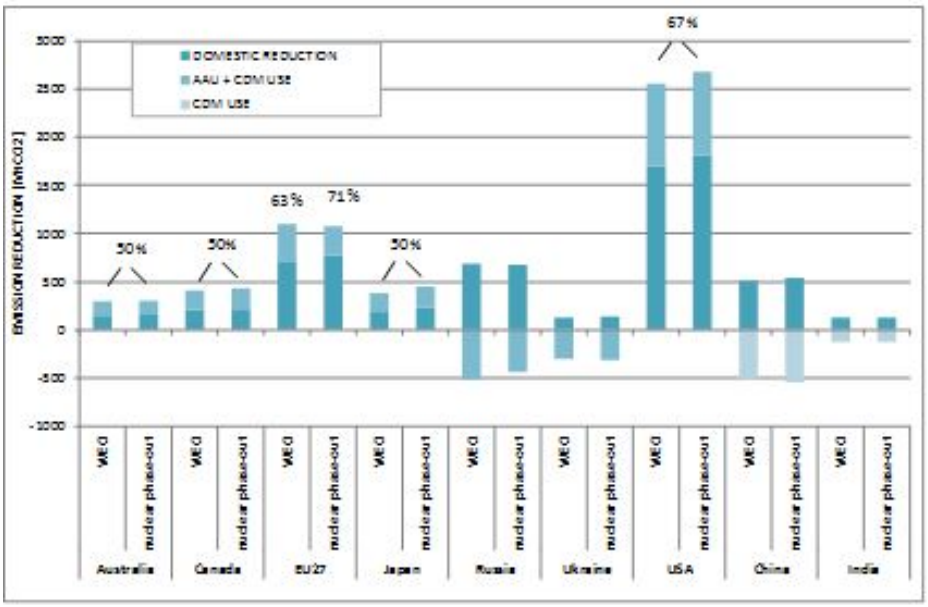
Since trading between Annex I countries is not limited, they face equal marginal abatement costs of 61 €/tCO_2e in the *WEO* scenario, unless their domestic compliance quota is binding. The nuclear phase-out results in an increase in the price of AAUs of about 24% compared to the reference *WEO* scenario. This increase reflects the (small) increase in required GHG emission reductions in the *nuclear phase-out scenario* compared to the *WEO scenario* (baseline effect; see also section 5.1.5) and the fact that nuclear power plants are no longer available as a mitigation option (mitigation cost effect; see also section 5.1.5). Similarly, the price of CERs at 30 €/tCO_2e is about 19% higher in the *nuclear phase-out scenario* compared to the *WEO 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.

5.1.2 Emission reductions and pattern of compliance

For most countries the increase in prices for emission certificates between the *reference* and the *nuclear phase-out 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 policy scenarios versus WEO reference baseline and nuclear phase-out baseline in 2020 (all trade scenario)



Note: negative bars indicate emission certificates or credits sold to other countries; percentage figures indicate the domestic compliance share for net-buyers of certificates

Typically, 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 case*, i.e. *WEO reference baseline*, and *nuclear phase-out baseline*, respectively. 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 slightly lower in the *nuclear phase-out case* than in the *WEO case*. Russia not only faces higher baseline emissions in the *nuclear phase-out 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.

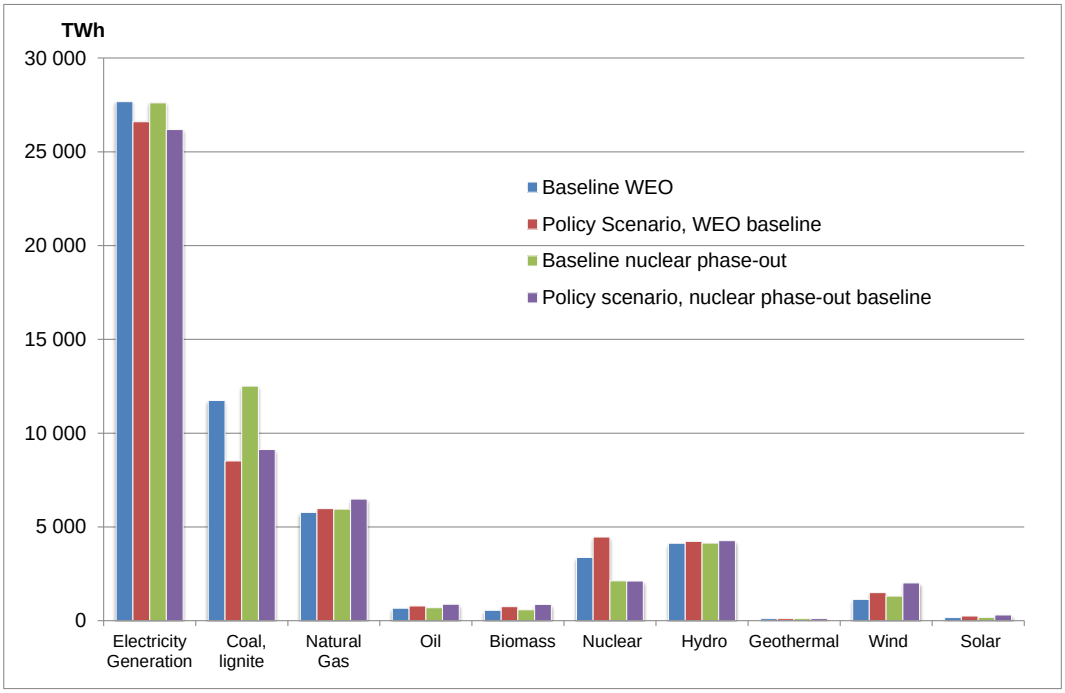
For China and the Ukraine, which are net sellers of certificates, the trading volume is slightly higher in the *nuclear phase-out scenario* than in the *WEO scenario*. In contrast to Russia, countries such as India and the Ukraine, where the share of nuclear power in the reference baseline

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.

5.1.3 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 (*WEO reference baseline* and *nuclear phase-out baseline*). While in the *WEO scenario* nuclear power generation increases notably, in the *nuclear phase-out 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 scenario* compared to the *WEO scenario.* These developments go together with a 4% reduction in both global and Annex I electricity demand in the *WEO scenario* and – because of the fairly stronger deployment of more expensive low-carbon technologies – with a 5% reduction in the *nuclear phase-out scenario*.

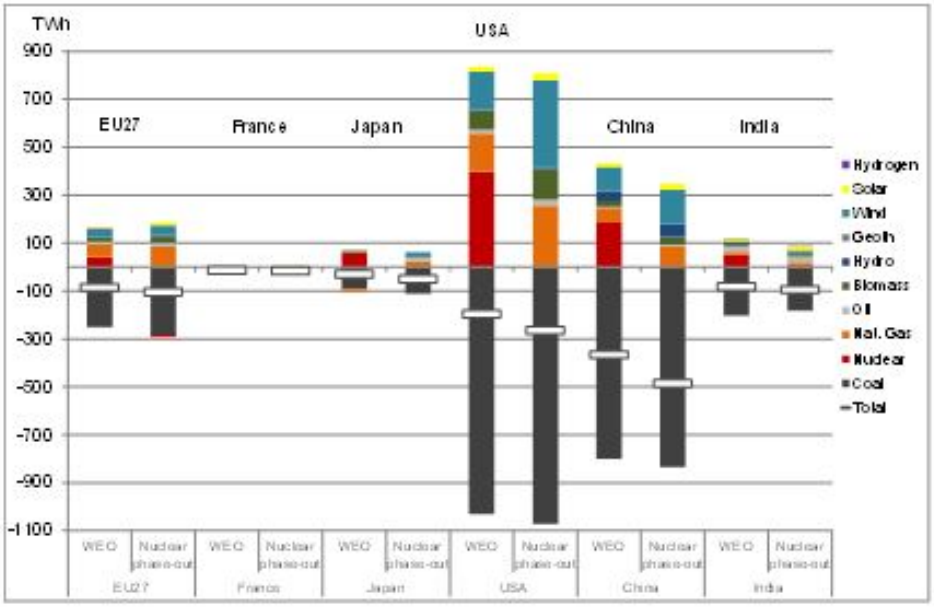
Figure 5 Global electricity generation by fuel in 2020 for baseline and policy scenarios (all trade scenario)



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 (as well as Table A1 in the Annex) show 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 sce-*

nario than in the *WEO scenario*. In the USA and China, the effects are of an order of magnitude larger than in other "high nuclear" countries[2].

Figure 6 Changes in electricity generation in 2020 for high nuclear energy countries (policy scenarios versus WEO and nuclear phase-out baselines)

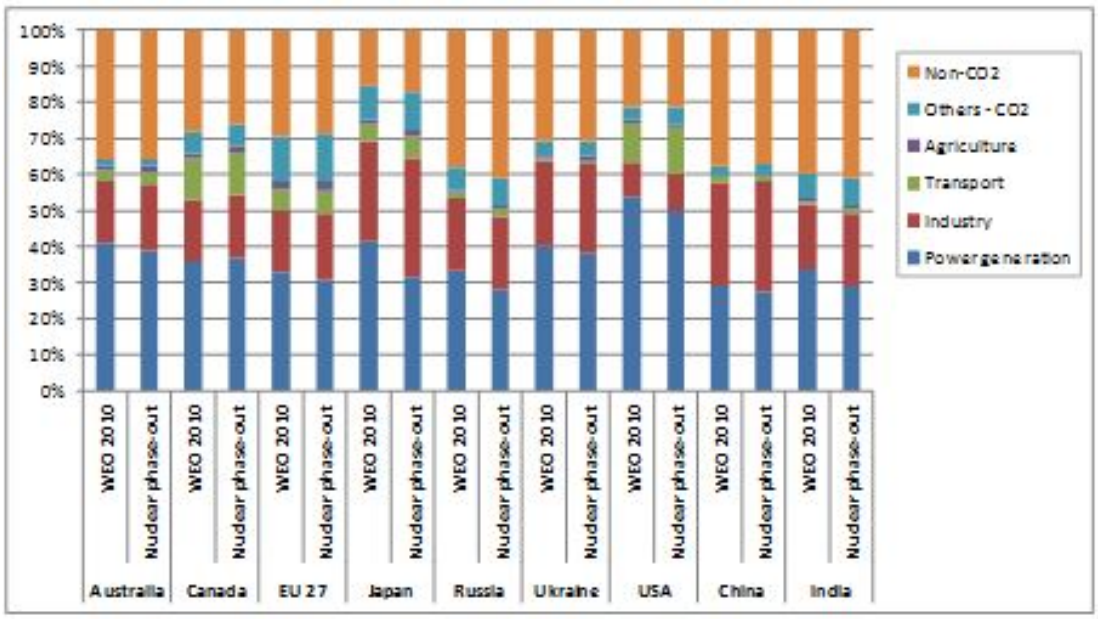


Consequently, all Annex I countries but the EU experience an increase in CO_2e emissions in the power sector in the *nuclear phase-out scenario* compared to the *WEO scenario*. Hence, those Annex I countries need to realize additional mitigation efforts in other domestic sectors or purchase certificates 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, *WEO*) of total emission reductions. As can be seen in Figure 7, the share of the power sector in domestic mitigation efforts is lower in the *nuclear phase-out case* than in the *WEO 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).

[2] Please note that 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 7 Relative contribution of domestic sectors to emission reductions in 2020

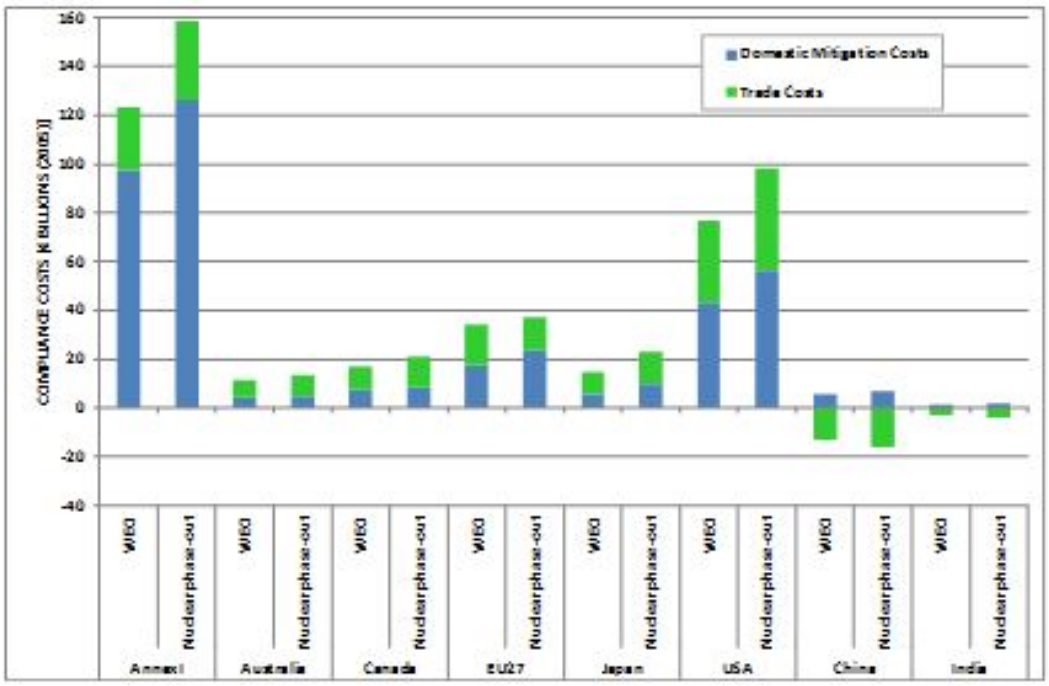


5.1.4 Compliance costs

Compliance costs[3] are measured as the sum of mitigation costs for domestic efforts (domestic mitigation costs) plus the net costs of purchasing and selling certificates (trade costs). The compliance costs in 2020 for the policy scenario compared to both the *WEO reference scenario* and the *nuclear phase-out scenario* are shown in Figure 8. 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% compared to the WEO scenario, but effects vary significantly across countries.

[3] Due to the nature of the model applied in this analysis, macroeconomic effects are not considered here, e.g. increases or decreases in production, imports or exports.

Figure 8 Compliance costs in 2020 (all trade scenario)



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 the EU compliance costs amount to 34 and 37 billion € in the two policy cases. In comparison, Japan faces the highest relative increase in compliance costs (+58%), followed by the USA (+28%) (see Figure 9). In contrast, the Ukraine and Russia, who are net sellers of AAUs, as well as India and China, who are net sellers of CERs, could 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 scenario*. Russia also benefits from the phase-out of nuclear energy, even though it sells fewer certificates in the *nuclear phase-out scenario* compared to the *WEO reference scenario*, but at a higher return (absolute figures on compliance costs can be found in Table A3 in the Annex).

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 9 Change in compliance costs induced by nuclear phase-out (all trade scenario)

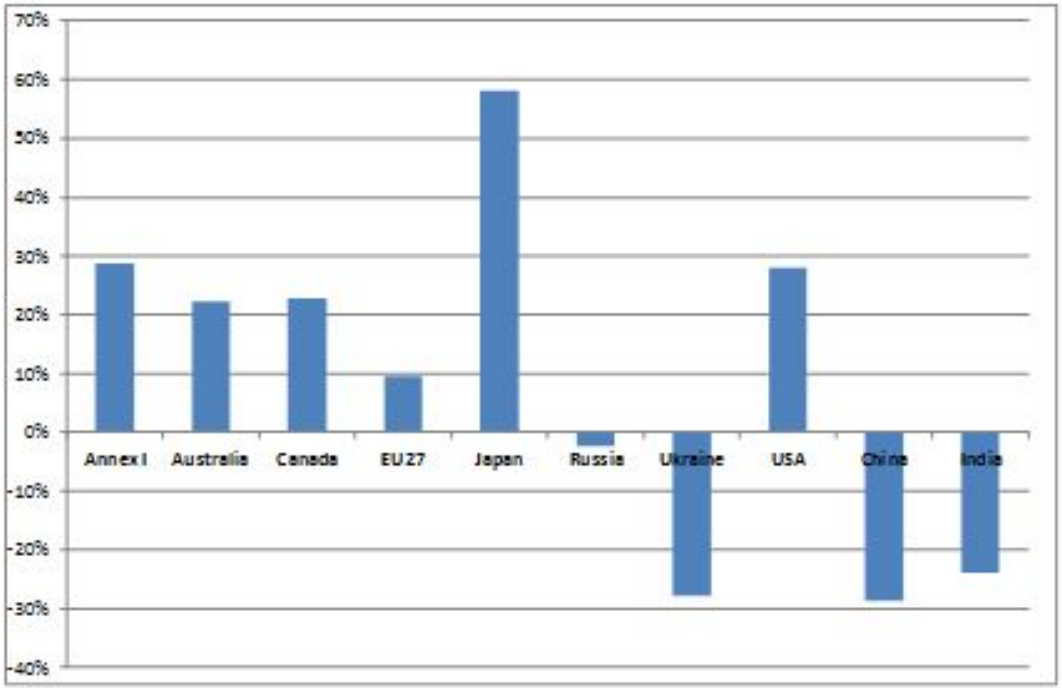


Figure 10 Compliance costs as share of GDP (all trade scenario)

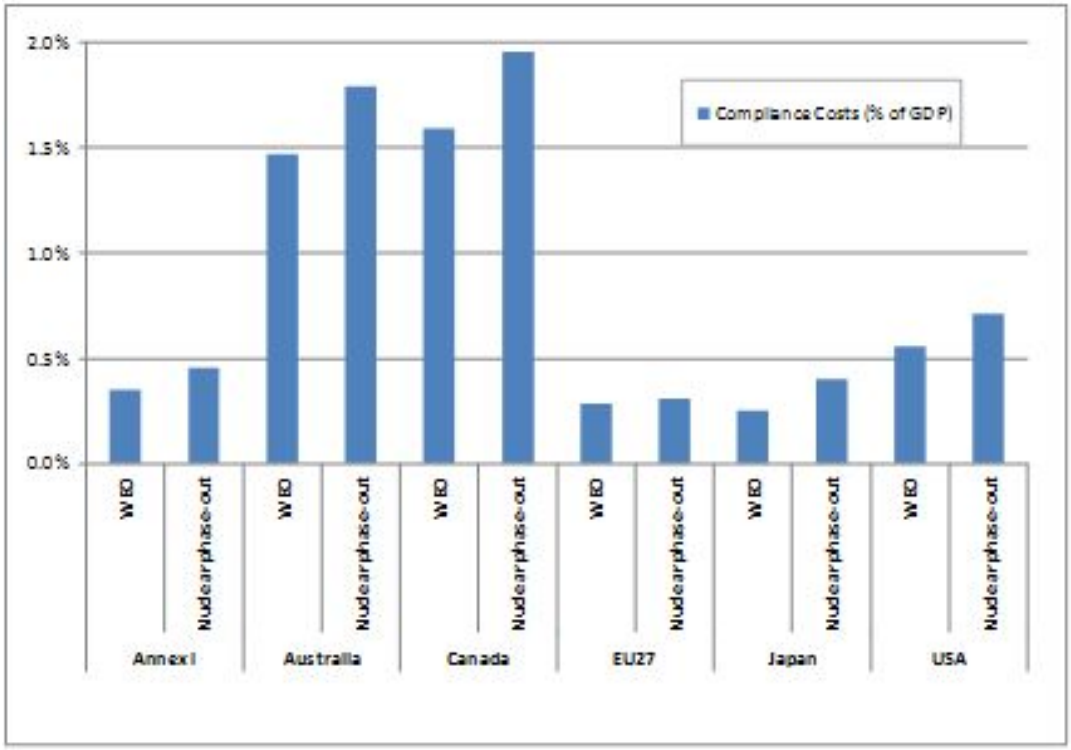


Figure 10 displays the compliance costs as a share of GDP for the group of Annex I countries and for Annex I countries with positive compliance costs. Compliance costs for the entire group of Annex I are around 0.4% of GDP. That is, in general, costs to meet the 30% reduction targets are low, but differences exist across countries. These differences generally depend on the strictness of the targets and the countries' mitigation potential and mitigation costs. Total compli-

ance costs are by far highest in the USA, followed by the EU (see Figure 8). 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, and slightly higher, i.e. between 1 and 2% of GDP, for Australia and Canada (see Figure 10). Likewise, the nuclear phase-out increases the compliance costs as a share of GDP in Annex I countries by only 0.1 percentage points. 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 8), this increase amounts to a relatively small overall economic burden only.

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

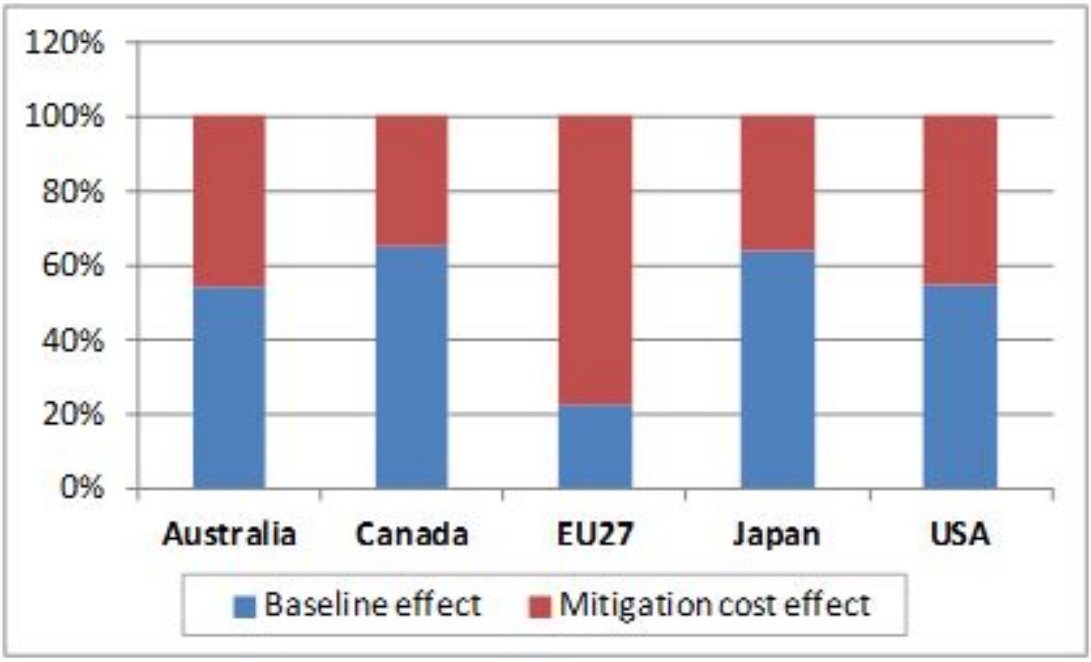
Figure 8 illustrates that the effects of a nuclear phase-out differ across countries depending on the share of nuclear in the power mix and on the importance of nuclear compared to other domestic mitigation options. To gain additional insights into the factors underlying the differences in countries' 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 of each country due to the global increase in baseline emissions in the *nuclear phase-out case* compared to *WEO* (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 in an *adapted baseline policy scenario*, assuming the baseline emissions from the *nuclear phase-out case*, but employing the mitigation cost curves derived under the *WEO reference 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 *WEO reference scenario*. The baseline effect is then calculated as the differences in compliance costs between the *adapted baseline policy scenario* and the *WEO scenario*. Note that, since the phase-out of nuclear energy leads to higher global baseline emissions than in the *WEO scenario*, certificate prices are also higher in the adapted baseline policy scenario.

To quantify the *mitigation cost effect*, we recalculate each country's compliance costs in a *adapted mitigation cost policy scenario*, employing the mitigation cost curves from the *nuclear phase-out scenario*, but assuming the emissions from the *WEO 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* scenario. The mitigation cost effect is then calculated as the differences in compliance costs between the *adapted mitigation cost policy scenario* and the *WEO scenario*.

Any difference in costs between the *nuclear phase-out scenario* and the *WEO scenario*, which cannot be explained by the sum of the baseline effect and the mitigation costs effect, is captured by a residual. The residual is divided proportionally between the *baseline* and the *mitigation cost effect*. Note that for all five countries, the residual is only around 10%. The results of this decomposition analysis are shown in Figure 11.

Figure 11 Baseline effect and mitigation cost effect in 2020 (all trade scenario)



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 in the order of 7% due to the phase-out of nuclear energy. For Japan, the mitigation cost effect only explains around 40% of the compliance cost increase, i.e. the loss of nuclear power as a mitigation option in Japan only accounts for around 40% of the overall compliance cost increase. For the USA, the increase in baseline emissions explains about 55% of the overall compliance cost increase, while losing nuclear as a mitigation option accounts for 45% 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 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 a remarkable increase in baseline emissions (see Figure 3). 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 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 *WEO reference baseline*. For the mitigation costs effect, there is a direct impact (i.e. losing nuclear as a mitigation option), and also an indirect effect.

5.2 KP2 trade scenario

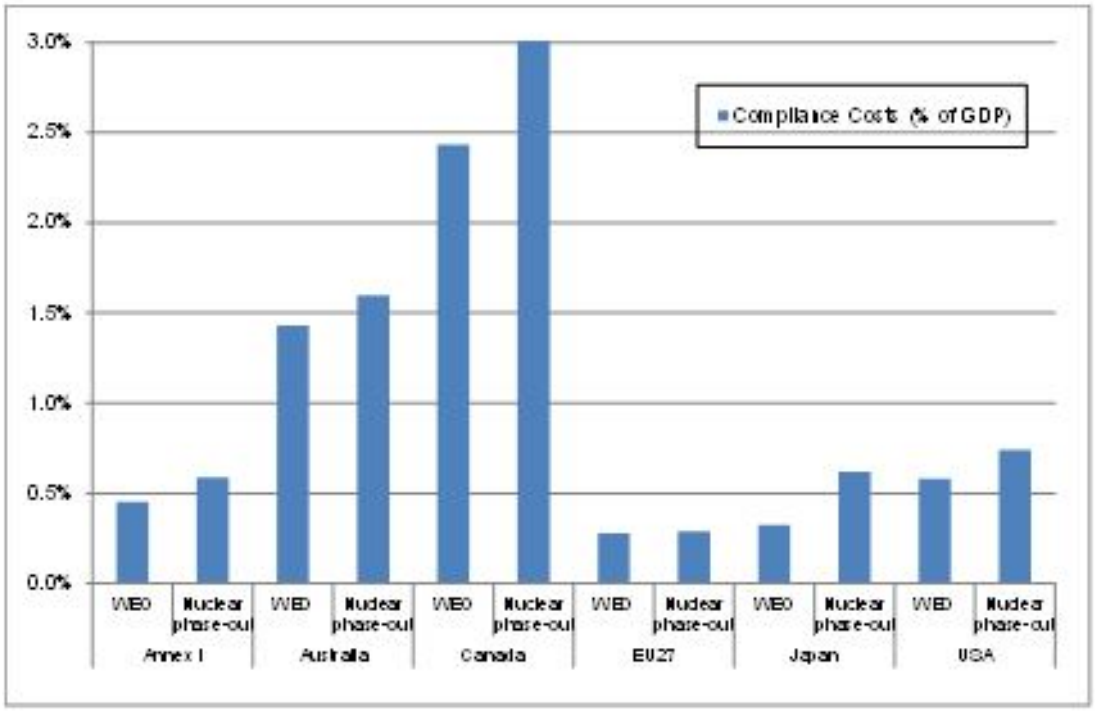
When trading of AAUs (but not CERs) is limited to the countries participating in a second Kyoto period the USA, Japan, and Canada cannot purchase AAUs and Russia cannot sell AAUs. Hence, compared to the *all trade scenario*, certificate prices in the *KP2 trade scenario* are substantially lower. Prices of AAUs are 19% lower (62°€/t CO_2e compared to 76 €/t CO_2e*)* and prices of CERs are 8% lower (28°€/t CO_2e compared to 30°€/t CO_2e*).*

Table 3 Certificate prices in 2020 (KP2 trade scenario

	WEO reference [2005€/tCO_2e]	Nuclear phase-out
AAUs	59	62
CERs	24	28

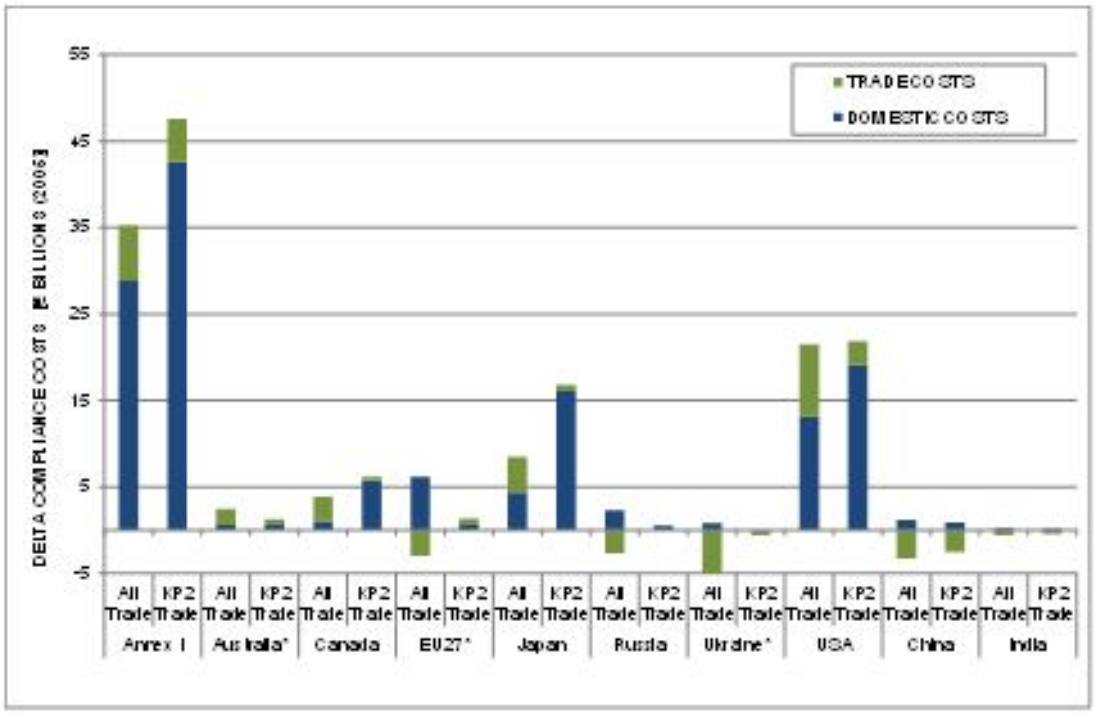
The limit in trading and the resulting changes of both AAU and CER prices lead to differences in total compliance costs for Annex I countries. In the *KP2 trade scenario* total compliance costs of Annex I countries to meet the mitigation targets are 28% higher in the *WEO* case and 29% higher in the *nuclear phase-out case* compared to the *all trade scenario* (see Figure 13). On the one hand, these figures reflect efficiency gains from certificate trading in the *all trade scenario,* as more countries are involved in trading and marginal abatement costs can more efficiently be equalized. On the other hand, they also illustrate that the nuclear phase-out increases global compliance costs when trading of certificates is restricted. Compliance costs as a share of GDP in the KP2 trade scenario are shown in the Figure below and the difference in total compliance costs of the *WEO* and *Nuclear Phase-out scenarios* for each the *KP trade* and *all trade* scenarios are shown in Figure 13.

Figure 12 Compliance costs as share of GDP (KP2 trade scenario)



Both Figures show that the increase in compliance costs due to the nuclear phase-out is more pronounced in those countries that no longer participate in KP trading than in those countries that continue to trade. For countries where certificate trading is no longer feasible, compliance needs to be achieved mainly through domestic action, supplemented by a small share of CERs. In Japan, the nuclear phase-out leads to an increase in compliance costs by about 120% in the all *trade scenario* (see Section 5.1.4). This cost increase amounts to almost 200% if Japan can no longer purchase AAUs from other Annex-I countries (*KP2 trade scenario*; see Figure 13). The main important part of this increase is founded in an increase in domestic compliance costs ().

Figure 13 Differences in compliance costs between nuclear phase-out and WEO scenario (all trade and KP2 trade scenarios)



*country allowed to trade in *KP2 scenario*

Similarly, in Canada the phase-out of nuclear energy increases total compliance costs by about 50%, and domestic compliance costs by more than 500% if Canada is banned from purchasing AAUs (*KP2 trade scenario*). In comparison, in the USA, additional compliance costs due to the nuclear phase-out do not differ much between the *trade all scenario* and the *KP2 trade scenario*. Domestic compliance costs to pursue the nuclear phase-out in the USA are about 40% higher without trade *(KP2 trade scenario)*, but about the same amount is saved on expenditures for certificates. Thus, unlike Japan or Canada, the USA may substitute the purchase of certificates by domestic reductions at rather modest additional costs.

In contrast, in Russia, the additional compliance costs induced by the nuclear phase-out turn from negative costs (Russia is a net-seller of certificates in the *trade all scenario*) to positive costs in the *KP2 trade scenario* because Russia cannot generate any revenue from selling AAUs. In this case, Russia reduces its domestic emissions to just meet its own emission target. The nuclear phase-out doubles these domestic mitigation costs, however to a minor extent.In the *all trade scenario,* the additional compliance costs induced by the nuclear phase-out are lower since the AAUs are generated to receive revenues and the nuclear phase-out has no additional

impact on the strategic decision to generate AAUs. For the other net-seller countries (China, India, Ukraine), less revenue can be generated from selling certificates as prices are lower in the *KP2 trade scenario* than in the *all trade scenario*.

At the same time, countries which face stringent emission targets but which may trade certificates (i.e. Australia, EU) benefit from lower certificate prices in the *KP2 trade scenario*. Because of these lower price, in the *KP2 trade scenario* the additional compliance costs due to a nuclear phase-out are almost 60% lower for the EU and about 50% lower for Australia than in the *all trade scenario*.

In sum, the difference in compliance costs between the nuclear phase-out and the *WEO scenario,* i.e. the additional costs of meeting the targets, for the group of Annex I countries are 35% higher in the *KP2 trade scenario* than in the *trade all scenario*.

6 Conclusions

In the wake of the Fukushima nuclear accident in 2011, support for nuclear power has declined in many countries. 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. Annex I countries are assumed to face a uniform 30% reduction rate compared to their 1990 GHG emission levels. The targets for non-Annex I countries are based on their NAMAs submitted under the Copenhagen Accord / Cancun Agreement. Our country-specific analyses of compliance costs recognize that a nuclear phase-out may increase baseline emissions because nuclear has to be substituted by other fuels (baseline effect), and that nuclear power is no longer available as a mitigation option (mitigation cost effect). We also explore the role of certificate trading on the costs of meeting the climate targets when nuclear energy is not longer available as a mitigation option.

Simulations of the new baseline suggest that a global phase-out of nuclear power by 2050 leads to a drop of the share of nuclear energy from 12% to 8%. However, this reduction is almost entirely offset by a stronger deployment of fossil fuels and slight reduction in electricity demand. As a result, by 2020 global GHG emissions in the baseline increase by 2% under a nuclear phase-out and the emission reductions required to meet the exemplary climate policy targets increase by 3% globally, and by 7% for Annex I countries. For countries with a higher share of nuclear energy in the power mix, this increase may be larger (e.g. 13% for Japan). In comparison, emissions for the EU and most non-Annex I countries are hardly affected in the nuclear phase-out case in the respective time horizon.

The analysis of two policy scenarios towards climate policy, *All Trade* and *KP2 Trade*, respectively, gives the following picture:

When certificate trading is not restricted (apart from the assumed domestic compliance quota of 50%), the nuclear phase-out increases AAU prices by 24% and total compliance costs of Annex I countries by 28%. But these effects differ substantially across Annex I countries. Japan (+58%) and the USA (+28%) face the largest relative increase, while China, India and Russia benefit from the phase-out because the additional revenues from selling certificates outweigh the mitigation cost effect. The increase of compliance costs in the EU are +9%.

In comparison, the increase in compliance costs in relation to GDP is rather modest for the group of Annex I countries, and highest for Australia and Canada (0.3 and 0.4 percentage points). Thus, 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 as compared to the reference case. To meet the 30% emission reduction targets for 2020, domestic efforts in Annex I countries involve the power sector, in particular. As expected, 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 higher generation costs of electricity reduce demand by around 4% compared to the baseline. 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). Under a nuclear phase-out,

generation costs increase stronger than in the *reference scenario*, and lowers the demand by 5% compared to the baseline.

Decomposing the overall changes in countries' compliance costs due to a nuclear phase-out into a baseline effect and a mitigation cost effect yields additional insights. 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.

When trading of AAUs is restricted to those Annex I countries which have committed to a second Kyoto period, Canada, Japan, and the USA can no longer rely on certificate trading for compliance and must intensify their domestic mitigation efforts. Annex I countries which are allowed to trade (e.g. Australia, EU) benefit from lower certificate prices when trading is restricted, while net sellers of certificates such as China or India are made worse off. Compared to the scenario without restrictions on certificate trading, compliance costs of Annex I countries are about 28% higher than in the *WEO reference scenario*, and 29% higher than in the *nuclear phase-out scenario*. These figures reflect the savings in overall compliance costs, which may be realized via emissions trading.

In sum, our results on the costs of climate policy corroborate the thrust of the existing literature which typically finds the costs of complying with the 2°C target to be rather small, when compared to current policy developments. Our results further support those studies in the literature, which conclude that a slow deployment or a phase-out of nuclear energy only leads to a modest increase in global compliance costs, in particular, if trading of certificates is allowed. Hence, in the short-term a nuclear phase-out does not drastically change the global picture with respect to mitigation costs. However, individual effects can be significant as e.g. in the case of Japan which has to be taken into consideration in the context of international climate change negotiations.

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. Thus, 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.

7 References

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Endnotes

1 The new government, which was elected in late 2012, has announced that it would re-evaluate the previous government's decision to abandon nuclear power.

2 Carbon capture and storage technologies are assumed not to be available before 2020. For a more detailed description and applications of the POLES model see, for example, Criqui (2001) or Russ and Criqui (2007).

3 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).

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

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

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

7 Belarus, Kazakhstan and the Ukraine might withdraw again though, because of an amendment to the Kyoto Protocol that requires all nations' emission targets to remain below their average 2008-2010 emission levels in the second commitment period. See Amendment G to the Kyoto Protocol http://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf

Annex

Table A1 Power generation by fuel and country in 2010 and 2020 (TWh)

		Nuclear	Coal, lignite	Gas	Oil	Renewables	Total
World	2010	2797	8166	4420	1068	4225	20675
	2020: WEO	3373	11745	5773	672	6107	27670
	2020: nuclear phase-out	2125	12504	5950	696	6332	27608
Australia	2010	0	188	47	4	51	293
	2020: WEO	7	200	55	8	62	335
	2020: nuclear phase-out	0	205	56	8	62	334
Canada	2010	101	93	40	8	386	636
	2020: WEO	111	130	79	3	408	735
	2020: nuclear phase-out	69	154	86	2	416	733
EU 27	2010	894	832	761	76	616	3180
	2020: WEO	841	848	896	57	1049	3692
	2020: nuclear phase-out	734	852	891	56	1142	3676
Japan	2010	329	281	245	100	112	1065
	2020: WEO	388	325	300	58	164	1234
	2020: nuclear phase-out	224	365	389	69	181	1228
Russia	2010	160	204	472	23	188	1047
	2020: WEO	192	202	646	7	207	1253
	2020: nuclear phase-out	124	217	699	8	208	1256
Ukraine	2010	84	60	24	0	14	181
	2020: WEO	68	79	54	1	16	221
	2020: nuclear phase-out	65	82	52	1	20	221
USA	2010	817	1894	1017	48	484	4260
	2020: WEO	822	2172	832	3	772	4601
	2020: nuclear phase-out	634	2328	796	2	831	4592
China	2010	108	2957	51	3	857	3977
	2020: WEO	461	5051	213	1	1336	7062
	2020: nuclear phase-out	53	5393	232	2	1357	7037
India	2010	34	624	92	40	167	959
	2020: WEO	71	1147	152	38	240	1672
	2020: nuclear phase-out	26	1188	152	39	241	1672
Annex I	2010	2384	3551	2606	259	1851	10661
	2020: WEO	2428	3955	2861	137	2677	12070
	2020: nuclear phase-out	1850	4204	2969	146	2860	12040

Table A2 Power generation - share by fuel and country in 2010 and 2020 (TWh)

		Nuclear	Coal, lignite	Gas	Oil	Renewables
World	2010	14%	39%	21%	5%	20%
	2020: WEO	12%	42%	21%	2%	22%
	2020: nuclear phase-out	8%	45%	22%	3%	23%
Australia	2010	0%	64%	16%	1%	17%
	2020: WEO	2%	60%	17%	2%	19%
	2020: nuclear phase-out	0%	61%	17%	2%	19%
Canada	2010	16%	15%	6%	1%	61%
	2020: WEO	15%	18%	11%	0%	56%
	2020: nuclear phase-out	9%	21%	12%	0%	57%
EU 27	2010	28%	26%	24%	2%	19%
	2020: WEO	23%	23%	24%	2%	28%
	2020: nuclear phase-out	20%	23%	24%	2%	31%
Japan	2010	31%	26%	23%	9%	10%
	2020: WEO	31%	26%	24%	5%	13%
	2020: nuclear phase-out	18%	30%	32%	6%	15%
Russia	2010	15%	19%	45%	2%	18%
	2020: WEO	15%	16%	52%	1%	16%
	2020: nuclear phase-out	10%	17%	56%	1%	17%
Ukraine	2010	46%	33%	13%	0%	8%
	2020: WEO	31%	36%	24%	0%	7%
	2020: nuclear phase-out	29%	37%	24%	0%	9%
USA	2010	19%	44%	24%	1%	11%
	2020: WEO	18%	47%	18%	0%	17%
	2020: nuclear phase-out	14%	51%	17%	0%	18%
China	2010	3%	74%	1%	0%	22%
	2020: WEO	7%	72%	3%	0%	19%
	2020: nuclear phase-out	1%	77%	3%	0%	19%
India	2010	4%	65%	10%	4%	17%
	2020: WEO	4%	69%	9%	2%	14%
	2020: nuclear phase-out	2%	71%	9%	2%	14%
Annex I	2010	22%	33%	24%	2%	17%
	2020: WEO	20%	33%	24%	1%	22%
	2020: nuclear phase-out	15%	35%	25%	1%	24%

Table A3 GHG emissions in 2020 by country (Mt CO2e)

	WEO 2020		Nuclear phase-out 2020	
	Baseline	Target	Baseline	Target
Australia	591	293	599	293
Canada	825	414	845	414
EU27	4990	3897	4978	3897
Japan	1274	888	1342	888
Russia	2493	2325	2557	2325
Ukraine	476	649	474	649
USA	6835	4278	6962	4278
China	14810	14810	15154	15154
India	3609	3609	3657	3657
AI	18337	13477	18620	13483
NAI	33894	32806	34432	33320
World	52231	46283	53053	46803

Table A4 Compliance costs in 2020 for the policy scenarios, all trade

		Compliance costs (billion €)	Domestic Mitigation Costs (billion €)	Trade Costs (billion €)	Compliance Costs (% of GDP)
Annex I	WEO	123	97	26	0.35%
	Nuclear phase-out	159	126	32	0.46%
Australia	WEO	11	4.1	7.0	1.466%
	Nuclear phase-out	14	4.7	8.8	1.792%
Canada	WEO	17	7.4	9.6	1.592%
	Nuclear phase-out	21	8.4	12.4	1.955%
EU27	WEO	34	17.3	16.7	0.283%
	Nuclear phase-out	37	23.5	13.7	0.310%
Japan	WEO	15	5.5	9.1	0.256%
	Nuclear phase-out	23	9.9	13.1	0.406%
USA	WEO	77	43.0	33.6	0.558%
	Nuclear phase-out	98	56.1	42.0	0.714%
China	WEO	-7.5	5.7	-13.2	-0.1%
	Nuclear phase-out	-9.6	6.9	-16.5	-0.1%
India	WEO	-2	1.4	-3.2	-0.1%
	Nuclear phase-out	-2	1.5	-3.8	-0.1%

Table A5 Electricity generation 2020 for high nuclear electricity countries (policy scenarios versus WEO and nuclear phase-out baselines)

TWh in 2020			Electricity Generation	Coal, lignite	Natural Gas	Oil	Biomass	Nuclear	Hydro	Geothermal	Wind	Solar	Hydrogen
World	WEO	Baseline scenario	**27670**	11745	5773	672	560	3373	4131	115	1135	167	1
		Policy scenario	**26597**	8515	5974	786	751	4467	4236	115	1502	251	1
	Nuclear Phase-	Baseline scenario	**27608**	12504	5950	696	584	2125	4137	115	1316	180	1
		Policy scenario	**26186**	9126	6489	878	873	2113	4268	115	2019	305	1
USA	WEO	Baseline scenario	**4601**	2172	832	3	141	822	310	49	232	40	0
		Policy scenario	**4404**	1140	992	19	217	1220	316	49	390	61	0
	Nuclear Phase-	Baseline scenario	**4592**	2328	796	2	150	634	311	49	279	43	0
		Policy scenario	**4328**	1256	1052	27	278	634	318	49	642	71	0
China	WEO	Baseline scenario	**7062**	5051	213	1	56	461	1047	0	217	16	0
		Policy scenario	**6697**	4251	274	5	82	647	1088	0	319	31	0
	Nuclear Phase-	Baseline scenario	**7037**	5393	232	2	58	53	1050	0	232	17	0
		Policy scenario	**6551**	4559	317	9	92	53	1103	0	375	42	0
EU27	WEO	Baseline scenario	**3692**	848	896	57	191	841	360	6	432	60	0
		Policy scenario	**3606**	597	950	68	209	882	364	6	462	69	0
	Nuclear Phase-	Baseline scenario	**3676**	852	891	56	189	734	361	6	520	67	0
		Policy scenario	**3572**	573	977	71	216	722	365	6	561	81	0
France	WEO	Baseline scenario	**622**	28	29	0	8	450	56	0	45	7	0
		Policy scenario	**609**	16	29	0	7	445	56	0	46	8	0
	Nuclear Phase-	Baseline scenario	**615**	8	13	0	3	412	56	0	112	11	0
		Policy scenario	**600**	1	12	0	4	401	56	0	111	15	0
Japan	WEO	Baseline scenario	**1234**	325	300	58	27	388	97	3	27	9	0
		Policy scenario	**1204**	233	289	60	32	447	98	3	32	10	0
	Nuclear Phase-	Baseline scenario	**1228**	365	389	69	33	224	98	3	38	10	0
		Policy scenario	**1178**	253	415	81	35	224	99	3	57	10	0
India	WEO	Baseline scenario	**1672**	1147	152	38	24	71	174	0	59	6	0
		Policy scenario	**1590**	945	166	60	34	122	180	0	65	18	0
	Nuclear Phase-	Baseline scenario	**1672**	1188	152	39	24	26	174	0	61	7	0
		Policy scenario	**1577**	1006	170	65	37	26	181	0	70	23	0