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GLOBAL IMPLICATIONS OF JOINT FOSSIL-FUEL CONSUMPTION SUBSIDIES REFORM AND NUCLEAR PHASE-OUT: AN ECONOMIC ANALYSIS

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NOTE BY THE SECRETARIAT

The Climate Change chapter of the OECD Environmental Outlook to 2050 presented an analysis of various global climate mitigation and energy reform scenarios. The Outlook found that phasing-out subsidies to fossil-fuel consumption to end users in emerging and developing countries may have positive effects for both economic welfare and environmental pressure, i.e. emissions of greenhouse gases. The Outlook showed the value of having sufficient flexibility in the energy system, but also illustrated that future energy systems that rely less on nuclear power are feasible and may be compatible with an ambitious climate policy, albeit at greater cost. The Outlook results also revealed that both nuclear power and fossil fuel-based power with carbon capture and storage (CCS) can be seen as a transitory technology on a pathway to a low-carbon energy system, implying that there may be important interaction effects with fossil fuel subsidy reform.

The present report follows up on the analysis in the Outlook by focusing on the consequences of two hypothetical policies for the global economy and the energy system: a multilateral energy consumption subsidies reform and a progressive nuclear phase-out. It also highlights potential interactions induced by the simultaneous implementation of both policy reforms. It then overlays these policy reforms with a climate change mitigation policy, and presents the increased interaction effects that emerge when carbon emissions are priced, and then identifies pathways for the energy system to achieve these various policy objectives simultaneously at least cost. The report specifically presents quantitative analysis of a stylised representation of these policy reforms using the ENV-Linkages model.

This report was prepared by Bertrand Magné, Jean Chateau and Rob Dellink of the OECD secretariat. The report has benefited from valuable comments on an earlier draft by Helen Mountford, Shardul Agrawala, Anthony Cox and Ronald Steenblik of the OECD secretariat, and feedback from several delegates after the presentation of preliminary results at the WPCID meetings of September 2012 and April 2013. Elizabeth Corbett provided excellent editorial assistance.
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EXECUTIVE SUMMARY

Overview

This report draws upon the OECD’s global recursive-dynamic general equilibrium model ENV-Linkages and provides an in-depth analysis of two policies featured in the Climate Change chapter of the *OECD Environmental Outlook to 2050* (OECD, 2012). The report examines the economic consequences to 2035 and the energy supply mix adjustments of a simultaneous implementation of i) a simultaneous, progressive phase out of fossil-fuel consumption subsidies, leading to reduced demand for fossil fuel energy resources, and ii) a progressive, global phase out of nuclear power, mostly affecting OECD countries, China and Russia. This nuclear policy simulation is purely illustrative and does not reflect a view on actual or proposed policies by countries. Relying less on nuclear power leaves little room to manoeuvre in transforming the energy mix into a sustainable and low carbon system and is likely to increase the costs of such a transformation. The analysis is then transposed in the context of climate change mitigation by adding a carbon pricing scheme to the policy mix. The corresponding implications for economic activity, energy trade patterns and CO$_2$ emissions shed light on the interactions between the three types of policies.

The nuclear phase-out scenario projects a nuclear power capacity halved by 2035 compared with the Baseline; this corresponds to USD 120 billion reduction in value-added of the global nuclear industry for that year. The cumulative reduction to 2035 in nuclear value-added of a progressive nuclear phase-out is USD 1 trillion, to the benefit mainly of operators of conventional fossil fuel power plants. The nuclear phase-out leaves GDP and real household consumption marginally affected in most energy importing countries; negative impacts are concentrated in countries with a large share of nuclear power and relatively few (domestic) alternatives. A multilateral fossil-fuel subsidy reform reduces demand for fuels in previously subsidized developing and emerging economies, thus pushing down international fossil fuel prices and altering the patterns of global energy use, as the lower international prices induce an increase in demand in all countries. When implemented separately, a nuclear phase-out implies increased global CO$_2$ emissions, whereas the fossil-fuel subsidy reform and the joint implementation of both policies result in a decrease in global CO$_2$ emissions. The combined policies help save the equivalent of the total primary energy currently consumed in Russia, mostly thanks to the fossil-fuel subsidy reform. Adding carbon pricing to the policy mix of OECD countries as well as China brings about multiple benefits, reducing their energy bill and achieving large amounts of climate change mitigation at low cost.

Key messages

i. A policy to progressively phase out subsidies to energy consumption is a cost-effective and sustainable way to reduce greenhouse gas emissions and wasteful consumption of fossil fuels.

ii. Progressively phasing out nuclear power would increase fossil fuel demand and GHG emissions and have a negative impact on the economy, which may be significant in some countries.

iii. The overall reduction in energy use that could be achieved in 2035 by non-OECD countries from subsidy phase out corresponds to the volume of energy currently consumed by the entire Chinese power sector alone, in the order of 1100 Mtoe. Globally, combining this with a policy of reducing nuclear capacity could help save about 750 Mtoe of fossil fuel energy, or the equivalent of the total primary energy currently consumed in Russia.
iv. Multilateral reform of fossil-fuel consumption subsidies would reduce the European Union’s oil bill in 2035 by a quarter. The subsidy phase out reform would have an impact primarily on oil exporters, who would experience substantial cuts in trade revenues, primarily because of the reduced global demand. Furthermore, Middle-East energy exporters would progressively take over Russia’s market share thanks to lower costs of oil production; their exports, however, would still be lower than in the Baseline scenario by around 11% in 2035.

v. In the absence of carbon pricing policy, coal and natural gas would be the cheapest substitutes for abandoned nuclear energy, notably in the European Union. Their role would also be further reinforced in those countries where energy subsidies are phased out multilaterally.

vi. In 2035, the total reduction in nuclear sector activity due to a nuclear power phase out policy would account for about USD 120 billion of value-added, with two-thirds of the lost value occurring in OECD countries. The global, cumulative loss to 2035 in nuclear value-added of a progressive nuclear phase-out would be USD 1 trillion. This loss of nuclear activity would lead to increased fossil-fuel electricity generation, whose value-added would increase by USD 80 billion in the absence of new environmental constraints.

vii. The multilateral fossil-fuel subsidy reform would lead to a 0.5% increase in global GDP in 2035. Indonesia and India would see the largest benefits in terms of economic growth. The simulated policy of a progressive abandonment of nuclear energy would result in negative consequences on GDP in countries which rely more heavily on nuclear energy.

viii. By 2035, energy subsidy reform would be expected to boost economic activity as it reduces an inefficient market intervention. At a global level, the multilateral energy subsidy reform implies a reduction in global energy demand that in turn reduces international energy prices. This translates into a net increase of value-added created by energy intensive industries of more than USD20 billion in 2035. Only industrial activities in the Middle-East and to a lesser extent in Russia are negatively affected by the multilateral fossil-fuel subsidy reform, since energy prices paid by firms increase in these regions. The nuclear power phase out policy, when implemented alone, barely influences the activity levels of energy intensive industries as the impact on electricity prices remains limited.

ix. Applying an exogenous carbon tax to the power sector and energy intensive industries in OECD countries and China (by 2035 the assumed carbon tax reaches USD 100 per tonne in OECD countries and USD 50 per tonne in China) would induce significant switching towards renewable energy, the share of which in the global electricity mix would increase from 28% to 55% relative to the Baseline. The applied carbon tax would deliver CO2 emission reduction that outstrips the extra release of carbon stemming from less nuclear energy in the mix. The full policy package, including energy subsidy phase out, nuclear power phase out and carbon pricing, would lead to a 9% cut in global CO2 emissions, as the emissions increase from nuclear power phase out is small compared to the emission reduction impacts of the fossil-fuel subsidy reform and the carbon tax.

x. The full set of policies would reduce global GDP by 0.3% below the Baseline. Households would also modify their consumption patterns. The qualitative direction of country effects is comparable to GDP deviations but the magnitude is slightly larger.

xi. While there are mechanisms linking the different policies, not least through connected international energy markets, economic interactions between the nuclear power phase out policy and the other policies examined in this report are limited. Interaction effects could be stronger if the analysis were extended to include a wider set of policies such as a reform of support on fossil fuel production or use in OECD countries, an enhanced public support to renewable energy deployment or a wider carbon pricing regime. However, the potential for energy fuel switching within the energy system limits spill-over effects to the rest of the economy, as shown by simulations for e.g. China.
GLOBAL IMPLICATIONS OF JOINT ENERGY SUBSIDY TO CONSUMER REFORM AND NUCLEAR PHASE-OUT: AN ECONOMIC ANALYSIS

1. Introduction

1. In 2009, G20 leaders adopted a declaration to “rationalize and phase out over the medium term inefficient subsidies to energy consumption that encourage wasteful consumption”. The joint IEA, OPEC, OECD, and World Bank reports (2010 and 2011 update) show that substantial energy subsidies to consumers are in place in emerging and developing countries, while OECD countries use a combination of tax expenditures and direct budgetary support to fossil fuel producers and consumers. Currently more than half of the subsidies in emerging and developing countries result in under-priced electricity or the burning of more coal and natural gas. The other half favours oil consumption. Phasing out such subsidies can provide environmental gains, not least through lower emissions of greenhouse gases, and potentially also be welfare improving (Burniaux and Chateau, 2011; OECD, 2012). As fossil fuel policy reform gains momentum worldwide, it will progressively restore electricity prices that better reflect generating costs, and will reduce reliance on fossil fuels by driving investments towards alternative low-carbon energy technologies.

2. In parallel, nuclear power may be seen as a bridging and competitive element of the energy mix in the transition towards a decarbonised economy. Following the March 2011 accident at Japan’s Fukushima nuclear power station, nuclear power faces significant policy uncertainty in some countries; Germany, Switzerland and Belgium, have decided to cancel license renewals for nuclear power plant operators or are contemplating shutting down nuclear power plants. See Kurosawa and Hagiwara (2012) for an assessment of the consequences of nuclear phase-out in Japan; CDC Climat (2012) and Keppler (2012) discuss the economic consequences for Germany; Bretschger et al. (2012) focus their analysis on the Swiss economy; Bauer et al. (2012) carry out a global assessment.

3. This paper examines the mid-term economic consequences and the changes in the energy technology mix of a simultaneous implementation of i) a progressive fossil-fuel subsidy reform in emerging and developing countries and ii) a progressive global phase out of nuclear energy, affecting mainly OECD countries and Russia with large existing nuclear power capacities, together with China and India, where the prospects for development of newly-built nuclear capacity are by far the largest. This nuclear policy simulation is purely illustrative and does not reflect a view on actual or proposed policies by countries. The analysis is then transposed in the context of climate change mitigation to depict the corresponding implications for CO₂ emissions, to assess the interactions between the two energy policies, and to derive how the associated costs are affected by the different policies. The interactions between the different policies are described in a stylised setting where carbon pricing and markets emerge progressively in developed economies as well as in China. Other countries, including for instance OPEC countries and most of the developing world, are assumed to conduct domestic energy consumption subsidies reforms without adopting any carbon pricing policy.

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1 Ellis (2010) gives a comprehensive overview of modelling and empirical studies to study the effects of the fossil fuel subsidy reform.
4. Relying less on nuclear power leaves little room to manoeuvre in transforming the energy mix into a sustainable and low carbon system. The combination of these two policy changes could stimulate a quicker deployment of alternative technologies, including renewables, at moderate costs. This would underline the importance of policy measures to enhance energy savings measures as the main mitigation instrument in the medium-term across the entire spectrum of activities (IEA, 2012, Chateau et al., 2014a). But this situation is complicated by endogenous feedback effects as energy markets are internationally tightly linked and competition occurs among energy sources. Thus, even if these policies occur in different countries, they mutually affect each other and the outcome for the energy system, the economy and the environment are not a priori clear. Potential policy conflicts between an energy subsidy reform and a nuclear phase-out may arise. Consequently, an applied numerical assessment is warranted to identify the direct and indirect effects of these policy changes.

5. The policy orientations at stake and the richness of the modelling framework employed in this analysis provide fertile ground to confront and discuss their multi-dimensional aspects. For example, it can provide insights into the potential additional economic burden stemming from higher energy prices as faced by some consumers. Indeed, earlier OECD analysis has shown that reforming the subsidies to energy consumption can in itself be welfare enhancing to the extent these subsidies are inefficient (Burniaux and Chateau, 2011). However, in the absence of yet-economical alternatives to oil products or coal, natural gas and nuclear energy for power generation, transport fuels and electricity prices to end-users in the countries that undertake this policy reform are likely to increase, thereby leading to an expected reduction in fossil fuel demand. In turn, this reduced demand for fossil fuels would lower global fuel prices, and therefore induce an upward push on fuel demand in (mostly OECD) countries that do not reform their energy policies. The responses of household welfare and the activity levels of productive sectors to changes in energy retail prices as well as other induced price changes consecutive to the reforms are inspected.

6. The energy trade implications of these policies are also discussed by distinguishing countries that are primarily energy producers from those that are mostly energy consumers: many major oil and natural gas exporters are fast growing economies that are sensitive to fossil-fuel subsidy reforms while several have been considering the development of domestic nuclear power programmes in parallel; their counterparts, essentially certain OECD countries, may mobilize funding for more expensive technologies with greater ease to address both policy issues and to reconcile them with longer run climate objectives.

7. This paper is structured as follows. Section 2 outlines the rationale for the analysis and introduces the modelling approach. Section 3 discusses the results of the two energy policies in absence of a climate change mitigation policy, while Section 4 adds climate policy to the mix. Section 5 concludes.

2. Rationale for the analysis and modelling approach

8. This section is devoted to the introduction of the modelling strategy, to the presentation of current trends in the energy landscape and to the key policy elements under examination.

2.1 The ENV-Linkages modelling framework

9. It is expected from a theoretical point of view that both policies, on subsidies to energy consumption and nuclear power availability, when taken in isolation, might bring about opposite outcomes, be it on the extent of fossil fuel reliance, on welfare implications or on derived CO₂ emissions. The policies induce various intra- and intersectoral energy fuel competition, in addition to macro-economic effects. Coal-fired, gas-fired and nuclear power plants compete for electricity generation while all end-users, i.e. production sectors and households, adjust their direct usage of all fossil fuels — namely refined oil, coal and natural gas — according to relative price changes. As baseload nuclear-based electricity generation is often one of the cheapest sources of electricity in terms of direct costs (OECD, 2010), phasing-out nuclear
would likely increase electricity prices relative to fossil-fuel prices. Similarly, reforming the support schemes of fossil fuel consumption is notably motivated by the expected increase in the prices of fossil fuels relative to prices of other primary factors, including capital, labour and natural resources. An applied global computable general equilibrium (CGE) framework is an appropriate analytical framework to draw quantitative conclusions about the sign and magnitude of these opposite effects. The analysis presented here is based on the OECD ENV-Linkages model, a global CGE model, featuring recursive dynamics and capital vintages. In recent years this model has been extensively used to study various impacts of fossil-fuel subsidy reforms (Burniaux and Chateau, 2011, Burniaux et al., 2011, the IEA, OPEC, OECD, and World Bank joint report, 2011). The climate change mitigation and energy technology scenarios conducted by the OECD for its 2012 Environmental Outlook to 2050 draw upon the same simulation tool. The model version used in this paper has benefited from a major baseline calibration overhaul compared with that contained in the Environmental Outlook in order to reproduce accurately most energy trends from the IEA Current Policies Scenario (IEA, 2012) for the period 2011-2035. The modelling framework used for the analysis is briefly described in Annex A1; an extensive description of the model can be found in Chateau et al. (2014b).

2.2 Representation of the policies

A stepwise procedure is followed to analyse the possible interactions, or possible conflicting outcomes, notably in terms of CO₂ emissions, of a multilateral fossil-fuel subsidy reform and a progressive, global nuclear power phase-out. The global economic impacts of implementing such policy reforms are underpinned by the following complex mechanisms:

- The behaviour of key energy suppliers and the endogenous competition between energy sources to transform energy into usable form (e.g. electricity and oil products)
- The end users (i.e. firms and households) reactions to endogenous price changes
- The significant effects on international trade dynamics

The impacts are felt even beyond those countries that implement the policy changes.

For the sake of clarity, each policy element is taken in isolation and then implemented in combination with each other. These two scenarios are sometimes referred to as the FF Sub and the Nuke scenarios and as the FF Sub & Nuke scenario when jointly implemented. In a further step, some illustrative elements of climate change mitigation policy are factored in to analyse further interactions and changes in relative prices of energy sources with CO₂ pricing schemes.

While the fossil-fuel subsidy reform and the nuclear power phase-out policies will be jointly examined, they remain largely sequential in nature because of the assumed pace of their respective implementation. Indeed, this fossil-fuel subsidy reform is assumed to take place progressively and terminate in 2020 whereas the bulk of nuclear power plants retirements, driving overall nuclear power capacity down in the absence of replacement, is modelled in this illustrative scenario to take place after 2020 even if the policy reform is implemented earlier.

a. A multilateral fossil-fuel subsidy reform scenario

Current trends in energy consumption subsidies

The current trends in energy consumption subsidies depicted below, and the absence of measures to reduce the heavy reliance on fossil fuels to meet rising energy demand, particularly in emerging and developing countries, provide the foundation of the Baseline scenario. The advantage of fossil fuel subsidy
reform for energy consumers has gained recognition worldwide. However, despite widespread acknowledgement of its policy benefits in terms of economic efficiency, alleviation of trade distortions, equity, energy security, resource conservation or environmental protection, only limited progress towards reform has been made. Despite some progress in recent years, current levels of subsidization remain high in several countries (Figure 1). In 2011, fossil-fuel consumption subsidies in developing and emerging economies totalled USD 523 billion (IEA, 2012), while in OECD countries tax expenditures and other measures supporting fossil fuel production and consumption amounted to USD 55-90 billion per annum in recent years (OECD, 2013). Households are the largest beneficiaries of consumption subsidies. More than half of global spending on fossil fuel consumption subsidies concern oil used for personal transportation or residential electricity and natural gas usage. Russia, China and India together accounted for a fifth of the fossil fuel consumer subsidies in emerging and developing countries, representing 73% of coal subsidies, 21% of natural gas subsidies, 12% of oil subsidies and 31% of electricity subsidies (IEA, 2012). Koplow (2012) reports recent but isolated efforts to revisit these subsidies in countries such as China and India. Indonesia and Mexico have conducted reforms with partial success so far.

![Figure 1. Volume of fossil-fuel consumption subsidies by fuel for selected countries in 2011](source: IEA (2012a))

**Policy reform**

14. The subsidy removal posited here is assumed to be implemented progressively from 2013 to 2020 in all countries where subsidies are currently in place, eventually leading to total elimination by 2020. Government savings from energy subsidy removal are returned to consumers via lump sum transfers. As mentioned earlier, support for fossil fuel production in OECD countries is not included in this analysis, because it has not been possible as yet to reflect this support in the modelling framework.

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2 Bazillion and Onyeji (2012) point at infrastructural and institutional deficiencies which are not appropriately factored into the decision-making process of reforming the support to fossil fuel consumption and which may make these policies sometimes ineffective.

3 The IEA dataset contains fossil-fuel subsidies to end-users in 35 non-OECD countries in addition to two OECD countries, Mexico and South Korea.
b. **Nuclear power phase-out scenario**

**Current trends in power plant constructions**

15. Some of most ambitious plans to build new power plants in coming years are being made by non-OECD countries. Over the next 20 years, only coal-fired electrical capacity is expected to decrease significantly across OECD countries. This is partly due to expected efficiency gains in installed coal power plants, but mostly due to a progressive switch to gas-fired power plants, particularly in the United States, where shale gas exploitation has been transforming the energy landscape for the last decade. The countries experiencing the fastest economic growth and sustained energy needs, including China and India, are currently building considerable amounts of new coal, natural gas and nuclear power capacity. In the IEA New Policies Scenario, China and India combined account for about 60% of the coal-fired capacity built by 2035 (IEA, 2012). As plants currently under construction are shaping future energy capacity, much of the energy system will be locked into a high fossil fuel dependency for several decades to come unless ambitious policies are introduced to reverse such trends.

16. Nuclear power generation in the Baseline scenario is calibrated to reproduce the IEA Current Policies Scenario of the World Energy Outlook 2012 (IEA, 2012). Both Baseline and nuclear phase-out global capacities are shown in Figure 2. Mid-term projections in both the Baseline and the policy cases take into account detailed existing capacity and planned constructions on a country basis. They are derived from the IAEA Power Reactor Information System (PRIS) database.

**Figure 2. Regional nuclear power capacity projections in the Baseline and assumed in the Nuclear Phase-Out scenario**

![Nuclear Power Capacity Projections](source)

*Source: OECD analysis based on IAEA PRIS Database.*

**Policy reform**

17. The net installed nuclear power capacity in the Nuclear Phase-Out scenario is determined exogenously. The nuclear power phase-out scenario rests on the hypothetical assumption that governments...
decide unilaterally to opt out of nuclear energy. The stylised scenario assumes that current plans for building new nuclear plants are maintained until 2020, but that no new construction plans will be approved afterwards thereafter. Existing plants will serve their economic lifetime and will not be dismantled prematurely. Therefore, differences between Baseline trends and Nuclear Phase-Out scenarios materialize only after 2020. The motivation or rationale for countries to opt out of nuclear is not specified or discussed in this analysis, and the stylised scenarios are not meant to reflect a perspective on actual changes in existing policies. Consequently, the simulations are purely meant as hypothetical illustrations of a "what-if" scenario. The nuclear power phase-out scheme assumes a global implementation for the sake of simplicity.

According to the Nuclear Phase-Out scenario, global capacity still rises significantly in the coming years and will be 30% higher than current capacity. The Russian nuclear capacity in 2020 would be 42% higher than today’s level. China’s capacity would quadruple by 2020. These trends reflect Japan’s 7.5GW capacity loss after the Fukushima accident. The trends also reflect German, Swiss and Belgian plans not to replace existing capacity as well as France’s decommissioning of the Fessenheim power plant by the end of 2016. Overall, the capacity installed in 2035 is broadly in line with the IEA Low Nuclear Case scenario (IEA, 2011, chapter 12). By 2020, cumulative nuclear power capacity additions across OECD countries would represent a quarter of the total projected 100 GW. Remaining additions would be built in the BRIC countries, with China alone representing over half of that new capacity. Nuclear fleet expansion in other countries would be negligible. The estimated world nuclear power capacity in the nuclear phase-out scenario reaches about 430 GW in 2020, starting from the current 390 GW, and falls to about 280 GW by 2035, a 55% reduction compared with the Baseline. Average nuclear capacity factors reflecting WEO 2011 nuclear power generation trends by country are then applied to installed capacities to derive nuclear power production constraints. Table A.2 in the Annex provides further details on nuclear power capacity additions and retirements by country and by scenario over the projection period.

3. Effects of multilateral fossil-fuel subsidy reform and nuclear power phase-out without carbon regulation

3.1 Impact on energy use

The multilateral subsidy reform (FF Sub scenario) makes fossil fuel energy more expensive to end-users in (mainly non-OECD) countries implementing it. The reduced fossil fuel demand in large countries conducting the reform puts a downward pressure on international prices. This reduces the reference international oil prices by 11% in 2035. In turn, OECD countries would face lower energy prices and increase their consumption of coal and natural gas, albeit moderately. This leakage effect is highlighted in Burniaux and Chateau (2011). However, the decrease in fossil-fuel energy demand in non-OECD countries more than offsets the demand stimulus in OECD countries. As such, the overall impact of the reform is an international price decrease of all fossil fuels, relative to Baseline levels, and an expected reduction in fossil fuel consumption globally (Figure 3).

In the absence of incentives to move away from fossil fuels (e.g. through carbon taxes or enhanced support to the deployment of renewable energy), the reduced reliance on nuclear energy in the Nuke scenario is the source of extra fossil fuel use to produce electricity. Coal and natural gas substitute for nuclear power in countries where nuclear capacity grows significantly under Baseline conditions, i.e. China, India, Russia, South Korea and the United States. In the same spirit, it should be noticed that even in the case of energy subsidy reform alone the generation of renewable-based electricity will decrease. The reason for this decline in use of renewables is that the reform of the electricity subsidy to consumers leads to a reduction in total electricity production, from all sources, and hence also from renewables. The relative

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4 In our modelling framework, the nuclear phase-out takes the form of a constraint (i.e. an upper bound) on the activity level of the nuclear sector.
prices of electricity production are not affected by the consumer subsidy reform, and hence there is no incentive to increase the renewables share in electricity generation.

**Figure 3. Per cent deviation in primary energy by fuel type in 2035 relative to Baseline w/o additional policy**

When both policies are conducted in parallel, and without carbon regulation, interaction effects are small and both effects are almost additive. The impact of the fossil-fuel subsidy reform dominates the impact of the nuclear power phase-out because the reform covers all sectors of energy consumption, does not only apply to electricity production, and is much broader in scope. The overall reduction in energy use achieved in 2035 by non-OECD countries corresponds to the volume of energy currently consumed by the entire Chinese power sector alone, that is to say 1 100 Mtoe. Globally, the combined policies help save about 750 Mtoe of fossil fuel energy, which is equivalent to the total primary energy currently consumed in Russia.

### 3.2 Impact on energy trade patterns

The fuel switch generated by fossil-fuel subsidy reform and by opting out of nuclear power has direct and significant impacts on energy trade patterns and security of supply for large energy importers. These policies encourage countries importing large volumes of primary energy to adjust their fuel mix, to change their energy supply sources, and thereby potentially reduce their energy spending. Alternatively, some large energy exporters see their exporting revenues sizeably reduced, as explained below. Table 1 provides an overview of adjustments in net trade flows of oil, natural gas and coal for key importing and exporting countries, as percentage deviations from the Baseline. More details on non-energy related trade effects of phasing out fossil-fuel consumption subsidies can be found in Burniaux et al. (2011).

As seen in the previous section, most OECD countries would benefit from lower international energy prices induced by the subsidy reforms carried out by their non-OECD counterparts. Natural gas prices decrease the most, relatively, which creates an opportunity to enhance the switch from coal to gas and possibly help comply with regulatory constraints on CO₂ emissions. The reform amplifies current trends to diminish reliance on petroleum products in OECD countries, as stringent fuel economy standards
encourage the adoption of more efficient vehicles. Consequently, the European Union sees its oil bill decreasing in 2035 by an additional quarter, relative to the Baseline case. Korea’s oil imports decline by about 8%, although oil import volume increases slightly. This is a result of lower international oil prices once subsidy reform is implemented. Multilateral fossil-fuel subsidy reform is primarily detrimental to African and Russian oil exports which lose 27% and 17% in value respectively in 2035, primarily because of reduced global demand. Middle-East countries, whose breakeven production costs are lower, progressively gain market share; nonetheless, their exports fall by only about 11% in 2035 compared with the Baseline Scenario. Since oil remains an uneconomical means to generate electricity in most countries, it does not compete directly with nuclear energy. Therefore, a policy aiming solely to lower reliance on nuclear energy would have insignificant effects on the oil bill of key importers.

24. Coal and natural gas would be both directly affected by fossil-fuel subsidy reform and the nuclear power phase out. OECD imports of fossil fuels follow similar patterns, but the effects on coal would be more pronounced: it appears to be the fuel of choice to replace nuclear power plants, to the detriment of environment. In the Baseline, nuclear power capacity sees the largest increase in South Korea (+36% by 2035), right after China. This large capacity increase and its heavy dependence on fossil fuel imports make South Korea particularly exposed to such nuclear phase-out policies. Phasing out nuclear power in South Korea after 2020 would lead to a large increase in natural gas and coal imports (in value terms), rising to 24% in 2035. Adding the subsidies phase-out to this approach maintains the role of coal as a substitute for nuclear energy in South Korea. This extra consumption of coal would be partly counterbalanced by reduced expenditures on natural gas. Similarly, the European Union also would be expected to increase its dependence on coal and gas in the case of joint fossil fuel subsidy reform and enhanced nuclear power plants decommissioning. The potential for natural gas consumption growth in the European Union remains more limited than in South Korea, because a lot of switching from coal to natural gas has already taken place in the European Union and because of its emissions and renewable energy targets for the year 2020 as stipulated by EU climate and energy package.

25. As the current scale of support to fossil fuel consumption in China is modest, conducting a subsidy reform would lead to a limited increase in fossil fuel prices domestically which would be off-set by lower international prices for natural gas. The overall effect in China would be a modest down swing in gas imports, which diminish by less than 2% in the mid-term, starting from a low base. A slow decline in coal imports would occur in the longer run when only subsidy reform is conducted. When nuclear power plants are removed from the electricity mix, the demand for imported natural gas and coal would resume moderate growth (+5%) later in the projection period when import volumes are far greater. Despite a decrease in domestic gas consumption following subsidy reform, Middle-East countries are expected to grow gas exports by almost 10% in 2035 in the policy scenario, taking over Russian market shares. Russia and Australia would reinforce their positions as leading coal suppliers, increasing their coal export revenues by 5% to 10% in 2035, when both policies are implemented.

26. The United States have been experiencing profound changes in their energy landscape over the past decade with the fast development of shale oil and shale gas exploitation as emphasized by the IEA (2012). The increase in domestic primary energy production together with the implementation of the policies assumed in this analysis would further reduce their reliance on foreign oil in the long run (not shown).

27. Without carbon pricing or other carbon emission regulations, fossil fuels directly compete with nuclear power for electricity generation, and therefore the implementation of appropriate policy measures might be needed to deter a switch towards cheaper but more polluting options in a scenario restricting nuclear energy and also to mitigate energy security concerns.

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5 As a result, Middle-East governments may experience less difficulty in balancing budgets (IEA, 2011).
Table 1. Per cent deviation in net trade balance for selected countries relative to Baseline: Energy import bill vs. energy export revenues

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</table>

3.3 Macro-economic impacts

a. Sectoral value-added

28. The changes in (relative) fossil fuel prices induce sizeable changes in fuel demand by all sectors, which in turn affect the sectoral value-added. Energy intensive industries and power utilities are expectedly sensitive to these transformations. The value-added changes for these industries are depicted in Figure 4.

29. The nuclear share of global electricity generation diminishes from about 10% in the Baseline in 2035 to 6% in 2035 in the phase-out scenarios. As a sizable number of nuclear power plants have not reached the end of their technical lifetime by 2035, the phase-out policy would only lead to a very partial elimination of nuclear energy by that date. The decline of nuclear energy would be most distinct in Japan and South Korea, where the decrease is almost three-fold and in the European Union where the share of nuclear power is almost halved. In 2035, the total reduction in nuclear activity due to the phasing-out policy accounts for about USD 120 billion of value-added (i.e. about half of global nuclear industry value), two-thirds of it occurring in OECD countries (Figure 5). The nuclear phase out scenario would exhibit a cumulative loss to 2035 in nuclear value-added of USD 1 trillion worldwide. This loss of nuclear activity
would be largely transferred to fossil fuel-based electricity generation, which grows by USD 80 billion in the absence of environmental constraints.

**Figure 4. Per cent deviation in Value-Added in energy intensive industries, fossil fuel-based and nuclear electricity generation, relative to Baseline in 2020 and 2035**
30. Fossil fuel electricity generation also appears quite sensitive to the fossil fuel subsidy reforms, predominantly in countries where they are the highest, such as Middle-East countries and Russia. Conventional electricity generation in these two regions would be expected to see more than a USD 40 billion reduction in value-added in 2020 as a result of the reform. This reduction would be expected to more than double in 2035. Subsidies to energy consumption removal alone would incur a slight decrease in the value of nuclear-generated electricity as there is very limited scope for nuclear energy to expand beyond Baseline figures.

31. Fossil-fuel subsidy reform percolates throughout the entire economy by reallocating primary factors (i.e. capital and labour) across all sectors and particularly across energy intensive industries. It improves the overall efficiency of resource allocation and makes fossil fuel energy cheaper for most OECD countries, especially European countries. Subsidy reform in non-OECD countries leads to more expensive energy and a slight contraction of their energy intensive activities by 2020. In the longer run, fast economic development and a growing demand for iron, steel, cement and chemicals stimulates production activity in China and India. This translates into a net increase of value-added created by energy intensive industries of more than USD 20 billion in 2035. In the long run, only large energy exporters, such as Middle-Eastern countries and to a lesser extent Russia, would be expected to see their industrial activities negatively affected by fossil-fuel subsidy reform. In those countries, a lower contribution of nuclear power to the generation mix hardly affects the activity levels of energy intensive industries, as the switch from nuclear energy to fossil fuels has little impact on energy prices faced by end-users.

b. GDP and household consumption

32. The two policies analyzed in this section, be they combined or not, would have limited impacts on global GDP because expenditures on electricity from nuclear power and energy consumption subsidies are small in comparison with spending on other goods and services. In the baseline, the nuclear industry is projected to account for a mere 0.3% of total value-added in 2035. The effect of a policy which aims to progressively abandon nuclear energy would be therefore limited on a global scale but would vary across countries depending on the share of nuclear power in the energy mix (Figure 6). Finally, the multilateral
fossil-fuel subsidy reform leads to a 0.5% increase in global GDP in 2035. Indonesia and India receive the most benefits in terms of economic growth. The policy barely affects GDP in African countries whose reduction in oil export revenues would be largely compensated by other economic gains.

33. The effects of nuclear phase-out on household consumption are expected to generally be limited. First, the share of household budget allocated to electricity expenses is lower than 3% in all the regions considered. Second, the policy of phasing out nuclear power affects households directly only through the increase in the retail electricity price (the effect on household income of increased energy production costs remains too indirect to have a sizeable impact). Nevertheless, such impacts are more pronounced in countries where shutting down nuclear power plants would have more drastic impacts on the energy system. The nuclear power phase-out scenario would lead to higher electricity prices in countries such as Japan, South Korea, in the European Union and in EFTA countries, which would reduce overall household spending on consumption and services by 0.2% to 0.5% in 2035. Due to the renewed interest in fossil fuels in countries that close down nuclear power plants, fossil fuel exporting countries (primarily Russia and OPEC member states) increase their revenues. This has a moderate, positive effect on their household consumption levels.

34. When nuclear phase-out and fossil-fuel subsidy reform are combined, large fossil fuel importers benefit from both cheaper international energy prices and more efficient resource allocation, which reverses trends in consumption\(^6\). Globally, household consumption increases by 0.2% in 2035. OECD countries are on average better off as they benefit from indirect effects generated by fossil-fuel subsidy reform. Changes in relative energy prices lead to substantial shifts in production patterns in China and India, particularly in energy intensive industries and in the manufacturing sector. Household consumption in India and Indonesia respectively increase by about 4% and almost 6% in 2035, relative to the Baseline, without additional policy measures. As far as fossil-fuel exporting countries are concerned, the impacts on consumption are in general negative. They exhibit income gains stemming from a better allocation of resources in their economy. However, they suffer from a net degradation of their terms of trade, due to a lower demand for their oil and gas exports (Burniaux et al., 2011).

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\(^6\) Efficiency gains due to a better allocation of energy resources, together with further macro-economic impacts of both multilateral and unilateral fossil-fuel subsidy reforms, are documented in Burniaux and Chateau (2011) and are not reproduced here.
Figure 6. Per cent deviation in GDP and real household consumption by country in 2035 compared to baseline

%Deviation in GDP in 2035

- World: +0.5%
- USA: -0.1%
- Japan: -0.1%
- European Union: +0.0%
- Russia: -0.5%
- China: +0.3%
- India: +2.6%
- Indonesia: +3.7%
- Middle East: +1.3%

%Deviation in Household Total Consumption in 2035

- World: +0.2%
- USA: -0.1%
- Japan: -0.1%
- European Union: +0.1%
- Russia: -1.7%
- China: +0.5%
- India: +4.1%
- Indonesia: +5.5%
- Middle East: -2.3%
4. Interaction between fossil-fuel subsidy reform, nuclear power phase-out and climate policy

4.1 Assumptions

35. Illustrative climate policy scenarios provide further insights into the interactions between climate policies and the combined fossil-fuel subsidy reform and nuclear power phase-out. For this illustrative scenario, a tax is applied to CO$_2$ emissions from the electricity sector and energy-intensive industries of OECD countries and China, where nuclear power phase-out has the most sizeable implications and where various carbon pricing initiatives are currently underway. The assumed carbon price follows a linearly rising trend starting from USD 0.0 in 2012 to USD 100 per tonne CO$_2$ in 2035 (or starts from existing levels in the European Union, Australia and New Zealand and converges to the linear trend). In China, it is assumed to rise linearly to reach USD 50 per tonne in 2035. Households are excluded from the taxation regime. This carbon policy simulation is purely illustrative and does not reflect a view on actual or proposed policies by countries. Since the policies combined in this analysis are energy-specific, we restrict the modelled climate policies to the mitigation of CO$_2$ emissions stemming from energy use.

4.2 Impact on the energy system

36. Imposing a price on CO$_2$ from fossil-fuel combustion alters the energy mix and increases the price of fossil fuels for energy transformation industries and ultimately for end consumers, thereby creating incentives to reduce global energy demand (Figure 7). The USD 100 per tonne carbon tax faced by OECD countries in 2035 induces an increase in the share of renewable energy in the electricity mix from 28% to 55%, relative to the Baseline. In this case, the pace of renewables deployment is comparable to the IEA 450 scenario patterns for the power generation sector (IEA, 2012). Nuclear power phase-out increases this share by another three percentage points in OECD countries.

37. The impact of the fossil-fuel subsidy reform in non-OECD countries has a wider impact on their fossil fuel energy use than the sole implementation of the carbon tax which, in this scenario, only affects China. The energy security implications of the climate scenarios are not detailed here but the Table A.4 in the Annex provides a summary of regional outcomes.

Figure 7. Per cent deviation in primary energy by fuel in 2035 relative to Baseline without carbon regulation
4.3 **Impact on CO\textsubscript{2} emissions from fossil fuel combustion\textsuperscript{7}**

Globally, the multilateral fossil-fuel subsidy reform helps cut CO\textsubscript{2} emissions by almost 5\% in 2020 and 6.5\% in 2035 relative to the Baseline, even in the absence of carbon pricing (Figure 8 and Table 2). When nuclear energy is progressively phased-out, CO\textsubscript{2} emissions exceed Baseline levels in 2035 by 1.6 \% (+0.8 GtCO\textsubscript{2}) as a result of intensified fossil fuel burning. Combining these policies finally translates into a 4.9\% reduction in global CO\textsubscript{2} emissions. The introduction of carbon pricing remains the most effective way to discourage intensive fossil fuel burning: this sole policy leads to a 15\% (-6.9 GtCO\textsubscript{2}) reduction in CO\textsubscript{2} emissions. Adding the implementation of fossil-fuel subsidy reform delivers almost 3 GtCO\textsubscript{2} of additional mitigation in 2035. Phasing out nuclear power increases global emissions by +0.5GtCO\textsubscript{2} compared with the sole carbon tax case. With the assumed carbon pricing scheme in place, the benefit of CO\textsubscript{2} emission reduction from fossil-fuel subsidy reform outweighs the additional carbon emitted by having less nuclear energy in the mix. With the three policies in place, the 2035 global CO\textsubscript{2} emissions from fossil fuel combustion are almost 10 GtCO\textsubscript{2} lower than in the Baseline, 4.5 GtCO\textsubscript{2} higher than current levels, and most closely in line with a least-cost 550ppm concentration stabilisation target (IPCC, 2007 and OECD, 2012).

**Figure 8. Per cent deviation in global CO2 emissions from fossil fuel combustion in 2035 relative to Baseline (numbers in brackets give absolute differences with Baseline emission in 2035)**

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Per cent deviation in global CO\textsubscript{2} emissions from fossil fuel combustion in 2035 relative to Baseline (numbers in brackets give absolute differences with Baseline emission in 2035)}
\end{figure}

\textsuperscript{7} Impacts on all greenhouse gases emissions by country in the multilateral energy subsidy scenario relative to the Baseline are provided in Figure A1 in the Annex.
Table 2. Deviation from Baseline energy-related CO2 emissions by country, 2020 and 2035 (GtCO2)

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<tr>
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OECD countries show similar emission reductions in 2035 when only a carbon tax regime is implemented, and when it goes hand in hand with less reliance on nuclear energy. In both cases the United States and the European Union reduce their total emissions by respectively almost 30% (-1.5 GtCO2) and 25% (-0.9 GtCO2). This highlights how fossil fuel prices endogenously adjust to carbon charges to steer fossil energy demand. Several rent mechanisms transfer simultaneously between fossil energy exporters, consumers and the nuclear industry. Since the carbon price is fixed in both policy simulations, fossil fuel and nuclear electricity prices are the only adjusting variables. The introduction of a carbon price reduces fossil fuel prices (and resource revenues for exporting countries) and increases domestic energy prices (and tax revenues for governments). Naturally, other price adjustments in non-energy primary factors and goods occur simultaneously in a general equilibrium setting. Nuclear phase-out tends to push fossil fuel demand up, and fossil fuel prices with it. Indeed, even fostered — subsidized — renewable-energy-based electricity generation cannot fully compensate for the reduction in nuclear power supply. Interestingly, in the nuclear power phase-out case, fossil fuel prices (excl. the carbon tax) increase enough to eventually discourage extra fossil fuel demand, thus returning some rent from the nuclear industry back to fossil fuel exporters.
40. In this stylised carbon tax scenario, carbon leakage to countries that do not implement carbon pricing policies, including Russia and India, remains very limited. When nuclear power phase-out is added to the carbon tax scenario, leakage becomes slightly larger (primarily because costs increase in countries that implement carbon pricing and have nuclear in the Baseline), but remains small. Adding fossil-fuel subsidy reform to the mix does not necessarily completely prevent such carbon leakage, but emissions decrease in these countries as well, as it becomes efficient to reduce their fuel use.

41. Furthermore, this analysis confirms the pivotal role of China in curbing global emissions and the effectiveness of carbon pricing policies in this country. A USD 17.00 tax per ton of CO$_2$ in 2020, covering the power sector and industries, is sufficient to drive Chinese emissions down by 1.4 GtCO$_2$. However, combining an economy-wide reform of support to fossil fuel consumption with carbon pricing in non-OECD countries allows for almost a doubling of their emissions reduction in 2020 compared with carbon pricing alone.

4.4 Macro-economic impacts

42. The introduction of a climate policy entails significant changes in relative prices of energy, capital and labour and thus translates into deeper consequences for the entire economy. In OECD countries and China, where carbon pricing is introduced, the model results reflect a negative effect on GDP and household real consumption because (future) environmental benefits from reduced climate change damages are not factored in (Figure 9) – however, it is important to note that these losses reflect only the costs of the carbon tax policy, and not the economic or environmental benefits of reducing climate impacts. As illustrated in the previous section, on the contrary, fossil-fuel subsidy reform would lead to more efficient use of resources and benefits in most countries. The simultaneous effects of applying all three policies in China do not significantly alter the economic burden compared with carbon pricing alone. However, a carbon tax implemented in OECD countries and China doubles the economic losses in Russia. Combining a climate policy and an effective fossil-fuel subsidy reform brings about multiple benefits to OECD countries: reduced energy bills and achievement of climate change mitigation at slightly lower costs. As India, Indonesia and Middle-East countries are absent from the carbon tax scheme the full policy scenario boosts their GDP: they benefit from an improved competitive edge over countries that do implement carbon pricing. India and Indonesia experience a GDP increase of 2.5% to 3.5%. Households also face relative price changes indirectly and modify their own consumption patterns. The qualitative direction of country effects is comparable to GDP deviations but the magnitude is slightly larger.
Figure 9. Per cent deviation in GDP and real household consumption by country with climate policy in 2035

%Deviation in GDP in 2035

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%Deviation in Household Total Consumption in 2035

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<td>+4.3%</td>
<td>+4.0%</td>
<td>+4.0%</td>
</tr>
<tr>
<td>Middle East</td>
<td>-3.7%</td>
<td>-2.0%</td>
<td>-1.5%</td>
<td>-1.0%</td>
</tr>
</tbody>
</table>
5. Concluding remarks

43. This paper aims to identify, through the lens of the ENV-Linkages model, the channels of interactions between i) a reform of schemes that support the wasteful consumption of fossil fuel resources, ii) a progressive nuclear phase-out and iii) a climate policy. Whilst the model simulations remain stylised and the numerical results should be interpreted with caution, a number of general observations can nevertheless be made.

44. According to this analysis, in a Baseline context without climate policy, progressively reducing the reliance on nuclear energy produces a notable increase in coal and natural gas consumption and hence an increase in CO$_2$ emissions (amounting to just over 1.5 percent of global emissions). Appropriate policy measures could therefore be needed if countries wish to avoid larger switches towards cheaper fossil fuel energy and to address energy security concerns from such a policy approach. The phase-out scenario projects a nuclear capacity that is halved by 2035 as compared with the Baseline, equivalent to value-added losses of USD 120 billion in the nuclear industry for that year. The global, cumulative loss to 2035 in nuclear value-added of a progressive nuclear phase-out is USD 1 trillion. In the absence of environmental constraints, lower nuclear activity is compensated by higher fossil fuel-based generating capacity, which represents an extra value-added of USD 80 billion worldwide. Nuclear power phase-out leaves GDP and real household consumption marginally affected in energy importing countries. In the absence of ambitious climate goals, the reduced reliance on nuclear energy for electricity generation would likely have limited side-effects on international markets of non-energy goods and services.

45. The analysis shows that a multilateral reform of energy consumption subsidies is more likely to affect international fossil fuel prices and alter patterns of global energy use. Lower international fossil fuel prices result from decreased demand in large developing countries due to the reform. Energy importers are encouraged to increase their consumption of coal and natural gas, particularly Japan and South Korea, the European Union and China. Energy intensive industries, chiefly in fast growing economies, benefit the most from cheaper fossil fuel prices, gaining USD 20 billion in economic activity in 2035. Subsidy reform also proves effective for restoring economic efficiency and enhancing global economic activity, leading to a 0.5% increase in global GDP in 2035 led by India and Indonesia whose GDPs increase by over 2.5% and 3.5% respectively.

46. While nuclear power phase-out increases electricity prices and leads to a decrease in household consumption in countries such as Japan, South Korea and the European Union, the fossil-fuel subsidy reform leads to an increase in GDP and a decrease in CO$_2$ emissions. When jointly implemented, the combined policies lead to an increase in global GDP of similar size to the stand-alone fossil-fuel subsidy reform, and a reduction of CO$_2$ emissions that is somewhat smaller. The combined policies help save a significant amount of primary energy, equivalent to that currently consumed in Russia. Removing the nuclear option from the energy mix would have undesirable consequences on CO$_2$ emissions unless countervailing measures are added to the policy mix. Globally, the energy consumption subsidies reform can help alleviate further switching towards fossil fuels through market adjustments but it falls short of creating enough incentives to drastically curb emissions. Climate policy instruments such as effective carbon pricing are necessary to meet ambitious climate goals. The illustrative climate scenario confirms that both energy subsidy phase out and nuclear energy can reduce certain negative macro-economic impacts appreciably while also allowing for significant emission reductions.

47. Herein we have given particular emphasis to fossil fuels and nuclear energy. For future research, it would be useful to analyse how, especially in times of scarce public resources and limited access to credit, economic instruments could improve energy efficiency and the deployment of clean energy. Such measures could possibly address concerns about energy security and climate change consequences of insufficient action mentioned earlier. The impact of the policies examined here on the deployment of carbon capture and storage (CCS) is also complex and has not been addressed herein due to its limited market emergence potential within the timeframe considered. But CCS could help reduce GHG emissions
and could start to play a major role within two decades (IEA, 2013). If substantial CCS capacity is built up, it could change the relative impacts of the nuclear phase-out and the energy subsidy phase out.
REFERENCES


CDC Climat (2012). German nuclear phase-out implications for the EU-ETS. Climate Brief.


ANNEX

A1. An overview of the ENV-Linkages model

48. The analysis is based on ENV-Linkages, a global recursive-dynamic neo-classical CGE model. ENV-Linkages, as a successor of the OECD GREEN model (Burniaux et al., 1992), shares its basic structure with e.g. World Bank-Linkage and MIT-EPPA models, featuring recursive dynamics and capital vintages. A more comprehensive model description is given in Chateau et al. (2014b).

49. Production in ENV-Linkages is assumed to operate under cost minimisation with perfect markets and constant return to scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The nesting of the production function for the agricultural sectors is further re-arranged to reflect substitution between intensification (e.g. more fertiliser use) and extensification (more land use) of activities; or between intensive and extensive livestock production. The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the different available technologies to generate electricity using a CES specification with a large degree of substitution. Non-fossil electricity technologies have a structure similar to the other sectors, except for a top nesting combining a sector-specific natural resource with all other inputs. This specification acts as a capacity constraint on the supply of these electricity technologies. The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. This implies relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo-classical growth model.

50. The energy bundle is of particular interest for analysis of climate change issues. Energy is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of “other fossil fuels”. At the lowest nest, the composite “other fossil fuels” commodity consists of crude oil, refined oil products and natural gas. The value of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

51. Household consumption demand is the result of static maximization behaviour which is formally implemented as an “Extended Linear Expenditure System”. A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward-looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

52. International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium. Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) addressed to domestic producers and the import demand.
CO₂ emissions from combustion of energy are directly linked to the use of different fuels in production. Other GHG emissions are linked to output in a way similar to Hyman et al. (2002). The following non-CO₂ emission sources are considered: i) methane from rice cultivation, livestock production (enteric fermentation and manure management), fugitive methane emissions from coal mining, crude oil extraction, natural gas and services (landfills and water sewage); ii) nitrous oxide from crops (nitrogenous fertilizers), livestock (manure management), chemicals (non-combustion industrial processes) and services (landfills); iii) industrial gases (SF6, PFC’s and HFC’s) from chemicals industry (foams, adipic acid, solvents), aluminium, magnesium and semi-conductors production.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the numéraire. As a consequence, real exchange rates are immediately adjusted to restore current account balance when countries start exporting/importing emission permits.

The version of the model used here represents the world economy in 25 countries/regions, each with 23 economic sectors, as illustrated in Table 3. These include five electric generation sectors, five agriculture-related sectors (including fishing and forestry), five energy-intensive industries, three fossil fuel extraction sectors, transport, refineries and distribution of petroleum products, services, construction and four other manufacturing sectors. The core of the static 2004 starting year equilibrium is formed by a set of Social Account Matrices (SAMs) that describe how economic sectors are linked; these are based on the GTAP 8 database (Narayanan et al., 2012). Many key parameters of the model are set on the basis of information drawn from various empirical studies and data sources (details given in Burniaux and Chateau, 2008).
<table>
<thead>
<tr>
<th>Commodities</th>
<th>Countries and regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>United States</td>
</tr>
<tr>
<td>Coal</td>
<td>Canada</td>
</tr>
<tr>
<td>Crude oil</td>
<td>European Union</td>
</tr>
<tr>
<td>Gas</td>
<td>EFTA &amp; Turkey</td>
</tr>
<tr>
<td>Refined oil products</td>
<td>Japan</td>
</tr>
<tr>
<td>Electricity*</td>
<td>South Korea</td>
</tr>
<tr>
<td></td>
<td>Australia and New Zealand</td>
</tr>
<tr>
<td><strong>Emission-intensive &amp; trade-exposed sectors</strong></td>
<td>Mexico</td>
</tr>
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<td>Chemicals</td>
<td>Russia</td>
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<tr>
<td>Non-metallic minerals</td>
<td>Caspian</td>
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<td>Iron and steel industry</td>
<td>Other European Annex I countries</td>
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<td>Non-ferrous metals</td>
<td>Brazil</td>
</tr>
<tr>
<td>Forestry, agriculture and fisheries</td>
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</tr>
<tr>
<td>Rice</td>
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</tr>
<tr>
<td>Other crops</td>
<td>ASEAN</td>
</tr>
<tr>
<td>Livestock</td>
<td>Other Developing Asia</td>
</tr>
<tr>
<td>Forestry</td>
<td>Other Latin America</td>
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<td>Fishery</td>
<td>Northern Africa</td>
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<td></td>
<td>Other Africa</td>
</tr>
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<td><strong>Other industries and services</strong></td>
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<td>Transport Equipment</td>
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<td>Paper–pulp–print</td>
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<tr>
<td>Fabricated Metal Products</td>
<td></td>
</tr>
<tr>
<td>Other Manufacturing Services</td>
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</tr>
<tr>
<td>Construction &amp; Dwellings</td>
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</tr>
<tr>
<td>Other Mining</td>
<td></td>
</tr>
<tr>
<td>Food Products</td>
<td></td>
</tr>
</tbody>
</table>

Source: * Electricity is split into five sectors: nuclear power, solar- and wind-based electricity, electricity from renewable combustibles and waste electricity, fossil fuel based electricity, and hydro- and geothermal-based electricity.
A2. Nuclear capacity by country

Table A2. Cumulative nuclear capacity additions and retirements over 2011-2035, and net installed capacities in 2035 by country

<table>
<thead>
<tr>
<th></th>
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<td>Baseline w/o Nuke</td>
<td>Baseline w/o Nuke</td>
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<tr>
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<td>9</td>
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</table>

A3. Fossil fuel subsidy removal

Figure A1. GDP and greenhouse gases deviation in the fossil fuel subsidy removal scenario, relative to Baseline w/o policy
### A4. Impact of climate scenarios on energy trade

#### Table A3. Per cent deviation in net trade balance for selected countries in climate scenarios relative to carbon-tax only policy: Energy Import Bill vs. Energy Export Revenues

<table>
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<tbody>
<tr>
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<td>2035</td>
<td>2020</td>
<td>2035</td>
</tr>
<tr>
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<td>-6.1%</td>
<td>-8.7%</td>
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<tr>
<td>European Union</td>
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<td>-26.9%</td>
<td>0.5%</td>
<td>-26.6%</td>
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<tr>
<td>China</td>
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<td>-12.3%</td>
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<td>India</td>
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<td>-28.5%</td>
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<tr>
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<td>10.1%</td>
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</tr>
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<td>-6.2%</td>
<td>1.1%</td>
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<td>Coal Importers</td>
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<td>China</td>
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<td>South Africa</td>
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