

Mitigation potential of removing fossil fuel subsidies: a general equilibrium assessment

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ABSTRACT

Quoting a joint analysis made by the OECD and the IEA, G20 Leaders committed in September 2009 to “rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption”. This analysis was based on the OECD ENV-Linkages General Equilibrium model and shows that removing fossil fuel subsidies in a number of non-OECD countries could reduce world Greenhouse Gases (GHG) emissions by 10%. Indeed, these subsidies are huge. The IEA reports that total energy-related consumption subsidies in 20 non-OECD countries accounting for 40% of the world energy demand amounted to 310 USD billion in 2007 (IEA, 2008). This represents 3 times the yearly aid flows to developing countries defined as the Official Development Assistance (ODA). This paper discusses the assumptions, data and both environmental and economics implications of removing these subsidies. It shows that, though removing these subsidies would amount to roughly a seventh of the effort needed to stabilize GHG concentration at a 450ppm, the full environmental benefit of this policy option can only be achieved if, in parallel, emissions are also capped in OECD countries. Finally, though removing these subsidies qualifies as being a “win-win” option at the global level, this is not true for all countries/regions. The paper also provides some discussion about the robustness of these results.

JEL codes: H23, O41, Q56

Keywords: fossil-fuel subsidies, general equilibrium models, GHGs emissions

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² The views of the authors do not necessarily represent the views of the OECD or of its member countries.

1. Introduction

1. In the September 2009 G20 Leaders Summit, G20 Leaders committed to “rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption”. This decision came after a joint analysis made by the OECD and the IEA showed that removing fossil fuel subsidies in a number of non-OECD countries could reduce world Greenhouse Gases (GHG) emissions by 10% (OECD, 2009). Indeed, these subsidies are huge. The IEA reports that total energy-related consumption subsidies in 20 non-OECD countries accounting for 40% of the world energy demand amounted to 310 USD billion in 2007 (IEA, 2008). This represents 3 times the yearly aid flows to developing countries defined as the Official Development Assistance (ODA). As indicated in Figure 1, energy consumption subsidies are quite substantial in some countries amount to 20% or 4% of Iran and Russian GDP, respectively. Even in oil-importing countries like China and India subsidies in terms of GDP are not negligible, respectively 1.1% and 2%. This article discusses the assumptions, data and results of the joint OECD/IEA analysis and provides some insight on the robustness of these results.

2. From a theoretical perspective, removing these subsidies should reduce global emissions, while bringing real income gains to countries that remove these subsidies. These gains arise from a more efficient reallocation of resources. Hence, this policy qualifies for being a “win-win” option as it brings both environmental and economic benefits.

3. However, governments are reluctant to remove these subsidies as they claim they are justified on equity grounds, i.e. to protect the access of the poor households to fossil fuels. This argument could be reversed as the budgetary savings obtained from subsidy removal give room to maneuver for implementing social support that could be more efficiently target to poor households. For example this access can be guaranteed by directly supporting the purchasing power of the poor without subsidizing uniformly all households, including the rich ones. The huge budgetary saving from removing these subsidies would give room of manoeuvre for policies more narrowly targeted to poor households.

4. The aim of this paper is to provide, thanks to model simulations, quantified estimates of the emission reduction and the real income/welfare gains that can be achieved by removing fossil-fuel subsidies. The remainder of this paper proceeds as follows. Section 2 discusses the nature of these subsidies, their scope, the existing data collected by the IEA and the methodology used to assess these subsidies. Section 3 discusses the environmental impact of removing these subsidies. Section 4 presents the real income implications of the subsidies removal. Section 5 checks the robustness of the results first regarding to the uncertainty in fossil-fuel database, next to uncertainty in the policy context in which subsidy removal is implemented and then regarding to fossil-fuel supply behaviour. Section 6 concludes.

2. Nature and scope of fossil fuel subsidies [This whole section has to be revised]

5. (to be done) Brief typology of the instruments used to subsidize the production and consumption of fossil fuels: mainly producer subsidies in OECD countries versus consumer subsidies in non-OECD countries.

The IEA price-gaps approach

6. Most of the data on energy consumption subsidies that have been published for multiple countries in recent years relate to oil, natural gas and coal (IEA, 2006 and 2008) or petroleum products only (Coady et al., 2010), and have relied on the measurement of price-gaps. Based on application of the price gap

approach to its dataset, the IEA estimates that fossil fuel subsidies to consumers amounted to US\$ 342 billion in 2007. This amount comprises subsidies to fossil fuels used in final consumption and subsidies to fossil-fuel inputs to electric power generation

7. In this paper we introduce in a general equilibrium model these fossil-fuel consumer subsidies in non-OECD countries estimated by IEA(2008) with a “price gap” approach. This methodology is described in the Box 1³. If it is the most common approach used in the literature to evaluate transfer supporting consumption through price instrument some author still argue that some could arise when applied to the case of energy. Koplow (2009) indicated that this methodology incorporates a number of underlying assumptions that should bear in mind: the identification of the appropriate price is not always obvious for electricity; international prices could in some periods been themselves distorted and the price-gap estimates do not capture producer subsidies. Regarding this last point, OECD (2003) suggested that the price-gap methodology tends to underestimate the level of subsidies in countries that use this kind of market-distorted instruments.

BOX 1. Quantification of Global Energy Subsidies by the IEA

Energy subsidies were calculated using a price-gap approach, which compares final consumer prices with reference prices that correspond to the full cost of supply or, where available, the international market price, adjusted for the costs of transportation and distribution. This approach captures all subsidies that reduce final prices below those that would prevail in a competitive market. Such subsidies can take the form of direct financial interventions by government, such as grants, tax rebates or deductions and soft loans, and indirect interventions, such as price ceilings and free provision of energy infrastructure and services.

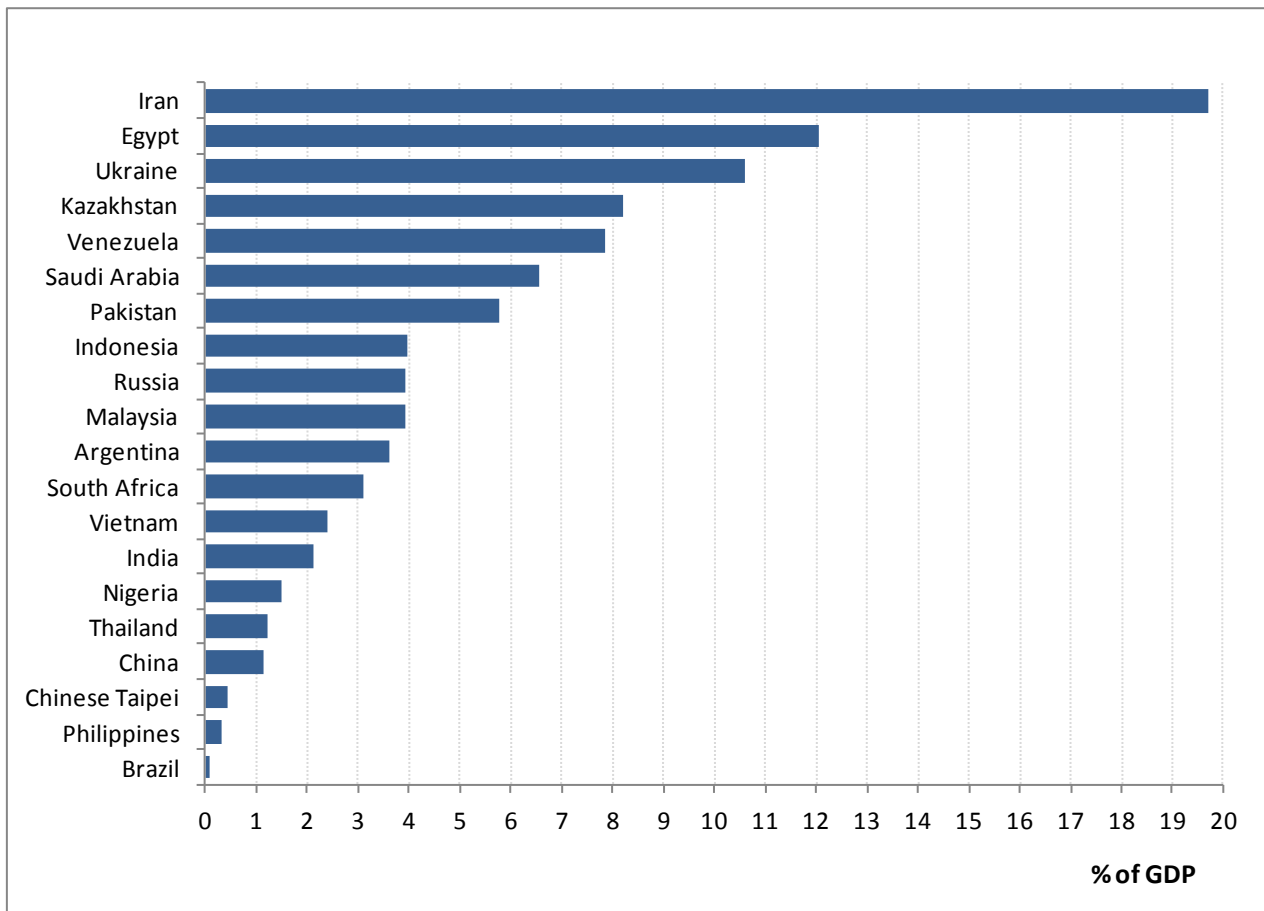
Simple as the approach may be conceptually, calculating the size of subsidies in practice requires a considerable effort in compiling price data for different fuels and consumer categories and computing reference prices. For traded forms of energy such as oil products, the reference price corresponds to the export or import border price (depending on whether the country is an exporter or importer) plus internal distribution. For non-traded energy, such as electricity, the reference price is the estimated long-run marginal cost of supply. VAT is added to the reference price where the tax is levied on final energy sales, as a proxy for the normal rate of taxation to cover the cost of governing a country. Other taxes, including excise duties, are not included in the reference price. So, even if the pre-tax pump price of gasoline in a given country is set by the government below the reference level, there would be no net subsidy if an excise duty large enough to make up the difference is levied. The aggregated results are based on net subsidies only for each country, fuel and sector. Any negative subsidies, i.e. where the final price exceeds the reference price, were not taken into account. In practice, part of the subsidy in one sector or for one fuel might be offset by net taxes in another. Subsidies were calculated only for final consumption, to avoid the risk of double counting: any subsidies on fuels used in power generation would normally be reflected at least partly in the final price of electricity. All the calculations for each country were carried out using local prices, and the results were converted to US dollars at market exchange rates.

Source : IEA (2006)

³ IEA (1999) provided a more detailed discussion of the price-gap approach and practical issues relating to its use in calculating subsidies and their effects.

8. This analysis covers 20 non-OECD countries amounting to roughly 40% of the world energy demand. The price wedges estimated for 2007 by energy sources and by countries/regions are significant in a number of cases (Table 2). To the extent that the pass-through of international energy prices on domestic markets is incomplete,⁴ these wedges are likely to have changed following the 2008 oil price spike and then again when oil prices fell. The first column of the Table shows the average wedges for all demands that are *effectively* subsidized in each country/region, thereby illustrating the magnitude of the wedges. The second column reports the average wedge across *all* demands, so that the gap between both columns reflects the coverage of the subsidies across demands. Countries not covered in the IEA database are included in regional aggregates (for instance, the Rest of the World region) by assuming zero wedges.

Figure 1. Fossil-fuel subsidies as a percentage of 2007 GDP



Source: Authors calculation on the basis of IMF(2009) GDP data, and IEA(2008) fossil fuel subsidies data.

This assumption is fairly conservative as it is likely that some of these countries also subsidize part of their energy consumption. The energy wedges differ across energy sources and countries/regions. Energy tends to be subsidised more heavily in Russia (especially for natural gas), India and non-EU Eastern European countries. By contrast, the subsidy rates estimated by the IEA for China are rather moderate. The subsidy rates in oil-producing countries and Rest of the World regional aggregates appear to be relatively low, but they are understated due to the incomplete country coverage of IEA estimates.

4. This is the case for instance when energy prices are set administratively.

Table 1. Energy price gaps¹ in 2007 as estimated by the IEA

Country	Energy	%deviation of domestic relative to world prices	
		Average subsidy rate over the demands that are effectively subsidised for each type of fuel	Average subsidy rate over the total demand for each type of fuel
China	Coal	-18.1	-0.5
	Gas	-27.0	-2.8
	Refined oil	-7.1	-2.0
	Electricity	-22.3	-3.2
India	Coal	0.0	0.0
	Gas	-53.6	-28.3
	Refined oil	-51.8	-10.1
	Electricity	-19.6	-9.1
Brazil	Coal	-40.4	-8.5
	Gas	0.0	0.0
	Refined oil	-14.4	-2.2
	Electricity	0.0	0.0
Russia	Coal	-51.6	-1.2
	Gas	-84.7	-26.8
	Refined oil	-23.6	-3.3
	Electricity	-48.9	-35.0
Oil-exporting countries ²	Coal	0.0	0.0
	Gas	-18.9	-5.9
	Refined oil	-29.2	-22.3
	Electricity	-21.9	-20.4
Non-EU Eastern European countries ³	Coal	-30.0	-4.9
	Gas	-39.6	-20.4
	Refined oil	-5.4	-1.8
	Electricity	-37.4	-20.7
Rest of the world	Coal	-2.1	-0.5
	Gas	-25.6	-7.7
	Refined oil	-8.5	-3.4
	Electricity	-6.7	-5.1

1. Energy subsidies are approximated by the difference in the domestic energy price and world prices.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

3. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

Source: Authors calculation on the basis of IEA(2008) fossil fuel subsidies data.

3. Environmental impact of removing fossil fuel subsidies in non-OECD countries

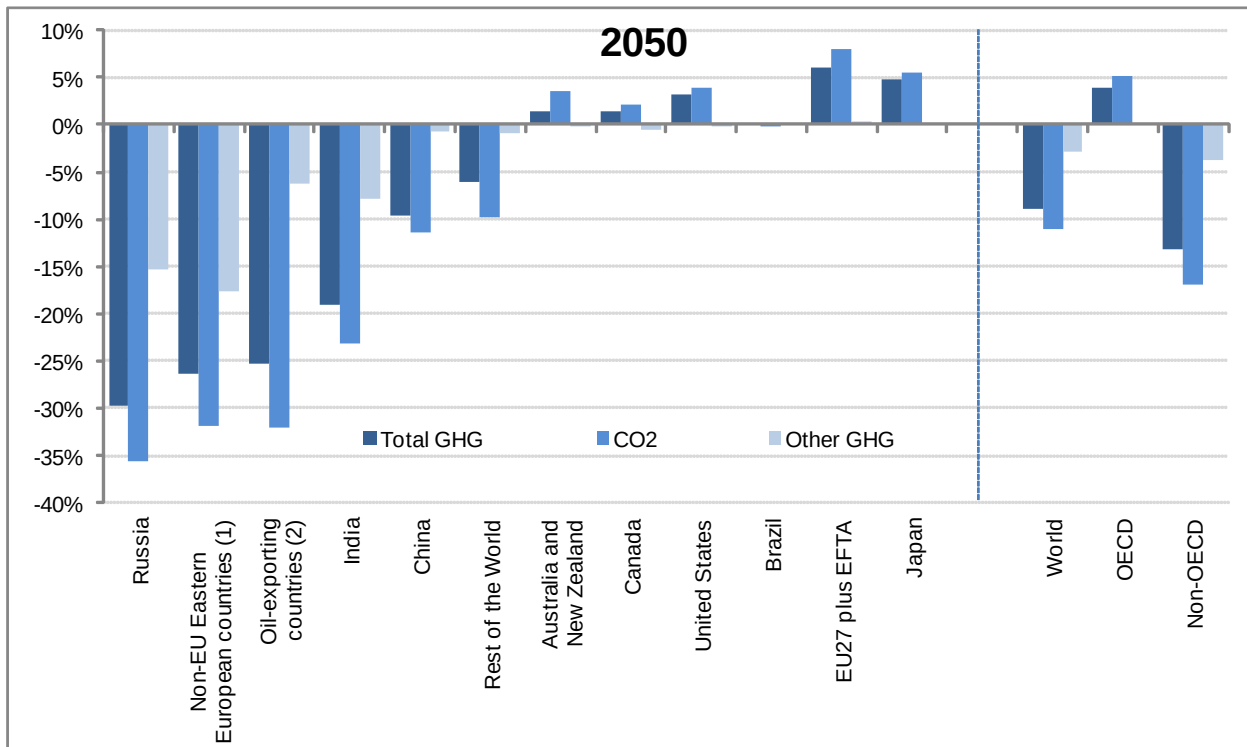
9. The impact of the subsidy reform is quantified by using the ENV-Linkages model developed by the Environment Directorate of the OECD. This model is a world General Equilibrium (GE) disaggregated by sectors and countries/regions and running up to 2050 using a recursive dynamics (see Burniaux and Chateau, 2009 or the Annex for a more detailed description of the model structure). All scenarios in this paper are shown relative to a baseline projection simulating the evolution of the world economy up to 2050 under the assumption of no climate change policy beyond those that are already in place. This projection is based on an underlying long-term growth scenario described in Duval and de la Maisonnette (2010). The price gaps estimated by the IEA(2008) for 2007 are introduced by calibration in the initial year of the model (2005) and they are supposed to remain constant in percentage up to 2050. In simulations of subsidy reforms, these price gaps are gradually phased-out over the period 2013 to 2020.

10. The **central scenario** considered in this paper assumes that all non-OECD countries remove their subsidies gradually from 2013 to 2020. If they do so, world GHG emissions could be reduced by 9.2% in 2050 relative to the baseline (Figure 2). This number is lower than the 10% reported in the forthcoming joint report for the G20 initiative. The main reason is that in the central scenario build here, emissions in OECD countries are not capped as they are in the joint report (see also below in section 5.b). This number is also slightly lower than the 9.7% reported in OECD(2009), as we have updated our macroeconomic baseline to take into account financial crisis since this publication.

11. This represents a seventh of the mitigation effort needed to put world emissions on a pathway that is compatible with stabilising concentration below 450 ppm of CO₂eq. The resulting drop of emissions of CO₂ from fossil fuels combustion is quite substantial in some countries/regions, amounting to around 30% or more in non-EU Eastern European countries, Russia and the Middle East. While CO₂ emissions from fossil fuels combustion fall by 20% in non-Annex I countries in 2050, they remain almost unchanged in Annex I countries. This is because reductions in Russia and non-EU Eastern European countries are offset by increases in those Annex I countries that do not subsidize their energy demand, reflecting leakages induced by falling world energy prices. This leakage is particularly pronounced in the EU where CO₂ emissions increase by 8% in 2050 relative to the baseline. Of the 6.3 GtCO₂ emission (from fuel combustion) reduction achieved by removing energy subsidies in non-OECD countries in 2050 (corresponding to a reduction of their emissions by 17%), around 11% is offset by an increase of emissions in OECD countries. With binding emission caps in OECD countries, carbon leakages would be contained, and the environmental benefits from subsidy removal would be larger (see last section).

12. Figure 2 also illustrates an additional environmental benefit from subsidy reform, namely the reduction of non-CO₂ gases, although by a lesser extent than CO₂ emissions (3% in 2050 relative to baseline compared with 11% for CO₂ emissions, see Figure 2). This illustrates the complementarities across gases. The last section will discuss how these complementarities are enhanced if emissions are capped in OECD countries.

Figure 2. Central scenario: Impact on 2050 GHG emissions (% change from the baseline)



1. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

4. Welfare implications of phasing-out fossil-fuel subsidies in non-OECD countries

13. If each non-OECD country were to remove its fossil-fuel subsidies unilaterally, it would record welfare gains⁵, in line with what is suggested by the theory (Figure 3).⁶ All countries/regions, with the exception of non-EU Eastern European countries⁷, report welfare gains ranging from 0.1% in Brazil to almost 2½ % in India and Russia in 2050. These gains arise from a more efficient allocation of resources

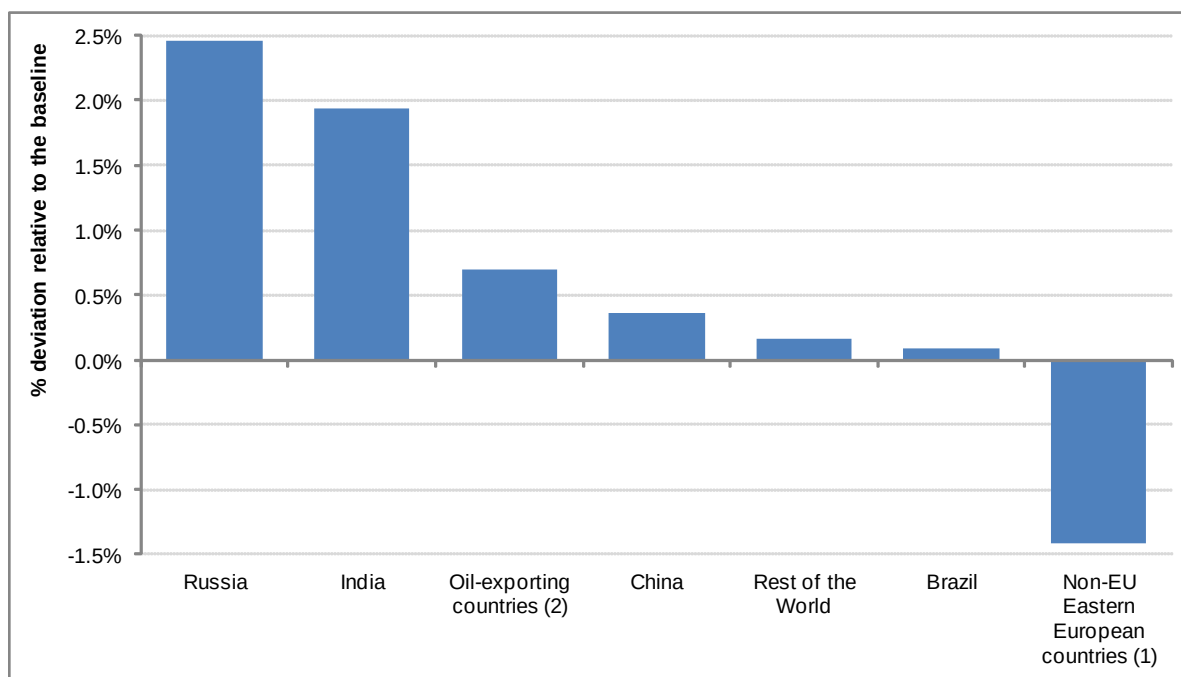
⁵ In this entire paper welfare changes are measured by the equivalent variation in income. This utility-based welfare measure does not incorporate the impacts of climate change.

⁶ It is often argued that subsidies are justified on equity grounds, for instance, to alleviate poverty. In this simulation, the budgetary saving obtained from the subsidy removal is entirely refunded to households in a lump-sum (non-distorting) way. This implies that subsidies to the consumption of fossil fuel are replaced by a direct and larger transfer to households. Alternatively, this transfer could be used to reduce other distorting taxes, which would increase the real income gain from subsidy removal, or to reduce poverty in a more targeted and efficient way than through a uniform subsidy to fossil fuel consumption.

⁷ This regional aggregate consists of very heterogeneous economies (Armenia, Azerbaijan, Belarus, Croatia, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan), where the removal of the subsidies induces a dramatic shift in the economic structure towards low-productivity sectors. The resulting overall productivity loss more than offsets the welfare gains from the subsidy removal.

across sectors. Therefore, from this perspective, the removal of fossil fuel subsidies brings in both environmental and economic benefits.

Figure 3. Unilateral removal of fossil fuel subsidies scenarios: Impacts on 2050 regional equivalent variation in income (% change from the baseline)



1. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

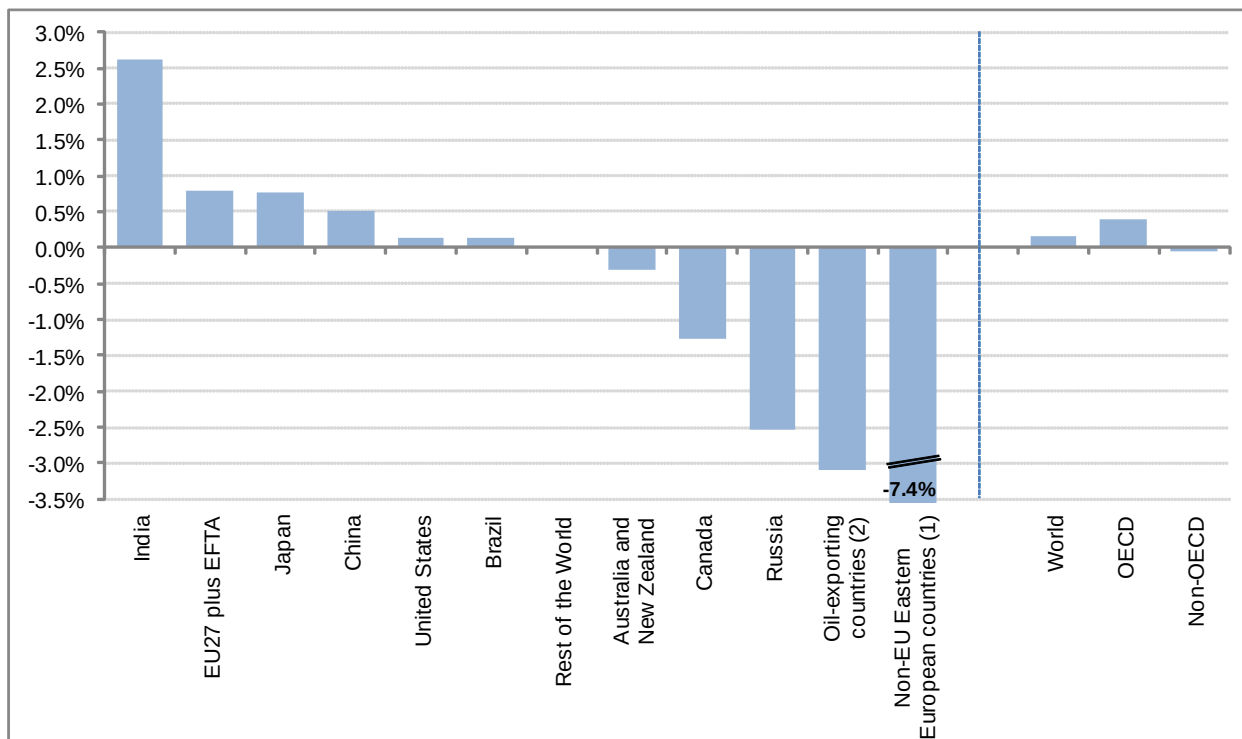
14. A different outcome would prevail in the central scenario, where there is a multilateral removal of energy subsidies in all non-OECD countries together (Figure 4). India would still benefit from welfare increases by more than 2.5% in 2050 relative to the baseline. But, in this scenario, some of the non-OECD countries that remove their subsidies, including Russia and the Middle East, would no longer enjoy the welfare gains they faced in scenarios where they act alone. This is because the efficiency gains from improved resource allocation would be more than offset by the terms-of-trade losses associated with the sharp fall in world energy prices that a multilateral removal of subsidies would induce.

15. Indeed, a multilateral removal of fossil fuel subsidies in non-OECD countries is simulated to induce a drop of the international fossil fuel prices. Reflecting assumptions about supplies responses, the international prices for crude oil and natural gas would fall in the central scenario by 8 and 13% respectively in 2050 relative to the baseline, while the international coal price only drops by 1%.

16. Energy-importing OECD countries, not least the EU and Japan, would enjoy significant terms-of-trade and welfare gains. Overall, the OECD area as a whole would gain more (0.4% in 2050) than the non-OECD area and the real income gain at the world level would be small, amounting to just 0.2% relative to

the baseline in 2050. This primarily reflects the fact that demand for energy goods is not sensitive to price, so that the distortive impact of energy subsidies and the gain from their removal are limited.⁸

Figure 4. Central scenario: Impact on equivalent variation in income - 2050 (percentage change from the baseline)



1. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

5. Uncertainties and robustness to alternative assumptions

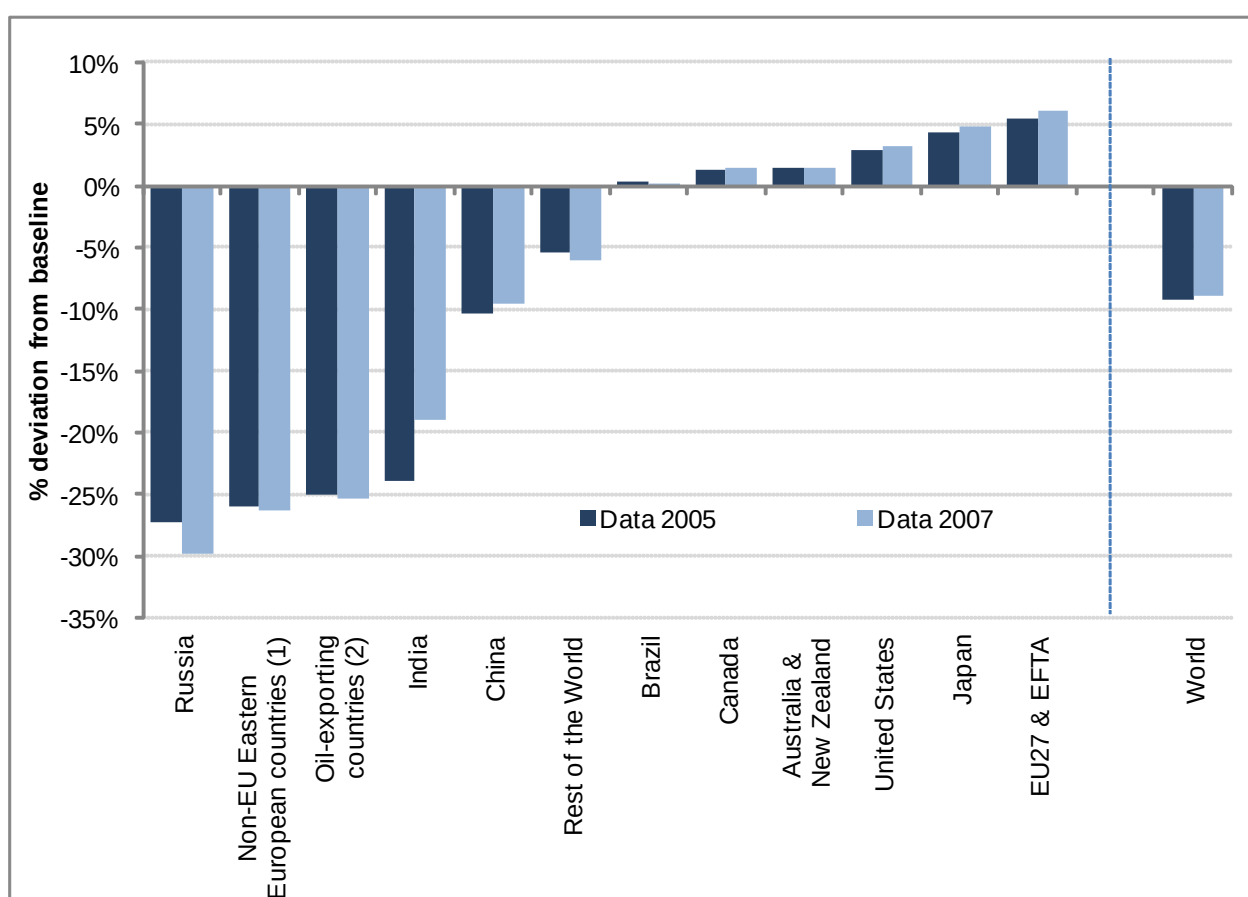
17. The above analysis relies on many assumptions that potentially affect the results. This section will address three sources of uncertainties: i) the country coverage and methodology used in estimating the price gaps; ii) the policy context in which subsidy removal is implemented; and, iii) the values of some key parameters, such as the supply elasticities of fossil fuels, that are critical in determining the environmental effectiveness of subsidy reform.

⁸ An additional explanation for the small magnitude of world real income gains is that the fall in world fossil fuel prices induces producers to reduce their supply, leaving more of their reserves in the ground. This leads to a GDP loss, ceteris paribus.

a. Reference years, country coverage and methodological assumptions

18. Price gaps are often calculated by using the corresponding world market price as a reference price. To the extent that world market prices are relatively volatile and that countries tend to isolate their domestic market from world market price fluctuations, for instance, by setting domestic prices administratively, price gaps are likely to change over time and the impact of subsidy reform depending on the year for which the price gaps are estimated. The IEA has estimated price gaps in 2005 and 2007 for 20 countries non-OECD amounting to roughly 40% of the world energy consumption. Figure 5 illustrates that the total reductions of GHG emissions at the world level obtained by removing these price gaps are quite similar whatever the year used as a reference for estimating these price gaps and, in both case, very close to 10%. The pattern of reductions across countries/regions is also roughly the same.

Figure 5. Impact on GHG emissions in 2050 of a removal of fossil-fuel subsidies as estimated by calculating prices gaps in 2005 and 2007 (percentage change from the baseline)



1. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

19. In the central scenario discussed in section 3 and 4, no fossil fuel subsidies are assumed in countries for which the IEA has not collected price gaps. This tends to underestimate the impact of subsidy reforms as, in many of these countries, fossil fuel consumption is effectively subsidized. An alternative assumption could be to assume that these countries subsidized their fossil fuel consumption at a rate equal to the corresponding average price gaps observed in countries covered by the IEA data base. The corresponding emission reduction in this case is only slightly larger than in the central case (10% reduction in 2050 instead of 9% in the central scenario: Table 2) as most of the additional emission reductions is compensated by higher leakage.⁹ In contrast, the equivalent variation gains at the world level are twice as high as in the central scenario, reflecting the higher welfare gain from subsidy reform achieved in the oil exporting regional aggregate, where the equivalent variation is simulated to fall by 1% only in 2050 compared with 3% in the central scenario. Hence, with more complete data coverage, the real income losses incurred by oil exporting countries would be lower than in the simulation discussed here.

20. Finally, the choice of an appropriate reference price for estimating the electricity price gaps is not so easy compared to fossil fuels, as electricity is almost not traded internationally. Given this uncertainty¹⁰, if we exclude subsidies to electricity from the subsidy reform, then the emission reductions is somewhat lower: 7% in 2050 compared with 9% in the central scenario (Table 2).

b. Context of implementation

21. The central scenario describes a situation where emissions in OECD countries are not subject to any constraint while fossil fuel subsidies in non-OECD countries are removed. This situation is not likely to be realistic. Indeed, after COP15 in Copenhagen, 75 countries, including all OECD countries, declared that they would restrict their emissions in 2020.

Example 1: OECD capped baseline emissions

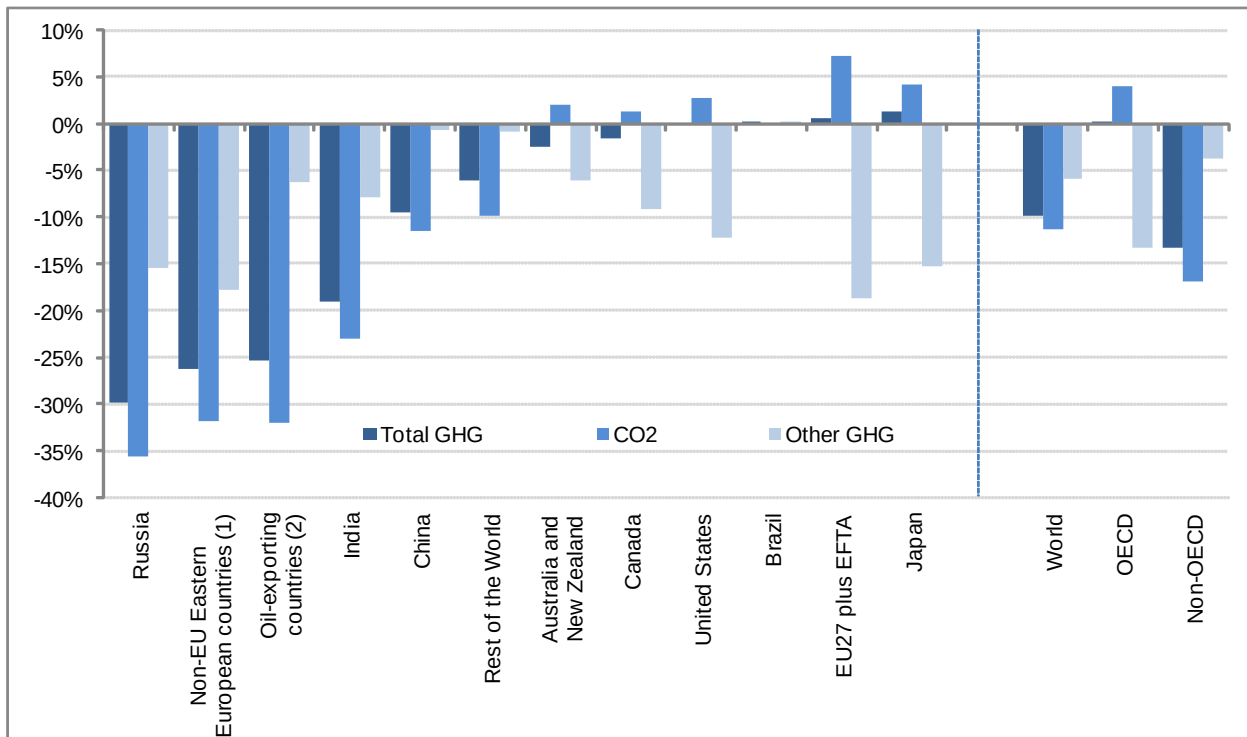
22. Therefore, if the impact of subsidy reform has to be quantified in such context, emissions in OECD countries should be capped in order to prevent emissions in these countries from exceeding a given level, as would be the case if these countries implemented their declared targets. In such a case, the total GHG emission reduction achieved at the world level is higher – 10% in 2050 instead of 9% with no cap – but, interestingly, the additional reduction exclusively concerns non-CO₂ gases that are reduced by 6% in 2050 compared with 3% in the no-cap case while the CO₂ reduction remains the same (11% in 2050 relatively to the baseline). The explanation relates to the way the emission cap is implemented in OECD countries. Total GHG emissions in these countries are capped to their baseline levels – such as to prevent leakages – but the cap is applied globally at the whole OECD level and including all gases (allowing for trading emissions across OECD member countries and gases). Therefore, the cap implies a small carbon price, common for all OECD countries and gases, that, as far as CO₂ is concerned, is largely offset by the fall of international fossil fuel prices resulting from the subsidy reform, hence inducing CO₂ to increase above their baseline level, as illustrated by Figure 6. As a result, the cap is met by cutting down non-CO₂

⁹ This is explained by the fact that most of the countries outside the IEA database have their energy consumption mainly based on refined oil products, hence a larger than average leakage rate as the supply of crude oil is assumed to be relatively inelastic.

¹⁰ In addition to the fact that this includes in principle subsidies to electricity sources that are not based on fossil fuels (nuclear, renewable, solar, wind and hydroelectric) and do not emit CO₂, although in practice these subsidies are small in the countries covered by the IEA database.

emissions, sometimes substantially as in the EU (- 19%) and in Japan (- 15%).¹¹ Similarly, when price gaps are extrapolated to non-OECD countries for which the IEA has not collected subsidy data, the emission reduction achieved at the world level if emissions are capped in OECD countries reaches 11% in 2050 against 10% with no cap. And then much of the reduction is obtained through mitigation of non-CO2 emission from fossil-fuel combustion.

Figure 6. Impact on GHG emissions in 2050 of a removal of fossil-fuel subsidies when emissions in OECD countries are capped (percentage change from the baseline)



1. This region includes Croatia and the Rest of Soviet Union (integrated by the following countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) according to the data aggregation in the GTAP database.

2. The region includes the Middle East, Algeria-Lybia-Egypt, Indonesia, and Venezuela.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

Example 2: declared targets level

23. However, if countries achieve their declared targets in 2020, while at the same time, non-OECD countries phase out their fossil fuel subsidies over the period 2013-2020, the total resulting emission reductions would be more substantial. Under a **minimum-action scenario**, with targets¹² that countries

¹¹ In addition, there is a small amount of emission trading across OECD countries with the EU and Japan buying emissions from the other OECD countries, as expected from their higher marginal abatement costs.

¹² Two scenarios about declared targets are considered here following OECD (2010). The **minimum action scenario** is characterized by unilateral commitments and targets, 20% offsets and no linking between annex I carbon markets. In this scenario, Annex I pledges amount to -13% from 1990 while non Annex pledges amount I pledges amount to -4% from BAU. The **ambitious action scenario** with more ambitious targets; 20% offsets and a global carbon market for Annex I countries. Annex I pledges amount to -17% from 1990 while non Annex pledges amount I pledges amount to -7% from BAU.

have been committing to after COP15, one could expect a reduction of world emissions by 11% relative to the baseline in 2020 (see lower part of table 2).

24. Countries have also announced maximum targets, like for instance, for the EU a reduction by 30% in 2020 relative to 1990 levels in case of multilateral action instead of 20% in case of unilateral action. This **ambitious-action scenario** would amount to a total emission reduction by 15% in 2020. The emission reduction expected from fossil fuel subsidy reform therefore amounts to 30% and 20% respectively of these declared targets. The Table 2 illustrates also that implementing these targets together with a subsidy reform in non-OECD countries would yield higher emission reductions (12% and 16%, respectively) at a lower economic costs, especially with respect to the more ambitious targets.

Table 2. World GHG reductions and equivalent variation in real income from phasing out fossil fuel subsidies under different assumptions in 2020 and 2050.

Simulation	% deviation from the baseline, 2020			
	Total GHG emissions		Welfare	
	2020	2050	2020	2050
Central scenario	-2.8%	-8.9%	0.1%	0.2%
Central scenario with emission cap in remaining countries	-3.3%	-9.9%	0.1%	0.2%
Central scenario but using IEA 2005 price gaps	-2.8%	-9.3%	0.0%	0.1%
Central scenario assuming average 2007 price gaps in countries outside IEA database	-3.6%	-9.7%	0.2%	0.4%
Same as previous scenario with emissions cap in remaining countries	-4.3%	-11.1%	0.2%	0.4%
Central scenario but without phasing-out electricity subsidies	-1.4%	-7.2%	0.0%	0.0%
Central scenario with higher fossil fuel supply elasticities	-3.5%	-11.3%	0.0%	0.1%
Central scenario with lower fossil fuel supply elasticities	-3.1%	-8.2%	0.2%	0.3%
Central scenario with inelastic fossil fuel supply	-1.6%	-2.0%	0.3%	0.5%
Declared targets and actions scenarios				
minimum-action scenario	-10.6%	n.a.	-0.5%	n.a.
minimum-action scenario with fossil-fuel subsidies phasing-out	-12.4%	n.a.	-0.5%	n.a.
ambitious-action scenario	-14.9%	n.a.	-0.6%	n.a.
ambitious-action scenario with fossil-fuel subsidies phasing-out	-15.8%	n.a.	-0.5%	n.a.

Source: OECD ENV-linkages model with the use of fossil fuel subsidies data for 2007 estimated by IEA (2008).

c. Values of fossil fuel supply elasticities

25. One of the largest uncertainty sources is related to the assumed values of the fossil fuel supply elasticities. The central scenario is based on the assumption that the supply of coal is much more elastic (with an elasticity equal to 10) than for crude oil and natural gas (with elasticities respectively equal to 1 and 0.8). As illustrated in the Table 2, lower supply elasticities yield lower emission reductions because a larger proportion of the emission reduction achieved in non-OECD countries is offset by emission increases in OECD countries. In the extreme case of completely inelastic fossil fuel supplies, the

environmental benefit of the subsidy removal becomes negligible, with the total emission reduction falling to 2% only.¹³

26. The sensitivity to the values of the fossil fuel supply elasticities also reveals a trade-off between environmental and economic benefits, hence modifying the balance between the two sides of the “win-win options”. In the ENV-Linkages model, the fossil-fuel extracting sectors (coal mining, crude oil and natural gas) are modelled assuming a Leontieff input structure and a specific factor corresponding to the use of the corresponding resource the supply of which is more or less elastic.¹⁴ Therefore, higher supply elasticities imply that more fossil fuel are left in the ground as a result of a subsidy removal, hence implying GDP losses in fossil-fuel producing countries that partly offset the welfare gains from the subsidy reform.¹⁵ Vice versa, if the supply of fossil fuel is completely inelastic at the world level, these negative supply impacts are suppressed yielding estimates of the welfare gains that are closer to what would be obtained in a standard static neo-classical framework (a gain of 0.5% of world welfare in 2050 but with very few environmental gains).

6. Concluding remarks

27. The consumption of fossil fuel is heavily subsidized in many non-OECD countries. To the extent, that these subsidies amount to a negative carbon price, their removal is an obvious first step in the process of pricing carbon worldwide. Based on a world general equilibrium model, this analysis has shown that removing these subsidies should bring both environmental and economic benefits. The latter however are likely to be unevenly distributed as most oil-exporting countries are likely to face real income reductions. However, the real income losses incurred by OPEC countries are relatively small as the losses from their terms-of-trade deterioration are mostly compensated by the welfare gains from the reform of their subsidies.

28. These results are reasonably robust for a number of alternative assumptions. However, the values of the supply elasticities of the various fossil fuels is critical in determining the trade-off between environmental and economics benefits. This raises the risk that overestimating these elasticities, in particular with respect to coal, may tend to overestimate the resulting reduction of GHG emissions. This highlights the importance of collecting more empirical evidence about the supply elasticity of fossil fuels, especially for coal.

¹³ This residual reduction is induced through interfuel substitutions, i.e. as most of the subsidies concerns refined oil products, the international oil price falls more than the coal and gas prices, hence inducing a reduction of emissions.

¹⁴ This specification implies that the production of coal, for instance, is proportionate to the amount of coal extracted or, in other words, that no more coal can be produced by substituting capital or labour to the extraction of the resource.

¹⁵ Although, in an intertemporal framework with finite fossil fuel reserves, these fossil-fuel resources left into the ground can be extracted later on, leading to GDP increase relative to the baseline projections. These GDP gains are not taken into account in this analysis as the version of the ENV-Linkages model used here does not incorporate fossil-fuel reserve depletion dynamics in a consistent way.

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ANNEX:

Overview of the OECD ENV-linkages model

The OECD ENV-Linkages General Equilibrium model is the successor to the OECD GREEN model for environmental studies, which was initially developed by the OECD Economics Department (Burniaux, et al. 1992) and is now hosted at the OECD Environment Directorate. GREEN was originally used for studying climate change mitigation policy and culminated in Burniaux (2000). It was developed into the Linkages model, and subsequently became the JOBS/Polestar that was used to help underpin analysis for the book OECD(2001). A version of that model is also currently in use at the World Bank for research in global economic development issues. Previous works using extensively the model include two books : OECD (2008) and OECD(2009). Exploration of some of the model's properties and some sensitivity analysis is reported in OECD (2006).

1. The structure of the model

Key features

The ENV-Linkages model is a recursive dynamic neo-classical general equilibrium model. It is a global economic model built primarily on a database of national economies. In the version of the model used here, the world economy is divided in 12 countries/regions, each with 25 economic sectors (Tables 1 and 2), including five different technologies to produce electricity. Each of the 12 regions is underpinned by an economic input-output table (usually sourced from national statistical agencies). The database has been built and maintained at Purdue University by the Global Trade Analysis Project (GTAP) consortium. A fuller description of the database can be found at Dimaranan (2006). Those tables identify all the inputs that go into an industry, and identify all the industries that buy specific products.

Table 3. ENV-Linkages model sectors

Labels	Description
1) Rice	Paddy rice: rice, husked and in the husk.
2) Other crops	Wheat: wheat and meslin
	Other Grains: maize (corn), barley, rye, oats, other cereals
	Veg & Fruit: vegetables, fruits, fruit and nuts, potatoes, cassava, truffles.
	Oil Seeds: oil seeds and oleaginous fruits; soy beans, copra
	Cane & Beet: sugar cane and sugar beet
	Plant fibers: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles
	Other Crops
3) Livestock	Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof
	Other Animal Products: swine, poultry and other live animals; eggs, in shell, natural honey, snails
	Raw milk
	Wool: wool, silk, and other raw animal materials used in textile
4) Forestry	Forestry: forestry, logging and related service activities
5) Fisheries	Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing
6) Crude Oil	Parts of extraction of crude petroleum & service activities incidental to oil extraction excl. surveying

7) Gas extraction and distribution	Pars of extraction of natural gas & service activities incidental to gas extraction excl. surveying distribution of gaseous fuels through mains; steam and hot water supply
8) Fossil Fuel Based Electricity	Coal, Coal gases, Natural gases and oil fired electricity (production, collection and distribution)
9) Hydro and Geothermal electricity	Hydroelectric power and Geothermal electricity
10) Nuclear Power	Nuclear Power
11) Solar & Wind electricity	Solar, Wind, Wave and Tide Electricity
12) Renewable combustibles and waste electricity	wood, wood waste, other solid waste ; industrial waste ; municipal waste ; biogas ; liquid biofuels & waste
13) Petroleum & coal products	Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel
14) Food Products	Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules Pig meat and offal. Preserves and preparations of meat, meat offal or blood, flours Vegetable Oils: crude and refined oils of soya-bean, maize, olive, sesame, groundnut, olive seeds Milk: dairy products Processed Rice: rice, semi- or wholly milled Sugar Other Food: prepared and preserved fish or vegetables, fruit & vegetable juices, prepared fruits, flours, Beverages and Tobacco products
15) Other Mining	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying
16) Non-ferrous metals	Non-Ferrous Metals: production and casting of copper, aluminum, zinc, lead, gold, and silver
17) Iron & steel	Iron & Steel: basic production and casting
18) Chemicals	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
19) Fabricated Metal Products	Fabricated Metal Products: Sheet metal products, but not machinery and equipment
20) Paper & Paper Products	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
21) Non-Metallic Minerals	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
22) Other Manufacturing	Textiles: textiles and man-made fibers Wearing Apparel: Clothing, dressing and dyeing of fur Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear Other Transport Equipment: Manufacture of other transport equipment Electronic Equipment: office, accounting and computing, radio, television and communication equipment Other Machinery & Equipment: electrical machinery, medical, precision and optical, watches Other Manufacturing: includes recycling Motor Vehicles: cars, lorries, trailers and semi-trailers Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials
23) Transport services	Other Transport: road, rail ; pipelines, auxiliary transport activities; travel agencies Water transport Air transport
24) Services	Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants;

	repairs of motor vehicles and personal and household goods ;
	Water: collection, purification and distribution
	Retail sale of automotive fuel
	Communications: post and telecommunications
	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding
	Insurance: includes pension funding, except compulsory social security
	Other Business Services: real estate, renting and business activities
	Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons
	Other Services (Government): public administration and defense; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and similar activities, activities of membership organizations n.e.c., extra-territorial organizations and bodies
25) Construction & Dwellings	Construction: building houses factories offices and roads
	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)

Table 4. Table 2. ENV-Linkages model regions

ENV-Linkages regions	GTAP countries/regions
1) Australia, New Zealand	Australia, New Zealand
2) Japan	Japan
3) Canada	Canada
4) United States	United States
5) European Union and EFTA	Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxembourg, Netherlands, Portugal, Sweden, France, Germany, United Kingdom, Italy, Spain, Switzerland, Rest of EFTA, Czech Republic, Slovakia, Hungary, Poland, Romania, Bulgaria, Cyprus, Malta, Slovenia, Estonia, Latvia, Lithuania
6) Brazil	Brazil
7) China	China, Hong Kong
8) India	India
9) Russia	Russian Federation
10) Oil producing countries	Indonesia, Venezuela, Rest of Middle East, Islamic Republic of Iran, Rest of North Africa, Nigeria
11) Rest of Annex 1 countries	Croatia, Rest of Former Soviet Union
12) Rest of the world	Korea, Taiwan, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of East Asia, Rest of Southeast Asia, Cambodia, Rest of Oceania, Bangladesh, Sri Lanka, Rest of South Asia, Pakistan, Mexico, Rest of North America, Central America, Rest of Free Trade Area of Americas, Rest of the Caribbean, Colombia, Peru, Bolivia, Ecuador, Argentina, Chile, Uruguay, Rest of South America, Paraguay, Turkey, Rest of Europe, Albania, Morocco, Tunisia, Egypt, Botswana, Rest of South African Customs Union, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Rest of Southern African Development Community, Mauritius, Madagascar, Uganda, Rest of Sub-Saharan Africa, Senegal, South Africa.

Production

All production in ENV-Linkages is assumed to operate under cost minimisation with an assumption of perfect markets and constant return to scale technology. The production technology is specified as nested CES production functions in a branching hierarchy. Figure 1 illustrates the typical nesting of the model's sectors (some sectors, like agriculture have a different nesting). The nesting of the electricity production is slightly different and is reported in Figure 2. In Figure 1 and 2, each node represents a constant elasticity of substitution (CES) production function. This gives marginal costs and represents the different substitution (and complementarity) relations across the various inputs in each sector. Each sector uses intermediate inputs – including energy inputs - and primary factors (labour and capital). In some sectors, primary factors include natural resources, *e.g.* trees in forestry, land in agriculture, etc.

In a way similar to Hyman *et al.* (2002), the top-level production nest considers final output as a composite commodity combining emissions of non-CO₂ gases and the production of the sector net of these emissions. In sectors that do not emit non-CO₂ gases, the corresponding emission rate is set equal to zero. For the purpose of calibration, these non-CO₂ gases are valued using an arbitrary very low carbon price. The following non-CO₂ emission sources are considered: *i*) methane from rice cultivation, livestock production (enteric fermentation and manure management), coal mining, crude oil extraction, natural gas and services (landfills); *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), aluminum, magnesium and semi-conductors production. The values of the substitution elasticities are calibrated such as to fit to marginal abatement curves available in the literature on alternative technology options (US-EPA, 2006b).

The second-level nest considers the gross output of sector (net of GHGs) as a combination of aggregate intermediate demands and a value-added bundle, including energy. For each good or service, output is produced by different production streams which are differentiated by capital vintage (old and new). Capital that is implemented contemporaneously is new – thus investment impacts on current-period capital; but then becomes old capital (added to the existing stock) in the subsequent period. Each production stream has an identical production structure, but with different technological parameters and substitution elasticities. Letting $X_{i,v}$ represents gross output of sector i (net of GHGs) using capital of vintage v , the equations representing production are derived from first order conditions [1]-[3] of the firm's profit maximisation objective.

$$INT_i = \sum_v \alpha_{i,v}^{INT} \times A_{i,v}^{\sigma_{i,v}^p - 1} \times \left(\frac{VC_{i,v}}{P_i^{INT}} \right)^{\sigma_{i,v}^p} \times X_{i,v} \quad [1]$$

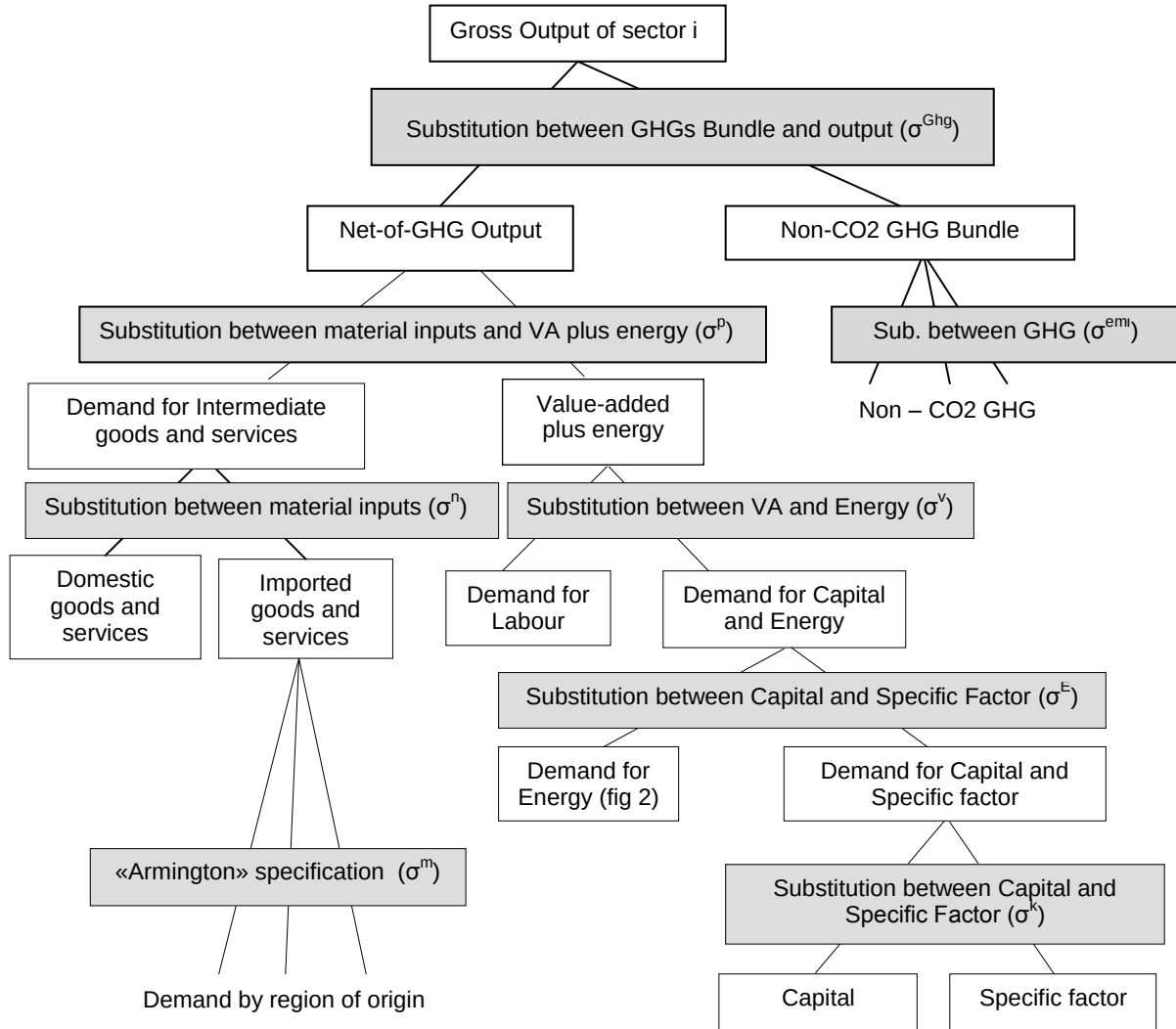
$$VA_{i,v} = \alpha_{i,v}^{VA} \times A_{i,v}^{\sigma_{i,v}^p - 1} \times \left(\frac{VC_{i,v}}{P_i^{VA}} \right)^{\sigma_{i,v}^p} \times X_{i,v} \quad [2]$$

$$VC_{i,v} = \frac{1}{A_i} \times \left[\alpha_{i,v}^{INT} (P_i^{INT})^{1-\sigma_{i,v}^p} + \alpha_{i,v}^{VA} (P_i^{VA})^{1-\sigma_{i,v}^p} \right]^{(1/(1-\sigma_{i,v}^p))} \quad [3]$$

where INT is the intermediate demand bundle (P^{INT} its price), VA represents value-added (P^{VA} its price), VC is unit variable cost of producing one unit of net of GHGs output (average costs include the cost of capital),

A is a technical change term. In order to determine the industry-wide cost that includes both capital vintages, there is an averaging (weighted) of variable costs across the two vintages.

Figure 7. Structure of production in ENV-Linkages



Note: see Table 3 for parameter values

In each period, the supply of primary factors (*e.g.* capital, labour, land and natural resources) is usually predetermined. On the right hand side of the tree in Figure 1 value-added¹⁶ is shown as being composed of a labour input [4] along with a composite capital/energy bundle [5]:

¹⁶ The valued-added bundle is specified as a CES combination of labour and a broad concept of capital. In the “crop” production sector, this capital is itself a CES combination of fertilizer and another bundle of capital-land-energy. The intention of this specification is to reflect the possibility of substitution between intensive and extensive agriculture. In the “livestock” sector, substitution possibilities are between bundles of land and feed, on the one hand, reflecting a similar choice between extensive and intensive livestock production, and of capital-energy-labour bundle, on the other hand.

$$L_i = \sum_v \alpha_{i,v}^L \times \lambda_i^{\sigma_{i,v}^V - 1} \times \left(\frac{P_{i,v}^{VA}}{W_i} \right)^{\sigma_{i,v}^V} \times VA_{i,v} \quad [4]$$

$$KE_{i,v} = \alpha_{i,v}^{KE} \times \left(\frac{P_{i,v}^{VA}}{P_{i,v}^{KE}} \right)^{\sigma_{i,v}^V} \times VA_{i,v} \quad [5]$$

where L represents labour (W its price), λ is the technical progress associated with labour, and KE is the capital-energy bundle (P^{KE} its price). The price of the value-added bundle, for generation v , is:

$$P_{i,v}^{VA} = \frac{1}{A_{i,v}} \times \left[\alpha_{i,v}^{KE} (P_{i,v}^{KE})^{1-\sigma_{i,v}^V} + \alpha_{i,v}^L \left(\frac{W_i}{\lambda_i} \right)^{1-\sigma_{i,v}^V} \right]^{(1/(1-\sigma_{i,v}^V))} \quad [6]$$

The value-added bundle (VA) is a sub-component of the top level node that produces sectoral net-of-GHGs output X_i . Similar sub-components also exist in formulating the capital and energy bundles. In fact, as shown in Figure 1, the capital is bundled with a sector-specific resource when one exists and energy is itself a bundle of different energy inputs.

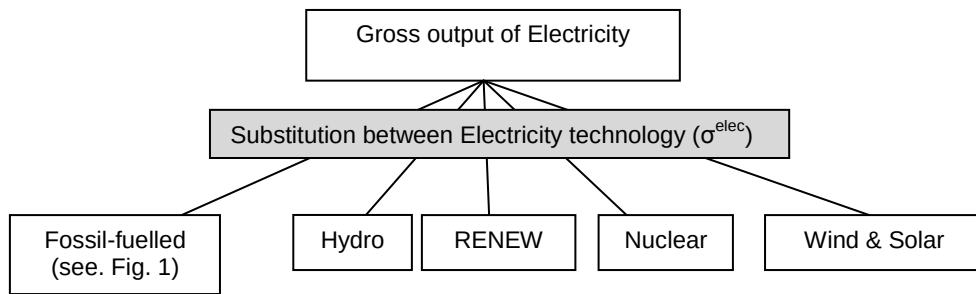
The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the five available technologies to generate electricity using a CES specification with a large value of the elasticity of substitution (Figure 2). The production of the non-fossil electricity technology (net of GHG and expressed in TeraWatt per hour) has a structure similar than for the other sectors, except a top nesting combining a sector-specific natural resource, on one hand, and all other inputs, on the other hands. This specification aims at controlling the supply of these electricity technologies given the value of the substitution elasticity.

The energy bundle is of particular interest for analysis of climate change issues. Energy, as reported in Figure 3, is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of the “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.

Given the dual streams of production (from old and new capital), there is a higher degree of substitutability between energy sources when capital is new, but after one year it becomes a sunk cost and falls to a low level of substitutability among energy sources. Moreover, in the sectors that produce fossil fuels (with the exception of natural gas), there is no substitutability between energy inputs. The low level of substitutability of energy when old capital is present is consistent with empirical findings by Arnberg and Bjorner (2007) who look at plant level changes in energy intensity. However, since this model includes the possibility of changes in industry composition, the overall responsiveness to energy price changes will be higher than these researchers found at plant levels.

Total output for a sector is the sum of two different production streams: resulting from the distinction between production with an “old” capital vintage, and production with a “new” capital vintage. The substitution possibilities among factors are assumed to be higher with new capital than with old capital. In other words, technologies have putty/semi-putty specifications. This will imply longer adjustment of quantities to prices changes. Capital accumulation is modelled as in traditional Solow/Swan neo-classical growth model.

Figure 2. Structure of electricity generation



See Fig. below for these technologies

Structure of production of non-fossil technologies

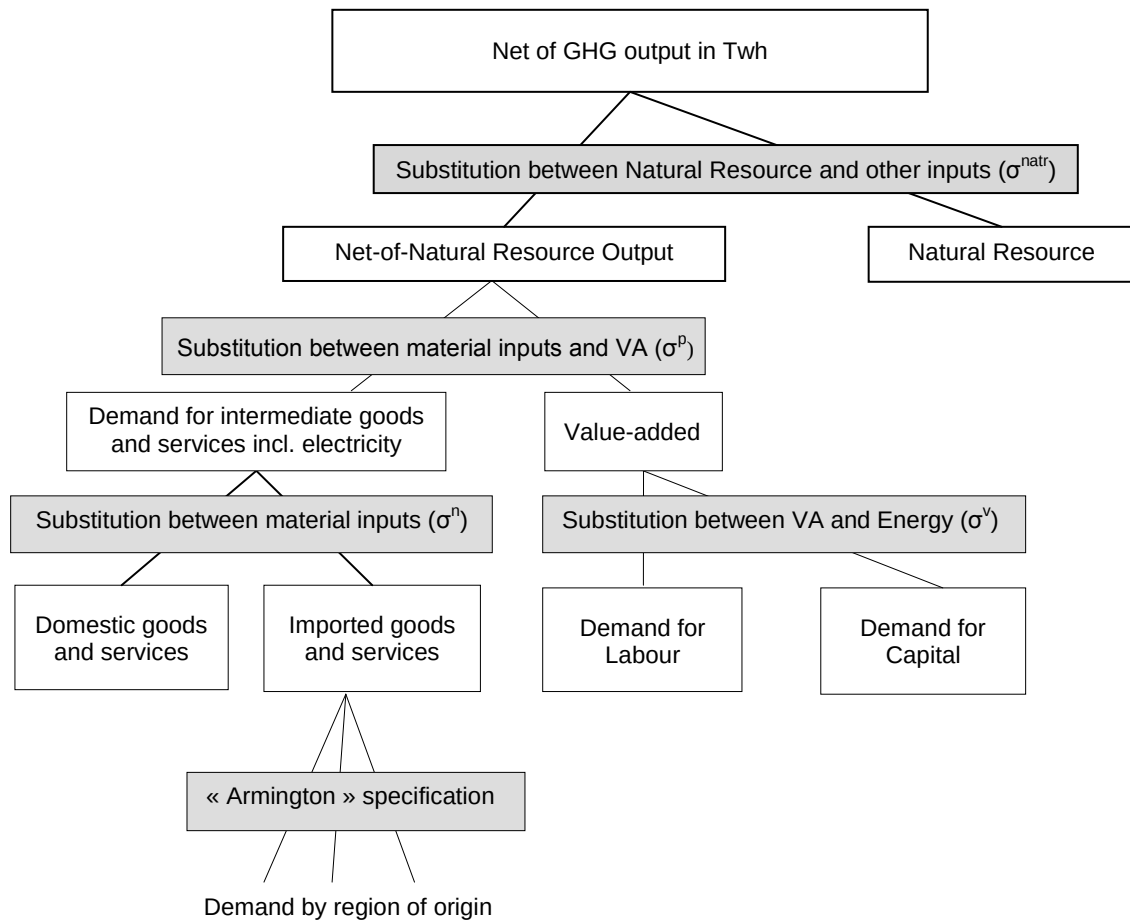
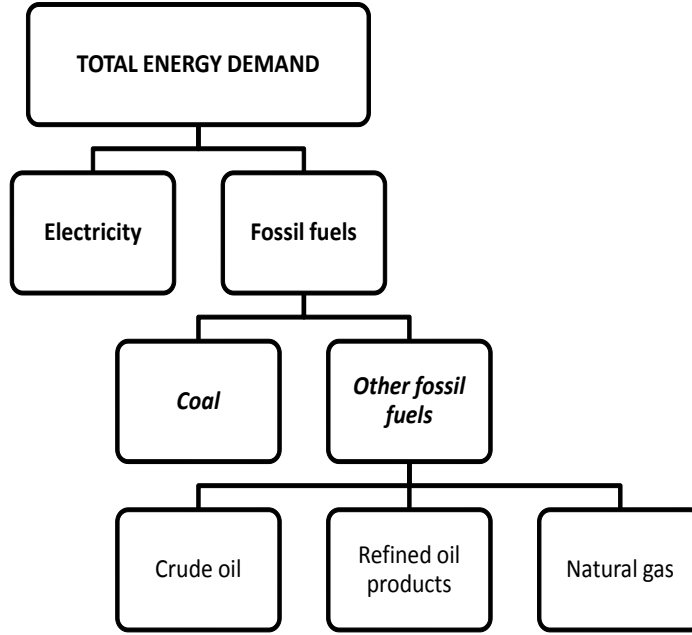


Figure 3. Structure of energy intermediate demands



Consumption

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 and therefore does not rely on a forward-looking behaviour by the consumer. Formally, a representative consumer maximises well-being (utility) subject to resource constraints:

$$\begin{aligned}
 \text{Max } U &= \sum_k \mu_k \ln(C_k - \theta_k) + \mu_s \ln\left(\frac{S}{P_s}\right) \\
 \text{Subject to } \sum_k P_k^c C_k + S &= Y, \quad \text{and} \quad \sum_k \mu_k + \mu_s = 1
 \end{aligned}$$

where U represents utility, C is a vector of k consumer goods, P^c is the vector of consumer prices, S represents the value of saving, P_s the relevant price of saving, and Y is total net-of-taxes income (completely allocated between consumption and savings). The parameter θ is the floor level of consumption – its main function is in making the utility function non-homothetic, which is consistent with considerable empirical evidence (*e.g.* Dowrick, *et al.* 2003). Since consumers are not represented with forward-looking behavior, some care needs to be exercised in studying policies that consumers may reasonably be expected to anticipate – either the policy itself or its consequences. For each country, the consumer’s objective function thus gives rise to household private consumptions [7] and saving [8]:

$$C_k = \text{Pop} \times \theta_k + \frac{\mu_k}{P_k^c} \times Y^*, \quad \text{where } Y^* = Y^c - \text{Pop} \times \sum_k P_k^c \times \theta_k \quad [7]$$

$$S = Y^c - \sum_k P_k^c \times C_k \quad [8]$$

where Pop represents population, Y^c represents household disposable income and Y^* is a *supernumerary* income (i.e. income above the subsistence level).

Foreign Trade

World trade is based on a set of regional bilateral flows. The basic assumption is that imports originating from different regions are imperfect substitutes. Therefore in each region, total import demand for each good is allocated across trading partners according to the relationship between their export prices. This specification of imports - commonly referred to as the Armington specification - formally implies that each region faces a reduction in demand for its exports if domestic prices increase. The Armington specification is implemented using two CES nests. At the top nest, domestic agents choose the optimal combination of the domestic good and an aggregate import good [9]. At the second nest, agents optimally allocate demand for the aggregate import good [11] across the range of trading partners r' .

$$XMT_i = \beta_i^m \times \left(\frac{PA_i}{PMT_i} \right)^{\sigma_i^m} \times XA_i \quad [9]$$

$$PMT_i = \left[\sum_r \beta_{i,r}^w PM_{i,r}^{1-\sigma_{i,r}^w} \right]^{(1/(1-\sigma_i^w))} \quad [10]$$

where XMT is the bundle of imports of a particular good or service (PMT its price) and XA represents the aggregate demand for domestically produced and import goods (PA is its price).

$$WTF_{r',i} = \beta_{r',i}^w \times \left(\frac{PMT_i}{PM_{r',i}^M} \right)^{\sigma_i^w} \times XMT_i \quad [11]$$

where $WTF_{r'}$ is import of a particular good or service from region r' . Its price, $PM_{r'}$, represents the domestic import price (e.g. domestic producer price of its partner r' adjusted for export tax or subsidy, transport margin, “iceberg” costs, and domestic tariffs).

Investment and Market goods equilibria

This version of the model does not include an investment schedule that relates investment to interest rates. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad. Investment as well as government demand use final goods according with a CES specification. Then, the total demand of a good in the economy is equal to the consumer final demand plus the intermediary demands from firms plus the intermediary demands by final good sectors, corresponding to government and investment expenditures.

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, according to the Armington principle, between the demands (both final and intermediary) addressed to domestic producers and the import demand (see below).

Government and long-term closure

Government collects income taxes, indirect taxes on intermediate and final consumption as well as possible carbon taxes, production taxes, tariffs, and export taxes/subsidies. Aggregate government expenditures are linked to real GDP. Since predicting corrective government policy is not an easy task, the

real government deficit is exogenous. The closure of the model implies that some fiscal instrument is endogenous – in order to meet government budget constraint. Given also a sequence of public savings (or deficits), the fiscal closure rule in ENV-Linkages is that the income tax rate adjusts to offset changes that may arise in government expenditures, or as a result of other taxes. For example, a reduction or elimination of tariff rates is compensated by an increase in household direct taxation, *ceteris paribus*. Alternative closure rules can be easily implemented.

For studying the impacts of climate change policy, four types of instruments have been developed: GHG taxes, global or specific by sectors, gases or emission sources; tradable emission permits (with flexibility between regions and sectors); offsets (including the Clean Development Mechanism) and regulatory policy (modelled as quantity constraints). Taxes and tradable permits are applied on inputs of fossil-fuel producing sectors (refined petroleum, natural gas, coal). They are applied, as well, on final demands of fossil-based energy. Regulatory policy has also been introduced in the model through a mechanism imposing a shadow cost on the firm's inputs or capital. It has the effect of changing the marginal cost of particular inputs, or changing the quantity of capital used to produce a given output, but does use market instruments. The analysis requires assumptions concerning the cost of the regulatory policy, but it breaks the link between policy instruments and revenue transfer that is inherent in tax policy and tradable permits.

Factor-income taxes as well as factor taxes and subsidies on factor supply have also been introduced as these instruments are distinguished in the GTAP version 6.2 database. From IEA databases we have also introduced fossil-fuel subsidies to energy demands.

Each region runs a current-account surplus (or deficit), which is fixed (in terms of the model *numéraire*). Closure on the international side of each economy is achieved by having, as a counterpart of these imbalances, a net outflow (or inflow) of capital, which is subtracted from (added to) the domestic flow of saving. These net capital flows are exogenous. In each period, the model equates investment to saving (which is equal to the sum of saving by households, the net budget position of the government and foreign capital flows). Hence, given exogenous sequences for government and foreign savings, this implies that investment is ultimately driven by household savings.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relatively to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. From the point of view of the model specification, this has an impact on the evaluation of international investment flows. They are evaluated with respect to the price of the numéraire good. Therefore, one way to interpret the foreign investment flows is as the quantity of foreign saving which will buy the average bundle of OECD manufacturing exports.

Dynamic Features

The ENV-Linkages model has a simple recursive dynamic structure as agents are assumed to be myopic and to base their decisions on static expectations concerning prices and quantities. Dynamics in the model originate from two endogenous sources: *i*) accumulation of productive capital and *ii*) the putty/semi-putty specification of technology, as well as, from exogenous drivers like population growth or productivity changes.

At an aggregate level, the basic capital accumulation function equates the current capital stock to the depreciated stock inherited from the previous period plus investment. Differences in sectoral rates of return determine the allocation of investment across sectors. The model features two vintages of capital, but investment adds only to new capital. Sectors with higher investment, therefore, are more able to adapt to

changes than are sectors with low levels of investment. Indeed, declining sectors whose old capital is less productive begin to sell capital to other firms (which they can use after incurring some adjustment costs).¹⁷

The substitution possibilities among production factors are assumed to be higher with the *new* than with the *old* capital vintages — technology has a putty/semi-putty specification. Hence, when a shock to relative prices occurs (*e.g.* tariff removal), the demands for production factors adjust gradually to the long-run equilibrium because the substitution effects are delayed over time. The adjustment path depends on the values of the short-run elasticities of substitution and the replacement rate of capital. As the latter determines the pace at which new vintages are installed, the larger is the volume of new investment, the greater the possibility to achieve the long-run total amount of substitution among production factors.

2. Calibration of the ENV-Linkages model

The process of calibration of the ENV-Linkages model is broken down into three stages. First, a number of parameters are calibrated, given some elasticity values, on base-year (2001) values of variables. This process is referred to as the static calibration. Second, the 2001 database is updated to 2005 by simulating the model dynamically over the period 2001-2005 and static calibration is performed again with price re-normalisation in order to express all variables in 2005 real \$US. Third, the baseline projection is obtained by defining a set of exogenous socio-economic drivers (demographic trends, labour productivity, future trends in energy prices and energy efficiency gains) and running the model dynamically again over the period 2005-2050.¹⁸

Static calibration of the model

Many key parameters are set on the basis of information drawn from various empirical studies and data sources (elasticities of substitution, income elasticities of demand, supply elasticities of natural resources, etc). Table 3 reports some key elasticities used in the current version of the model. Use of these parameters was illustrated in Figures 1 and 2, as well as by the equations in Section 3. Income elasticities of household demand as well as Armington elasticities are taken from the GTAP 6.2 database.

However, the information available on the values of these parameters is insufficient for the model simulation to be able to reproduce base-year data values. Given the modelling choices made with regard to the representation of both behaviours and structural technical relationships, some model parameters must be calculated to fit to the data for the initial year (expressed in 2001 \$US) of the version 6 of the GTAP database. As a general rule, the parameters used to do this are those whose impact on the outcomes in terms of variation rates remains limited (scale parameters) or parameters for which there are no empirical studies (CES share coefficients).¹⁹

¹⁷ Formally, at the sectoral level, the specific accumulation functions may differ because the demand for (old and new) capital can be less than the depreciated stock of old capital. In this case, the sector contracts over time by releasing old capital goods. Consequently, in each period, the new capital vintage available to expanding industries is equal to the sum of disinvested capital in contracting industries plus total saving generated by the economy.

¹⁸ The baseline simulation also contains the assumption that the EU Emission Trading System is implemented over the period 2006-2012, assuming a permits price that will rise gradually from 5 to 25 constant \$US in 2012 and for the years after.

Table 5. Table 3. Key parameter values

Key parameter		Value
σ^{Ghg}	Substitution between GHGs bundle and Net-of-GHGs Output	Substitution is from 0.03-0.05 for Agr. Sectors to 0.15-0.3 in some industrial emissions
σ^{p}	Substitution between material inputs and VA plus energy	Substitution between material inputs and VA plus energy is 0, except for new capital in manufacturing where it is 0.1.
σ^{n}	Substitution between material inputs	Substitution between material inputs is 0 for non services and non manufacturing sector and 0.1 for other sectors.
σ^{v}	Substitution between VA and Energy	0.05 for old capital vintages and 0.4 for new vintages in agriculture, forestry and fishing and fossil fuels sectors and varying from 0.2-0.27 (1.8-2.1 in other sectors)
σ^{f}	Substitution between inputs investment and government exp.	0.8
σ^{E}	Substitution between Capital and Energy	0 for old capital vintages, 0.2-0.8 for new vintages, but always 0 in coal and crude oil.
σ^{k}	Substitution between Capital and Specific Factor	Substitution between Capital and Specific Factor is 0
σ^{ELY}	Elasticity between Electricity & Non-electricity energy inputs	0.062 for old capital and 0.5 for new in electricity sector. 0.12 and 1 in other sector except fossil fuel where equals to 0 and chemicals where 0.08 and 0.4.
σ^{Coa}	Elasticity between Coal & Non-Coal bundle	0.03 for old capital and 0.25 for new in electricity sector. 0.12 and 1 in other sector except fossil fuel where equals to 0.
σ^{Ep}	Elasticity between energy inputs in Non-Coal bundle	0.25 for old capital vintages, 2 for new vintages, but always 0 in the energy sectors, except for Electricity
σ^{x}	Armington elasticity, domestic versus imports	Varies from 0.9 to 5 depending on sectors, identical across regions. GTAP data is used
σ^{W}	Armington elasticity, import sources	Same as σ^{x}
σ^{M}	Armington elasticity, intermediate goods imports	Same as σ^{x}
σ^{El}	Armington elasticity, energy imports	Same as σ^{x}
σ^{elec}	Elasticity between electricity technologies	10
σ^{natr}	Elasticity between specific resource and other inputs	Only for non-fossil electricity technologies, varying from 0.0-0.4

Dynamic calibration of the model

Ideally, an informed choice of prospective trends in exogenous variables would produce a set of acceptable scenarios. However, it is difficult to cover all these trends comprehensively. Furthermore, this would make comparisons of different alternative scenarios practically unmanageable. Therefore, the approach followed here considers only one single set of exogenous drivers while recognising that alternative sets may potentially generate somewhat different simulation results. The baseline projection allows calculating the values of a number of parameter over time (such as energy efficiency gains, for instance), in order to reproduce the evolution of the exogenous drivers. In any variants or policy

simulations, these parameter values are kept constant while all other variables in the model are fully endogenous.²⁰

The list of exogenous drivers specified in the baseline projection is the following:

- Demographic projections and employment trends,
- Aggregate average and sectoral labour productivity growth, controlled by calibration of technical progress coefficients embodied in labour,
- Autonomous efficiency gains for capital, land and specific natural resources,
- Autonomous efficiency gains of fertilizers in crops sectors and of the food bundle in livestock rearing,
- Supply of land and natural resources (excepted for fossil fuels sectors),
- International trade margins,
- Shares of public expenditure in real GDP,
- Public savings and flows of international savings,
- Energy demands (projected by using elasticities of demands to GDP), for all kind of fuels demands excepted crude oil, controlled by calibration of the Autonomous Energy Efficiency Improvements (named AEEIs) in energy use, by sector and type of fuel,
- International prices of fossil fuels, controlled by calibration of the potential supply of fossil fuels resources,
- Investment to GDP ratios, controlled by calibration of the marginal propensity to save of the households,
- Non-CO₂ fuel GHGs emissions, controlled by calibration of autonomous efficiency gains in non-CO₂ GHGs emissions, by sector and type of GHGs emissions,
- The share of each type of electricity-producing technology, controlled by calibration of the specific “natural resource”.

Note on data sources

Socio-economic variables such as population, apparent labour productivity or investment to GDP ratios are discussed in Duval and De la Maisonneuve (2009). Sectoral labour productivity growth rates used to calibrated the model are extracted from OECD-STAN database as well as Groningen Database for non-OECD countries.

AEEIs in energy uses have been dynamically calibrated on the basis of elasticities of each kind of energy demand to GDP for 2005-2030 as projected in the IEA's *World Energy Outlook* (2006-2008). These elasticities are assumed to evolve after 2030 in line with their projected trends over the period 2025-2030. The structure of electricity production between the five alternative technologies is calibrated based on the projections from the IEA's *World Energy Outlook* (2008). The evolution of the international import prices of fossil fuels are also controlled for in the baseline scenario. During the period 2005-2008, the model reproduces the historical evolutions and short run projections made by the IEA for its *World Energy Outlook 2008* report.

The non-CO₂ greenhouse gases need to be calibrated in the base year database. For this purpose, the price of these emissions is arbitrary set equal to 0.5 USD per ton of CO₂ equivalent in the upper bundle of the gross output. Emissions by source reported in US EPA (2006b) are associated to the sectors of ENV-

²⁰

For instance, in the baseline scenario, the technical progress embodied in labour is calibrated to reproduce given GDP trends. In contrast, in any policy variants, GDP is fully endogenous given this technical progress calculated in the baseline scenario.

linkages, and for sake of consistency GHGs levels in 2005 are adjusted to match IEA data in this study. It was not possible to associate all emission sources to an economic activity described in the model.²¹ For the period 2005-2020, the non-CO₂ emissions are calibrated on forecasts made by the US EPA by adjusting an autonomous efficiency parameter in the emissions bundle of the production function. After 2020 the trend over the period 2015-2020 is extended, except for agriculture sources of non-CO₂ GHGs emissions where the trend assumed is taken from the OECD Environmental Outlook (2008).

A carbon dioxide emissions database has been developed for GTAP (Lee, 2002) that uses data provided to GTAP by the International Energy Agency. The emission rates for non-CO₂ gases come from US-EPA (2006a). 27 sources of emissions over the 32 censed by US-EPA are implemented in the model.

From 2001-2005, current account balances as well as government savings are calibrated to match OECD-IMF historical data. After 2005, government deficits (or surplus) as well as current accounts deficits (or surplus) are assumed to gradually vanished (at an arbitrary 2.5% rate of reduction per year). However, the Chinese surplus and US deficit are assumed to disappear less rapidly (only after 2020).

Structural dynamic changes

In addition, the parameters relative to household demands (see equations 1-3) need to be recalibrated dynamically in the baseline simulation. The household preferences in ENV-Linkages include a minimum subsistence level of demand for each good that makes the utility function non-homothetic. However, when using the model over a rather long projection horizon, household income increase quite substantially and, if the minimum subsistence demands are not adjusted, income elasticity of demand for all goods converge towards unity. This problem is offset by adjusting the subsistence parameters in the baseline scenario for each period in order to reproduce the desired set of income elasticities. Moreover in the baseline simulation, income elasticities of demand are evolving over time assuming, a conditional convergence of household preferences (*e.g.* income elasticities of demand for non-energy goods) of the non-OECD countries to the OECD standard, based on relative income per capita.

In a model like ENV-Linkages that uses so-called Armington specifications to represent international trade flows, countries face downward sloping demand for their exports. Therefore, a fast-growing country would typically experience a decline in its relative factor prices, implying a depreciation of its real exchange rate, *ceteris paribus* (abstracting from the offsetting Balassa-Samuelson effect). This appears inconsistent with past history, which shows that imports from fast-growing countries have typically increased through the creation of new products rather than through price reductions (see in particular Krugman, 1989). In order to capture this historical feature in a simplified manner, the baseline projection further assumes a gradual exogenous increase in the share of non-OECD countries in the overall imports of OECD countries.

In addition, the increase in global competition is accompanied by growth in the use of services in production, in line with the argument advanced in OECD (2005). This is simulated by adjusting dynamically the input-output structure such as to increase the weight of services (in the broad sense of the term) in the composition of the bundle of intermediate goods, for non-agricultural and non-fossil fuels sectors.

21. Non-CO₂ emissions from forest and savannas' burning are not introduced. They correspond to less than 5% of the non-CO₂ emissions reported by the US EPA.