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An Overview of the OECD ENV-Linkages Model

VERSION 3

Jean Château, Rob Dellink, Elisa Lanzi

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By Jean Chateau, Rob Dellink and Elisa Lanzi, OECD

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ABSTRACT

This document provides a detailed technical description of the ENV-Linkages model. The OECD ENV-Linkages Computable General Equilibrium (CGE) model is an economic model that describes how economic activities are inter-linked across several macroeconomic sectors and regions. It links economic activity to environmental pressure, specifically to emissions of greenhouse gases (GHGs). The links between economic activities and emissions are projected for several decades into the future, and thus shed light on the impacts of environmental policies for the medium- and long-term future. In this paper specific attention is given to the equations that form the core of the model. The version of the model presented here is used for analysis carried out for the *OECD Environmental Outlook to 2050* (OECD, 2012). An updated version of the model is expected to play a key role in the new CIRCLE project (OECD, 2013).

Keywords**:** General equilibrium model, climate change, long-term scenarios

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RÉSUMÉ

Ce manuel donne une description détaillée du modèle ENV-Linkages. Le modèle ENV-Linkages de l'OECD est un modèle d'Équilibre Général Calculable (MEGC) qui décrit les relations économiques entre secteurs d'activité, pays et agents économiques. Le modèle associe les émissions de gaz à effet de serre aux différentes activités économiques reproduites. Les liens entre les émissions et les activités économiques sont projetés à un horizon de plusieurs décennies, mettant ainsi en avant les impacts à moyen et long terme des politiques environnementales. L'attention est portée dans ce document sur une description technique des équations sous-jacentes du modèle. La version du modèle présentée est celle utilisée dans les *Perspectives de l'environnement à l'horizon 2050* (OECD, 2012). Une version mise à jour du modèle jouera un rôle essentiel dans le nouveau projet CIRCLE (OCDE, 2013).

Mots-clés: Modèle d'équilibre général calculable, changement climatique, scénarios de long-terme

Classification JEL: D58, H23, O41, Q54, Q56

FOREWORD

This report presents a global (recursive-) dynamic computable general equilibrium model called ENV-Linkages. This version of the model (version 3) has been used to provide baseline and policy scenario projections in the *OECD Environmental Outlook to 2050: The Consequences of Inaction* (OECD 2012). It highlights how various firms and households interact in the economy, and how this in turn affects energy use and greenhouse gas emissions. The calibration of the model and resulting baseline projection is described in detail in a separate paper of the OECD Environment Working Paper series (Chateau, Rebolledo and Dellink, 2012, OECD Environment Working Paper no. 41). An updated version of the model is expected to play a key role in the OECD project on the feedbacks of environmental challenges on economic growth, called CIRCLE (OECD, 2013).

This report was authored by Jean Chateau, Rob Dellink and Elisa Lanzi of the OECD Environment Directorate. An abridged version of this document (ENV/EPOC(2010)16) was reviewed by delegates of the Environmental Policy Committee as part of the review process for the *Environmental Outlook to 2050*. A full draft was reviewed by technical experts (nominated by member countries) at the ad-hoc workshop of the CIRCLE project in October 2013. It was then submitted to EPOC for declassification under the written procedure and declassified after incorporation of all comments received. The authors are also grateful to modelling and editorial suggestions by Cuauhtemoc Rebolledo-Gómez, Bertrand Magné, Olivier Durand-Lasserve, François Chantret, and Shardul Agrawala of the OECD, to visitors Ruth Delzeit, Damian Mullaly and Lorenza Campagnolo, and especially to Jean-Marc Burniaux (formerly of OECD) for teaching us the finesses of global general equilibrium modelling.

More information on the baseline projections and applications using the ENV-Linkages model can be found at www.oecd.org/environment/modelling. More information on the CIRCLE project can be found here: www.oecd.org/env/indicators-modelling-outlooks/circle.htm. Further enquiries should be directed to Rob Dellink or Jean Chateau at the OECD Environment Directorate (email rob.dellink@oecd.org ; email: jean.chateau@oecd.org).

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AN OVERVIEW OF THE OECD ENV-LINKAGES MODEL: VERSION 3

1. Introduction

The OECD ENV-Linkages Computable General Equilibrium (CGE) model is an economic model that describes how economic activities are inter-linked across several macroeconomic sectors and regions. It links economic activity to environmental pressure, specifically to emissions of greenhouse gases (GHGs). The links between economic activities and emissions are projected for several decades into the future, and thus shed light on the impacts of environmental policies for the medium- and long-term future. The advantages of multi-sectoral, multi-regional (recursive-) dynamic GE models, like ENV-Linkages, involve their global dimension, their overall consistency and the fact that they are based on rigorous micro-economic foundations. These models are best suited to analyse the medium- and long-term implications of large policy shifts generating substantial reallocation across sectors and countries/regions and the associated direct and indirect effects. In that sense, these models are preferred tools for assessing and quantifying policy responses to a wide range of government initiatives such as climate change policies.

Some of the model's limitations in representing economic phenomena such as endogenous capital mobility and forward-looking behaviour complicate the types of policies that the model can adequately address. For example, in the model an announcement of future policy action would not affect immediate behaviour of firms and consumers. This may lead to overstating the cost of the policy upon actual implementation. On the other hand, insofar as people in reality do not change their behaviour in anticipation of the policy action, for instance because they deem it unlikely that the policy will be implemented in the way it is proposed, the model's response to the policy may be more appropriate. This example illustrates the need to present the model's results along with a clear discussion of the context in which the policies are assumed to operate. One important way to improve the robustness of the model results is to express the impact of policy changes on key indicators in terms of changes relative to a baseline scenario, rather than providing absolute numbers. This underlines the importance of relying on a realistic and accurate baseline which reflects the most recent trends and economic studies.

The ENV-Linkages model is the successor to the OECD GREEN model, 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 policies (see Burniaux, 2000). It was developed into the Linkages model (Van der Mensbrugghe, 2005), and subsequently became the JOBS/Polestar modelling platform that was used to help underpin the first *OECD Environmental Outlook* (OECD, 2001).

Previous work using the model includes development of a baseline to 2030 and a study of the consequence of structural changes (including some environmental implications) associated with economic growth. Much of the applied work with the model is reported in various chapters of the OECD *Environmental Outlook to 2030* (2008) and in the context of a joint project between the OECD Economics Department and the OECD Environment Directorate on the economics of climate change mitigation (OECD, 2009). Most recently, the model has been used extensively in the *OECD Environmental Outlook to 2050* (OECD, 2012). Section 5 further describes some of these and other recent applications. Model extensions that are foreseen in the near future, especially those for the new CIRCLE project, are briefly discussed in Section 6.

This document, which presents a description of the ENV-Linkages model version 3 (Summer 2012), is structured as follows. Section 2 introduces the model and briefly reviews its key features. Section 3 describes the structure of the model and discusses its main equations. Section 4 discusses the calibration method, first to fit the model on base year data, and second to dynamically produce a baseline emissions projection. Section 5 focuses on the recent developments in the model, while Section 6 briefly introduces some foreseen future model developments.

2. A brief overview of the ENV-Linkages 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. Each of the regions is underpinned by an economic input-output table (usually sourced from national statistical agencies). These tables quantify economic flows across the different economic agents, including purchases of intermediate products and primary factors in all industries and the associated production outputs, as well as sources of income for households and governments and the associated consumption expenditures.

All production in ENV-Linkages is assumed to operate under cost minimisation with an assumption of perfect markets and technologies that exhibit constant returns to scale. The production technologies are specified as multi-level ('nested') production functions that assume constant elasticities of substitution (CES) in a branching hierarchy. The top node thus represents an output – using intermediate goods combined with value-added – on the one hand, and non-CO_2 greenhouse gases (GHGs) in sectors that emit these gases as joint-products (see below), on the other hand. This structure is replicated for each output, where the parameterisation of the CES functions may differ across sectors. The intermediate goods combine the input of both domestic and foreign supply of produced goods and services, and the valued-added bundle is specified as a CES combination of labour and a broad concept of capital and energy.

Total output for a sector is composed of 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 price changes. Capital accumulation is modelled as in traditional Solow/Swan neo-classical growth model.

Household consumption demand is the result of static maximization behaviour which is formally implemented as an "Extended Linear Expenditure System" (ELES). A representative consumer in each region – who takes prices as given – optimally allocates disposable 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.

The government in each region collects various kinds of taxes in order to finance a given sequence of government expenditures. Further, given a sequence of public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification (Armington, 1969), 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.

All monetary flows are expressed in constant USD, using Purchasing Power Parities (PPP) as exchange rates for national currencies. The use of PPPs rather than market exchange rates (MER) ensures that also the price developments of non-traded commodities are taken into account when projecting economic developments of multiple regions.

Sectoral and regional aggregation

In order to be able to perform the numerical simulations, it is necessary to keep the total size of the model limited. In the version of the model used for the *OECD Environmental Outlook to 2050*, all economic activity within a region is aggregated into 22 economic sectors. In addition, 7 distinct electricity production technologies are identified to be able to appropriately simulate responses in the electricity sector to the climate policies. The aggregation of sectors facilitate the analysis of key parts of the economy that are particularly affected by climate policies, such as emission-intensive industries, energy, transport or agriculture for non-CO_2 GHGs emissions.

Similarly, most countries are grouped into geographical regions and only a few countries are separately identified in the model. In the *OECD Environmental Outlook to 2050* baseline projection, 29 regions are distinguished. This facilitates the comparison of results with other models, such as the IMAGE model suite (PBL, 2010), which is also used in the *Outlook* (see OECD, 2012). However, for the policy simulations of the *Outlook*, the regional aggregation is reduced to 15 regions. The sectoral and regional composition is described in detail in Chateau et al. (2011).

Greenhouse gas emissions

The largest contribution to emissions of greenhouse gases comes from CO_2 emissions from combustion of fossil fuels. The Global Trade Analysis Project (GTAP) has developed a database of carbon dioxide emissions (Lee, 2008) based on data from the International Energy Agency. ENV-Linkages uses this database to link emissions directly to the use of energy by producers and consumers, using fuel-specific emission coefficients. Thus, the mitigation options related to these emissions are fully endogenous in the model: emitters can either reduce the level of their activity that causes the emissions, invest in energy savings (*i.e.* substitute away from energy to other inputs in the production function) or switch between different fuels. In the electricity sector, there is an explicit representation of major alternative technologies to produce electricity, including fossil fuels, nuclear energy and several types of renewable energy technologies.

Non-CO_2 greenhouse gases are significant contributors to climate change. Approximately 30% of the human-induced greenhouse effect can be attributed to the non-CO_2 greenhouse gases (mostly methane and nitrous oxide). Burniaux (2000) reported that, for relatively modest reductions, in many cases abating non-CO_2 gases was cheaper than abating CO_2 from energy. This result has been upheld by other studies that have since been completed (Weyant and de la Chesnaye, 2006). The current version of the model incorporates several emission sources of non-CO_2 gases (methane, nitrous oxide and industrial gases). These gases are introduced by considering an additional nest at the top of the production function following Hyman *et al.* (2002). Note that emissions from land use remaining as cropland or pasture are also captured in the model in the marginal abatement cost (MAC) curve for non-CO_2 GHGs; for example, methane emissions from rice cultivation are a major source of emissions.

Land Use, Land Use Change and Forestry (LULUCF) is a major source of carbon emissions, especially through deforestation, but also acts as an essential carbon sink since trees and plants take up CO_2 from the atmosphere. In the current version of the model, LULUCF emissions are exogenously specified. For each policy simulation, the model uses a specification of a representative pathway of LULUCF emissions and associated emission reductions, including reduced emissions from deforestation and forest degradation (REDD). An effort is made to ensure consistency between these exogenous pathways and the endogenous model components. Further improvements to this specification are foreseen for the coming years (see Section 6).

3. The structure of the model

This section provides a methodological overview of the model, including the main equations for each part of the model.

3.1 Household behaviour

Consumption

Income generated by economic activity ultimately reflects demand for goods and services by final consumers. ENV-linkages represent consumers as being largely similar at the aggregate level of consumption. As such, the model postulates a representative consumer who allocates disposable income according to preferences among consumer goods and saving. In this version of the model, consumers purchase goods and services as produced by firms (i.e. a transition matrix to map produced goods into consumer goods is not implemented). The consumption/saving decision is static instead of forward-looking: saving is treated as a "good" and its amount is determined simultaneously with the demands for the other goods, the price of saving being set arbitrarily equal to the average price of consumer goods. This means that consumers are saving a constant proportion of their income and not adjusting it to reflect future events that may impact on income.

Formally, a representative consumer maximises well-being (utility) subject to resource constraints:

$$Max \quad U = \sum_i mpc_i \cdot \ln(C_i - Pop \cdot \theta_i) + mps \cdot \ln\left(\frac{S}{P^S}\right)$$

$$Subject\ to \quad \sum_i P_i^C \cdot C_i + P_i^S \cdot S = Y, \quad and \quad \sum_i mpc_i + mps = 1$$

Where U represents utility, C is a vector of i 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 income (completely allocated between consumption and savings). The parameter θ_i is the floor level of per capita consumption – its main function is in allowing non-unitary income elasticities of different consumption goods (C_i), which is consistent with considerable empirical evidence (*e.g.* Dowrick *et al.*, 2003), while keeping the utility function homothetic (in $C - \theta$). For each country, the consumer's objective function thus gives rise to household private consumption and saving.

Box 1a. Consumption equations

(1) Household demand based on LES preferences

$$xac_{r,i} = Pop_r \cdot \theta_{r,i} + \frac{mpc_{r,i} \cdot supy_r}{p\_xac_{r,i} + emc_{r,i}^{tot\_c} \cdot p\_carbon_{r,i}^{dm}}$$

Variables: *xac* Household demand in region r for commodity i
supy Supernumerary income

Box 1a presents the related model equation. To allow a correspondence with the computer code, a direct link to the GAMS equation, and the GAMS file it is contained in, is provided. **Common indices** used throughout the paper include:

r	Region
v	Capital vintage (old or new)
i	Production sector / produced good or service
s_el	Electricity production techniques
ener	Energy sectors
cr	Crops sectors
lv	Livestock sectors

Common notation includes:

a	Expenditure share parameter
λ	Exogenous Productivity parameter
ε	Elasticity
σ	Elasticity of substitution between production inputs
*p_**	Price of *
t	Tax rate
s	Subsidy rate

Household income and factor supply

Households derive income from supplying factors of production (labour, capital, land) to firms, subject to taxation. There are also direct transfers between households and governments, reflecting the net value of various transactions, such as income taxes and social security benefits.

Land mobility and extensification of the area used for production are introduced in two steps. First, land supply curves can be used to govern the introduction of currently unmanaged land. This requires information on the potential land supply by region, which is provided by the IMAGE model suite (PBL, 2010). The impact of the land supply curve in the model is to reduce the land supply elasticity over time as land use gets closer to the potential land use. Secondly, a multi-level transformation function captures a hierarchical mobility of land use across sectors. This transformation function describes the ease with which different land uses can be transformed into other uses. As a rule of thumb, the transformation between different crops is easiest, and transformation between cropland and livestock is easier than transformation between forestry and agriculture. The transformation elasticities for this function are based on the OECD PEM model (OECD, 2000).

Box 1b. Income and factor supply equations

(1) Household income

$$yh_r = p\_tland_r \cdot tland_r + p\_f_r \cdot fs_r + twage_r \cdot labs_r$$
$$+ trent_r \cdot kaps_r - depr_r + PIO\_xa_r \cdot trg_r + PIO\_xc_r \cdot ssp_r$$

Variables:	*yh*	Gross household income
	tland	Total land supply
	fs	Total supply of specific production factor (land; resource)
	twage	Average wage rate
	labs	Total labour supply
	trent	Average rent on capital services
	kaps	Total capital supply
	yd	Household income, net of income taxes

(2) Supernumerary income (after basic expenditures in LES specification)

$$supy_r = yd_r - Pop_r \cdot \sum_i \left\{ \theta_{r,i} \cdot \left[p\_xac_{r,i} + emc_{r,i}^{tot\_c} \cdot p\_carbon_{r,i}^{dm} \right] \right\}$$

(3) Household savings

$$sav_r^h = yd_r - \sum_i \left\{ xac_{r,i} \cdot \left(p\_xac_{r,i} + emc_{r,i}^{tot\_c} \cdot p\_carbon_{r,i}^{dm} \right) \right\}$$

Variables: *savh* Household savings

(4) Household Labour supply

$$labs_r = \left(1 - ur_r\right) \cdot ar_r \cdot Pop_r^{15}$$

(5) Household land supply, by sector, in multi-level CET function

$$tland_r = ats_r \cdot \left(\frac{p\_tland_r}{p\_tland_r^{ref}} \right)^{leps_r}$$

$$ts_{r,i} = a_{r,i}^{lnd1} \cdot tland_r \cdot \left(\frac{p\_land_{r,i}}{p\_tland_r} \right)^{\omega_r^{tl1}} \quad ; i \notin 'ag'$$

$$ts_r^{ag} = a_r^{lnd\_ag} \cdot tland_r \cdot \left(\frac{p\_land_r^{ag}}{p\_tland_r} \right)^{\omega_r^{tl1}}$$

$$ts_{r,i} = a_{r,i}^{lnd2} \cdot ts_r^{ag} \cdot \left(\frac{p\_land_{r,i}}{p\_land_r^{ag}} \right)^{\omega_r^{tl2}} \quad ; i \in 'ag', i \notin 'crops'$$

$$ts_r^{crops} = a_r^{lnd\_crops} \cdot ts_r^{ag} \cdot \left(\frac{p\_land_r^{crops}}{p\_land_r^{ag}} \right)^{\omega_r^{tl2}}$$

$$ts_{r,i} = a_{r,i}^{lnd3} \cdot ts_r^{crops} \cdot \left(\frac{p\_land_{r,i}}{p\_land_r^{crops}} \right)^{\omega_r^{tl3}} \quad ; i \in 'crops'$$

Variables: *ts* Supply of land to specific sector
tsag Intermediate aggregate of land supply for agricultural sectors
tscrops Intermediate aggregate of land supply for crops sectors

(6) Price of land in multi-level CET function

$$p\_tland_r = \left[\sum_{i \notin 'ag'} \left\{ \left(a_{r,i}^{lnd1} \cdot p\_land_{r,i} \right)^{1+\omega_r^{tl1}} \right\} + \left(a_r^{lnd\_ag} \cdot p\_land_r^{ag} \right)^{1+\omega_r^{tl1}} \right]^{\frac{1}{1+\omega_r^{tl1}}}$$

$$p\_land_r^{ag} = \left[\sum_{\substack{i \in 'ag' \\ i \notin 'crops'}} \left\{ \left(a_{r,i}^{lnd2} \cdot p\_land_{r,i} \right)^{1-\omega_r^{tl2}} \right\} + \left(a_r^{lnd\_crops} \cdot p\_land_r^{crops} \right)^{1-\omega_r^{tl2}} \right]^{\frac{1}{1-\omega_r^{tl2}}}$$

$$p\_land_r^{crops} = \left[\sum_{i \in 'crops'} \left\{ \left(a_{r,i}^{lnd3} \cdot p\_land_{r,i} \right)^{1-\omega_r^{tl3}} \right\} \right]^{\frac{1}{1-\omega_r^{tl3}}}$$

(7) Sector-specific factor supply for energy sectors (ener) and generic case

$$fs_{r,ener} = a_{r,ener}^{fs} \cdot \left(\frac{p\_f_{r,ener}}{PIO\_xa_r} \right)^{\omega_{r,ener}^{f}}$$

$$fs_{r,i} = a_{r,i}^{fs} \cdot \left(\frac{p\_f_{r,i}}{p\_f\_ref_{r,i}} \right)^{\omega_{r,i}^{f}} \quad ; i \notin ener$$

3.2 Production

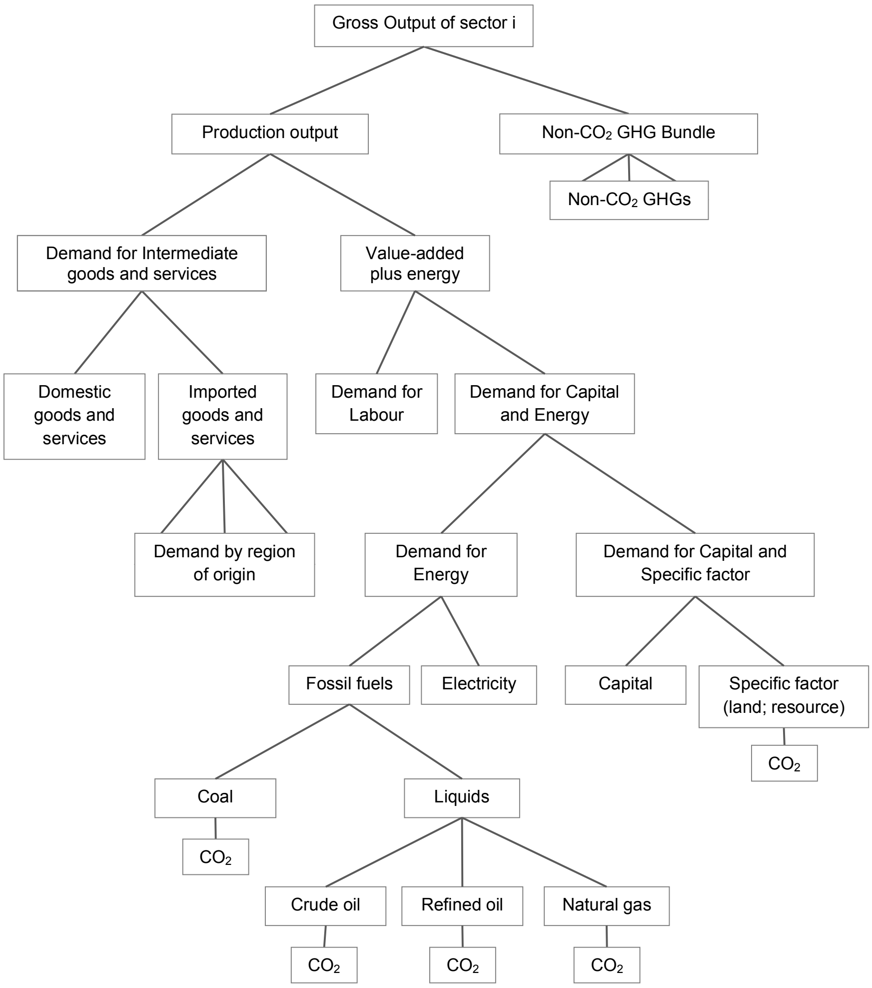
The generic production function

Firms in all sectors minimise the cost of producing the goods and services that are demanded by consumers and other producers (domestic and foreign). Production is represented by constant returns to scale technology. Figure 1 illustrates the typical nesting of the model's sectors. Note that some sectors, like agriculture, have a slightly different nesting to reflect peculiarities of these sectors (*e.g.* fertiliser use in crop production), as explained below.

In Figure 1, 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). Agricultural sectors also needs land input while in some sectors, primary factors also include a sector-specific natural resource factor, *e.g.* trees in forestry.

The top-level production nest considers final output as a composite commodity combining process emissions of CO_2 and non-CO_2 GHG emissions and the production of the sector net of these emissions. In sectors that do not emit such gases, the corresponding emission rate is set equal to zero. For the purpose of calibration, these gases are valuated using an arbitrary very low carbon price. The following non-CO_2 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, (see, for instance, US-EPA, 2006b).[1]

Figure 1. Generic structure of production in ENV-Linkages



Source: ENV-Linkages model.
Note: see Table 1 for parameter values.

[1] In reality, specific emission sources may be linked to specific inputs in the production function. Such links are not present in the current version of the model, but foreseen to be improved in a future version of the model. A complication of changing the nesting structure of these emission sources is that the specification of marginal abatement cost curves at the lower nesting level creates analytical complications that are not easy to overcome.

The second-level nest considers the gross output of each 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, differentiated by capital vintage (old and new). Capital that is implemented contemporaneously is new – thus investment has an effect 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 $X_{i,v}$ represent gross output of sector i (net of GHGs) using capital of vintage v, the equations representing production are derived from first-order conditions of the firm's profit maximization objective. 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.

The model includes adjustment rigidities. An important feature is the distinction between old and new capital goods. While new capital is fully malleable across sectors, and derived from an economy-wide investment function, old capital is assumed to be only partially mobile across sectors, reflecting differences in the marketability of capital goods across sectors. There is also homogeneity in the use of old and new capital.

On the right-hand side of the tree in Figure 1, value-added is shown as being composed of a labour input, along with a composite capital-energy bundle. The value-added bundle 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. As shown in Figure 1, the capital is bundled with a sector-specific production factor when one exists and energy is itself a bundle of different energy inputs.

The energy bundle is of particular interest for analysis of climate change issues. Energy, as reported in Figure 1, 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 based on existing literature and calibrated to imply a higher degree of substitution among the other fuels than with electricity and coal.

According to the vintage-structure of technologies, the fuel mix in energy production is more flexible when associated with new capital. For old capital vintage production technology the substitution possibilities between fuels are very limited. This difference between the short and long run substitution possibilities of energy is consistent with empirical findings by Arnberg and Bjorner (2007), who look at plant-level changes in energy intensity. However, since ENV-Linkages includes the possibility of changes in industry composition, the overall responsiveness to energy price changes will be higher than what these researchers found at plant level.

Once a sector's optimal combination of inputs is determined from relative prices, sectoral output (included GHGs) prices are calculated assuming competitive supply (zero-profit) conditions.

Box 2a. Generic production equations

(1) Aggregation of output across capital vintages

$$xp_{r,i} = \sum_{v} \left\{ xpv_{r,i,v} \right\}$$

Variables: *xp* Gross production aggregated over capital vintages
xpv Capital vintage specific production output

(2) Average unit price (over capital vintages) of total gross production

$$\frac{p\_p_{r,i}}{\left(1+t_{r,i}^{xp}\right)} \cdot xp_{r,i} = \sum_{v} \left\{ p\_xpv_{r,i,v} \cdot xpv_{r,i,v} \right\}$$

(3) Marginal user cost of gross production by capital vintage under perfect competition (top level production function)

$$tfp_{r,i} \cdot \left(1-t_{r,i,v}^{uvcv}\right) \cdot p\_xpv_{r,i,v} = \left(a_{r,i,v}^{nghg} \cdot \left(p\_xpv\_nghg_{r,i,v}\right)^{1-\sigma_{r,i,v}^{ghg}} + a_{r,i,v}^{ghg} \cdot \left(p\_xp\_ghg_{r,i}\right)^{1-\sigma_{r,i,v}^{ghg}} \right)^{\frac{1}{1-\sigma_{r,i,v}^{ghg}}}$$

(4) Gross production second level bundles

$$xpv\_nghg_{r,i,v} = a_{r,i,v}^{nghg} \cdot xpv_{r,i,v} \left(tfp\_GHG_{r,i}\right)^{\sigma_{r,i,v}^{ghg}-1} \cdot \left(\frac{\left(1-t_{r,i,v}^{uvcv}\right) \cdot p\_xpv_{r,i,v}}{p\_xpv\_nghg_{r,i,v}} \right)^{\sigma_{r,i,v}^{ghg}}$$

$$xp\_ghg_{r,i} = \sum_{v} \left\{ a_{r,i,v}^{ghg} \cdot xpv_{r,i,v} \cdot \left(tfp\_GHG_{r,i}\right)^{\sigma_{r,i,v}^{ghg}-1} \cdot \left(\frac{\left(1-t_{r,i,v}^{uvcv}\right) \cdot p\_xpv_{r,i,v}}{p\_xp\_ghg_{r,i}} \right)^{\sigma_{r,i,v}^{ghg}} \right\}$$

Variables : xpv_nghg Intermediate aggregate of production bundle (production output)
xp_ghg Intermediate aggregate of production bundle (Non-CO2 GHG bundle)

(5) Price of second level production bundles

$$tfp_{r,i} \cdot p\_xpv\_nghg_{r,i,v} = \left(a_{r,i,v}^{nd} \cdot \left(p\_nd_{r,i}\right)^{1-\sigma_{r,i,v}^{p}} + a_{r,i,v}^{va} \cdot \left(p\_va_{r,i,v}\right)^{1-\sigma_{r,i,v}^{p}} \right)^{\frac{1}{1-\sigma_{r,i,v}^{p}}}$$

$$p\_xp\_ghg_{r,i,v} = \left(\sum_{GHG} \left\{ a_{r,GHG,vs}^{emi\_prod} \cdot \left(\frac{p\_emis_{r,GHG,vs}^{PROD} + t\_carbon_{r,GHG,vs}^{pi}}{\lambda_{r,GHG,vs}^{emi\_prod}} \right)^{1-\sigma_{r,vs}^{emi\_prod}} \right\} \right)^{\frac{1}{1-\sigma_{r,vs}^{emi\_prod}}}$$

(6) "Demand" for non-CO2 GHG emissions

$$emis_{r,GHG,i}^{PROD} \cdot \left(p\_emis_{r,GHG,i}^{PROD} + t\_carbon_{r,GHG,i}^{pi}\right)^{\sigma_{r,i}^{emi\_prod}} =$$
$$a_{r,GHG,i}^{emi\_prod} \cdot xp\_ghg_{r,i} \cdot \left(\lambda_{r,GHG,i}^{emi\_prod}\right)^{\sigma_{r,i}^{emi\_prod}-1} \cdot \left(p\_xp\_ghg_{r,i}\right)^{\sigma_{r,i}^{emi\_prod}}$$

Variables: *emis* Emissions of non-CO2 GHGs not linked to specific inputs (incl. process emissions)

(7) Aggregate bundle of Intermediate Consumption

$$nd_{r,i} = \sum_{v} \left\{ a^{nd}_{r,i,v} \cdot xpv\_nghg_{r,i,v} \cdot \left(tfp_{r,i}\right)^{\sigma^{p}_{r,i,v}-1} \cdot \left(\frac{p\_xpv\_nghg_{r,i,v}}{p\_nd_{r,i,v}} \right)^{\sigma^{p}_{r,i,v}} \right\}$$

Variables: *nd* Intermediate aggregate of production bundle (intermediate deliveries)

(8) Price of aggregate bundle of intermediate deliveries

$$p\_nd_{r,ip} = \left(\sum_{nf} \left\{ a_{r,nf,ip} \cdot \left(\frac{p\_xap_{r,nf,ip}}{\lambda^{nd}_{r,nf,ip}} \right)^{1-\sigma^{n}_{r,ip}} \right\} + \sum_{ELY} \left\{ a_{r,ELY,ip} \cdot \left(\frac{p\_xap_{r,ELY,ip}}{\lambda^{nd}_{r,ELY,ip}} \right)^{1-\sigma^{n}_{r,ip}} \right\} \right)^{\frac{1}{1-\sigma^{n}_{r,ip}}}$$

(9) Intermediate demands (generally excluding energy inputs)

$$xap_{r,i,ip} \cdot = a_{r,i,ip} \cdot nd_{r,ip} \cdot \left(\lambda^{nd}_{r,i,ip}\right)^{\sigma^{n}_{r,ip}-1} \cdot \left(\frac{p\_nd_{r,ip}}{p\_xap_{r,i,ip}} \right)^{\sigma^{n}_{r,ip}}$$

Variables: *xap* Intermediate demand in sector i for goods produced by sector ip

(10) Value added bundle

$$va_{r,i,v} = a^{va}_{r,i,v} \cdot xpv\_nghg_{r,i,v} \cdot \left(tfp_{r,i}\right)^{\sigma^{p}_{r,i,v}-1} \cdot \left(\frac{p\_xpv\_nghg_{r,i,v}}{p\_va_{r,i,v}} \right)^{\sigma^{p}_{r,i,v}}$$

Variables: *va* Intermediate aggregate of production bundle (value added bundle)

(11) Price of value added bundle

$$p\_va_{r,i,v} = \left(a^{kte}_{r,i,v} \cdot \left(p\_kte_{r,i}\right)^{1-\sigma^{v}_{r,i,v}} + a^{ls}_{r,i,v} \cdot \left(wage^{s}_{r,i}\right)^{1-\sigma^{v}_{r,i,v}} \right)^{\frac{1}{1-\sigma^{v}_{r,i,v}}}$$

(12) Demand for labour

$$ld^{s}_{r,i} = \sum_{v} \left\{ a^{ls}_{r,i,v} \cdot va_{r,i,v} \cdot \left(\frac{p\_va_{r,i,v}}{wage^{s}_{r,i}} \right)^{\sigma^{v}_{r,ip,v}} \right\}$$

$$labd_{r,i} \cdot \lambda^{l}_{r,i} = ld^{s}_{r,i}$$

Variables: *ld* Productivity-adjusted (“efficiency units”) labour demand
labd Labour demand in number of people

(13) Wage for productivity-adjusted labour

$$wage^{s}_{r,i} = \frac{wage_{r,i}}{\lambda^{l}_{r,i}}$$

(14) Sectoral wages

$$wage_{r,i} \cdot \left(1 - t_r^{inc}\right) = \left(1 + t_{r,i}^{fac} - s_{r,i}^{fac}\right) \cdot wdist_{r,i} \cdot twage_r$$

(15) Demand for aggregate capital-energy-resource and capital-resource bundles

$$kte_{r,i,v} = a_{r,i,v}^{kte} \cdot va_{r,i,v} \cdot \left(\frac{p\_va_{r,i,v}}{p\_kte_{r,i,v}}\right)^{\sigma_{r,i,v}^{v}}$$

$$kt_{r,i,v} = a_{r,i,v}^{kt} \cdot kte_{r,i,v} \cdot \left(\frac{p\_kte_{r,i,v}}{p\_kt_{r,i,v}}\right)^{\sigma_{r,i,v}^{e}}$$

Variables: *kte* Intermediate aggregate of production bundle (capital-energy-resource bundle)
kt Intermediate aggregate of production bundle (capital-resource bundle)

(16) Price of aggregate capital-energy-resource and energy-resource bundles

$$p\_kte_{r,i,v} = \left(a_{r,i,v}^{e} \cdot \left(p\_xep_{r,i,v}\right)^{1-\sigma_{r,i,v}^{e}} + a_{r,i,v}^{kt} \cdot \left(p\_kt_{r,i,v}\right)^{1-\sigma_{r,i,v}^{e}}\right)^{\frac{1}{1-\sigma_{r,i,v}^{e}}}$$

$$p\_kt_{r,i,v} = \left(a_{r,i,v}^{f} \cdot \left(\frac{p\_f_{r,i}}{\lambda_{r,i}^{ff}}\right)^{1-\sigma_{r,i,v}^{k}} + a_{r,i,v}^{k} \cdot \left(\frac{rent_{r,i,v}}{\lambda_{r,i,v}^{k}}\right)^{1-\sigma_{r,i,v}^{k}}\right)^{\frac{1}{1-\sigma_{r,i,v}^{k}}}$$

(17) Demand for capital

$$kapdv_{r,i,v} = a_{r,i,v}^{k} \cdot kt_{r,i,v} \cdot \left(\lambda_{r,i,v}^{k}\right)^{\sigma_{r,i,v}^{k}-1} \cdot \left(\frac{p\_kt_{r,i,v}}{rent_{r,i,v}}\right)^{\sigma_{r,i,v}^{k}}$$

Variables: *kapdv* Demand for capital (vintage-specific)

(18) Total demand for sector-specific production factor for sectors where capital and specific factor are close complements

$$ff_{r,i} = \sum_{v}\left\{a_{r,i,v}^{f} \cdot kt_{r,i,v} \cdot \left(\lambda_{r,i}^{ff}\right)^{\sigma_{r,i,v}^{k}-1} \cdot \left(\frac{p\_kt_{r,i,v}}{p\_f_{r,i}}\right)^{\sigma_{r,i,v}^{k}}\right\}$$

Variables: *ff* Demand for sector-specific production factor

(19) Energy bundle

$$xep_{r,i,v} = a_{r,i,v}^{e} \cdot kte_{r,i,v} \cdot \left(\frac{p\_kte_{r,i,v}}{p\_xep_{r,i,v}}\right)^{\sigma_{r,i,v}^{e}}$$

$$xep_{r,i,v}^{fossil} = a_{r,i,v}^{fossil} \cdot xep_{r,i,v} \cdot \left(\frac{p\_xep_{r,i,v}}{p\_xep_{r,i,v}^{fossil}}\right)^{\sigma_{r,i,v}^{ELY}}$$

$$xep^{liquids}_{r,i,v} = a^{liquids}_{r,i,v} \cdot xep^{fossil}_{r,i,v}\ {}_{r,i,v} \cdot \left(\frac{p\_xep^{fossil}_{r,i,v}}{p\_xep^{liquids}_{r,i,v}} \right)^{\sigma^{fossil}_{r,i,v}}$$

Variables: *xep* Aggregate demand for energy
xepfossil Aggregate demand for fossil fuel energy
xepliquids Aggregate demand for liquid fossil fuel energy

(20) Price of intermediate aggregates in the energy bundle

$$p\_xep_{r,i,v} = \left(\sum_e \left\{ a^{ep}_{r,e,i,v} \cdot \left[\frac{p\_xap_{r,i,v} + emc^{tot\_p}_{r,e,i} \cdot p\_carbon^{di}_{r,e,i}}{\lambda^{ep}_{r,e,i,v}} \right]^{1-\sigma^{ep}_{r,i,v}} \right\} \right)^{\frac{1}{1-\sigma^{ep}_{r,i,v}}}$$

$$p\_xep^{fossil}_{r,i,v} =$$

$$\left(a^{ep}_{r,'coal',i,v} \cdot \left[\frac{p\_xap_{r,'coal',i} + emc^{tot\_p}_{r,'coal',i} \cdot p\_carbon^{di}_{r,'coal',i}}{\lambda^{ep}_{r,'coal',i,v}} \right]^{1-\sigma^{coa}_{r,i,v}} + a^{liquids}_{r,i,v} \cdot \left(p\_xep^{liquids}_{r,i,v} \right)^{1-\sigma^{coa}_{r,i,v}} \right)^{\frac{1}{1-\sigma^{coa}_{r,i,v}}}$$

$$p\_xep^{liquids}_{r,i,v} = \left(\sum_{liq} \left\{ a^{ep}_{r,liq,i,v} \cdot \left[\frac{p\_xap_{r,liq,i} + emc^{tot\_p}_{r,liq,i} \cdot p\_carbon^{di}_{r,liq,i}}{\lambda^{ep}_{r,liq,i,v}} \right]^{1-\sigma^{liquids}_{r,i,v}} \right\} \right)^{\frac{1}{1-\sigma^{liquids}_{r,i,v}}}$$

(21) Intermediate demand for energy carriers

$$xap_{r,e,i} = \sum_v \left\{ a^{ep}_{r,e,i,v} \cdot xep_{r,i,v} \cdot \left(\lambda^{ep}_{r,e,i,v} \right)^{\sigma^{ep}_{r,i,v}-1} \cdot \left[\frac{p\_xep_{r,i,v}}{p\_xap_{r,e,i} + emc^{tot\_p}_{r,e,i} \cdot p\_carbon^{di}_{r,e,i}} \right]^{\sigma^{ep}_{r,i,v}} \right\}$$

$$xap_{r,'coal',i} =$$

$$\sum_v \left\{ a^{ep}_{r,'coal',i,v} \cdot xep^{fossil}_{r,i,v} \cdot \left(\lambda^{ep}_{r,'coal',i,v} \right)^{\sigma^{coa}_{r,i,v}-1} \cdot \left[\frac{p\_xep^{fossil}_{r,i,v}}{p\_xap_{r,'coal',i} + emc^{tot\_p}_{r,'coal',i} \cdot p\_carbon^{di}_{r,'coal',i}} \right]^{\sigma^{coa}_{r,i,v}} \right\}$$

$$xap_{r,liq,i} = \sum_v \left\{ a^{ep}_{r,liq,i,v} \cdot xep^{liquids}_{r,i,v} \cdot \left(\lambda^{ep}_{r,liq,i,v} \right)^{\sigma^{liquids}_{r,i,v}-1} \cdot \left[\frac{p\_xep^{liquids}_{r,i,v}}{p\_xap_{r,liq,i} + emc^{tot\_p}_{r,liq,i} \cdot p\_carbon^{di}_{r,liq,i}} \right]^{\sigma^{liquids}_{r,i,v}} \right\}$$

Agricultural production

The agricultural production function has been adjusted from the generic set-up illustrated in Figure 1 to take specific features of these sectors into account. In the "crop" production sector, this capital is itself a CES combination of fertilizer and another bundle of capital-land-energy.[2] 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. Production in other sectors is characterised by substitution between labour and a bundle of capital-energy (and possibly a sector-specific factor for primary resources).

Box 2b. Specific additional agricultural production equations

(1) Intermediate demand excl. energy and excl. specifically treated inputs for crops (*cr*) and livestock (*lv*) sectors

$$xap_{r,nnft,cr} = \frac{a_{r,nnft,cr} \cdot nd_{r,cr}}{\lambda^{nd}_{r,nnft,cr}}$$

$$xap_{r,nnfd,lv} = \frac{a_{r,nnfd,lv} \cdot nd_{r,lv}}{\lambda^{nd}_{r,nnfd,lv}}$$

(2) Price of intermediate demand excl. energy and specifically treated inputs

$$p\_nd_{r,cr} = \sum_{nnft} \left\{ a_{r,nnft,cr} \cdot \left(\frac{p\_xap_{r,nnft,cr}}{\lambda^{nd}_{r,nnft,cr}} \right)^{1-\sigma^{n}_{r,cr}} \right\}$$

$$p\_nd_{r,lv} = \sum_{nnfd} \left\{ a_{r,nnfd,lv} \cdot \left(\frac{p\_xap_{r,nnfd,lv}}{\lambda^{nd}_{r,nnfd,lv}} \right)^{1-\sigma^{n}_{r,lv}} \right\}$$

(3) Price of sector-specific value added bundles in crops and livestock sectors

$$p\_va_{r,cr,v} = \left(a^{ktef}_{r,cr,v} \cdot \left(p\_ktef_{r,cr} \right)^{1-\sigma^{v}_{r,cr,v}} + a^{ls}_{r,cr,v} \cdot \left(wage^{s}_{r,cr} \right)^{1-\sigma^{v}_{r,cr,v}} \right)^{\frac{1}{1-\sigma^{v}_{r,cr,v}}}$$

$$p\_va_{r,lv,v} = a^{ktel}_{r,lv,v} \cdot p\_ktel_{r,lv,v} + a^{tfd}_{r,lv,v} \cdot p\_tfd_{r,lv,v}$$

[2] Note that fertiliser-related emissions are not directly coupled to fertiliser use. Nonetheless, emission reductions through reduced fertiliser use are indirectly captured through the calibration of the marginal abatement cost curve.

(4) Demand for labour in crops and livestock sectors

$$ld^{s}_{r,cr} = \sum_{v} \left\{ a^{ls}_{r,cr,v} \cdot va_{r,cr,v} \cdot \left(\frac{p\_va_{r,cr,v}}{wage^{s}_{r,cr}} \right)^{\sigma^{v}_{r,cr,v}} \right\}$$

$$ld^{s}_{r,lv} = \sum_{v} \left\{ a^{ls}_{r,lv,v} \cdot ktel_{r,lv,v} \cdot \left(\frac{p\_ktel_{r,lv,v}}{wage^{s}_{r,lv}} \right)^{\sigma^{v}_{r,lv,v}} \right\}$$

(5) Demand for land in crops and livestock sectors

$$td_{r,cr} = \sum_{v} \left\{ a^{t}_{r,cr,v} \cdot kt_{r,cr,v} \cdot \left(\lambda^{t}_{r,cr} \right)^{\sigma^{k}_{r,cr,v}-1} \left(\frac{p\_kt_{r,cr,v}}{p\_land_{r,cr}} \right)^{\sigma^{k}_{r,cr,v}} \right\}$$

$$td_{r,lv} = \sum_{v} \left\{ a^{t}_{r,lv,v} \cdot tfd_{r,lv,v} \cdot \left(\lambda^{t}_{r,lv} \right)^{\sigma^{f}_{r,lv,v}-1} \left(\frac{p\_tfd_{r,lv,v}}{p\_land_{r,lv}} \right)^{\sigma^{f}_{r,lv,v}} \right\}$$

(6) Demand for sector-specific aggregated bundles in crops sectors

$$ktef_{r,cr,v} = a^{ktef}_{r,cr,v} \cdot va_{r,cr,v} \cdot \left(\frac{p\_va_{r,cr,v}}{p\_ktef_{r,cr,v}} \right)^{\sigma^{v}_{r,cr,v}}$$

$$kte_{r,cr,v} = a^{kte}_{r,cr,v} \cdot ktef_{r,cr,v} \cdot \left(\frac{p\_ktef_{r,cr,v}}{p\_kte_{r,cr,v}} \right)^{\sigma^{f}_{r,cr,v}}$$

Variables: ktef Intermediate aggregate of crops sectors production bundle (capital-energy-resource-fertiliser bundle)

(7) Price of sector-specific aggregated bundles in crops sectors

$$p\_ktef_{r,cr,v} = \left(a^{fert}_{r,cr,v} \cdot \left(p\_fert_{r,cr} \right)^{1-\sigma^{f}_{r,cr,v}} + a^{kte}_{r,cr,v} \cdot \left(p\_kte_{r,cr,v} \right)^{1-\sigma^{f}_{r,cr,v}} \right)^{\frac{1}{1-\sigma^{f}_{r,cr,v}}}$$

$$p\_kt_{r,cr,v} = \left(a^{t}_{r,cr,v} \cdot \left(\frac{p\_land_{r,cr}}{\lambda^{t}_{r,cr}} \right)^{1-\sigma^{k}_{r,cr,v}} + a^{k}_{r,cr,v} \cdot \left(\frac{rent_{r,cr}}{\lambda^{k}_{r,cr,v}} \right)^{1-\sigma^{k}_{r,cr,v}} \right)^{\frac{1}{1-\sigma^{k}_{r,cr,v}}}$$

(8) Demand for fertilisers in crops sectors

$$fert_{r,cr} = \sum_{v} \left\{ a^{fert}_{r,cr,v} \cdot ktef_{r,cr,v} \cdot \left(\frac{p\_ktef_{r,cr,v}}{p\_fert_{r,cr}} \right)^{\sigma^{f}_{r,cr,v}} \right\}$$

$$xap_{r,ft,cr} = a^{ft}_{r,ft,cr} \cdot fert_{r,cr} \cdot \left(\lambda^{ft}_{r,ft,cr} \right)^{\sigma^{ft}_{r,cr}-1} \left(\frac{p\_fert_{r,cr,v}}{p\_xap_{r,ft,cr}} \right)^{\sigma^{ft}_{r,cr}}$$

Variables: fert Demand for fertilisers

(9) Price of fertilisers in crops sectors

$$p\_fert_{r,cr} = \left(\sum_{ft} \left\{ a^{ft}_{r,ft,cr} \cdot \left(\frac{p\_xap_{r,ft,cr}}{\lambda^{ft}_{r,ft,cr}} \right)^{1-\sigma^{ft}_{r,cr}} \right\} \right)^{\frac{1}{1-\sigma^{ft}_{r,cr}}}$$

(10) Demand for sector-specific aggregates bundles in livestock sectors

$$ktel_{r,lv,v} = a^{ktel}_{r,lv,v} \cdot va_{r,lv,v}$$

$$kte_{r,lv,v} = a^{kte}_{r,lv,v} \cdot ktel_{r,lv,v} \cdot \left(\frac{p\_ktel_{r,lv,v}}{p\_kte_{r,lv,v}} \right)^{\sigma^{v}_{r,lv,v}}$$

$$tfd_{r,lv,v} = a^{tfd}_{r,lv,v} \cdot va_{r,lv,v}$$

Variables: *ktel* Intermediate aggregate of livestock sectors production bundle (revised value added bundle)
tfd Intermediate aggregate of crops sectors production bundle (land use-feed bundle)

(11) Price of sector-specific aggregated bundles in livestock sectors

$$p\_ktel_{r,lv,v} = \left(a^{kte}_{r,lv,v} \cdot \left(p\_kte_{r,lv,v} \right)^{1-\sigma^{v}_{r,lv,v}} + a^{ls}_{r,lv,v} \cdot \left(wage^{s}_{r,lv} \right)^{1-\sigma^{v}_{r,lv,v}} \right)^{\frac{1}{1-\sigma^{v}_{r,lv,v}}}$$

$$p\_kt_{r,lv,v} = \left(a^{f}_{r,lv,v} \cdot \left(\frac{p\_f_{r,lv}}{\lambda^{ff}_{r,lv}} \right)^{1-\sigma^{k}_{r,lv,v}} + a^{k}_{r,lv,v} \cdot \left(\frac{rent_{r,lv,v}}{\lambda^{k}_{r,lv,v}} \right)^{1-\sigma^{k}_{r,lv,v}} \right)^{\frac{1}{1-\sigma^{k}_{r,lv,v}}}$$

$$p\_tfd_{r,lv,v} = \left(a^{food}_{r,lv,v} \cdot \left(p\_feed_{r,lv} \right)^{1-\sigma^{f}_{r,lv,v}} + a^{t}_{r,lv,v} \cdot \left(\frac{p\_land_{r,lv}}{\lambda^{t}_{r,lv}} \right)^{1-\sigma^{f}_{r,lv,v}} \right)^{\frac{1}{1-\sigma^{f}_{r,lv,v}}}$$

(12) Demand for feedstocks in livestock sectors

$$feed_{r,lv} = \sum_{v} \left\{ a^{feed}_{r,lv,v} \cdot tfd_{r,lv,v} \cdot \left(\frac{p\_tfd_{r,lv,v}}{p\_feed_{r,lv}} \right)^{\sigma^{f}_{r,lv,v}} \right\}$$

$$xap_{r,fd,lv} = a^{fd}_{r,fd,lv} \cdot feed_{r,lv} \cdot \left(\lambda^{fd}_{r,fd,lv} \right)^{\sigma^{fd}_{r,lv}-1} \left(\frac{p\_feed_{r,lv,v}}{p\_xap_{r,fd,lv}} \right)^{\sigma^{fd}_{r,lv}}$$

Variables: *feed* Demand for feedstocks in livestock sectors

(13) Price of feedstocks in livestock sectors

$$p\_feed_{r,lv} = \left(\sum_{fd} \left\{ a^{fd}_{r,fd,lv} \cdot \left(\frac{p\_xap_{r,fd,lv}}{\lambda^{fd}_{r,fd,lv}} \right)^{1-\sigma^{fd}_{r,lv}} \right\} \right)^{\frac{1}{1-\sigma^{fd}_{r,lv}}}$$

Energy production

The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the five available technologies to generate electricity: fossil-fuel based, hydro and geothermal, nuclear, solar and wind, and renewable combustibles (incl. biomass) and waste. A CES specification is used with a large value for the elasticity of substitution to reflect that the different technologies produce very close substitute products. Fossil-fuel based electricity production, which is the main technology in the baseline projection, follows the generic production structure described above. Production of each of the non-fossil electricity technologies (net of GHG emissions and expressed in Terawatt hour) has a structure similar to that of the other sectors, except for a top nesting combining a sector-specific natural resource production factor on the one hand, and all other inputs on the other. This specification aims at controlling the penetration of these electricity technologies over time.

This version of the model explicitly incorporates two carbon capture and storage (CCS) technologies (gas-based electricity production with CCS and coal-based electricity production with CCS) in the power generation system as substitution technology to fossil-fuel based electricity. The method retained to incorporate CCS in the model is similar to that employed by the MIT-EPPA model (McFarland and Herzog, 2006). At the top level of the CCS nesting structure, substitution occurs between the value added bundle and a specific resource factor that is used to control the short-run penetration rate of the CCS technologies and to feature region specific capacity of carbon storage. Before 2025 this specific factor remains limited and CCS is only marginally exploited for relatively low carbon prices. After this date and if the price of carbon is such that CCS becomes profitable (see next paragraph), the specific resource is assumed to grow with the CCS technology's output. This kind of ad-hoc adjustment aims at mimicking a learning-by-doing process: the more electricity is produced with CCS, the more abundant its specific factor is. This calibration procedure ensures marginal, but positive, electricity production levels with CCS in the baseline where there is no price on carbon.

In the absence of a price on carbon, producing electricity with CCS will not be profitable since it is more costly than conventional fossil-fuel based technologies. The cost share structure of the CES technologies is assumed to be the same for all regions, but the total factor productivity level of these sectors and the energy efficiency parameters are calibrated in the baseline in order to reproduce the marginal cost of CCS and the fuel input utilization, both relative to those of the fossil-fuel electricity technology. The data used for calibrating CCS are derived from IEA (2004; 2010a): on average the relative cost of producing electricity with natural gas is 33% higher with CCS technology than with conventional technology, and 65% higher with coal. Although the relative cost difference is larger for coal than for gas, the higher carbon intensity of coal compared to gas imply that carbon pricing has a stronger effect on coal-based CCS than on gas-based CCS.

Box 2c. Specific additional energy production equations

(14) Demand electricity by source (*s_el*)

$$xp_{r,s\_el} = \left(tfp_{r,'elec'}\right)^{\sigma_r^{elec}-1} \cdot a_{r,s\_el}^{elec} \cdot \left(xp_{r,'elec'}\right) \cdot \left(\frac{p\_p_{r,'elec'}}{p\_p_{r,s\_el}}\right)^{\sigma_r^{elec}}$$

(15) Aggregate electricity price

$$p\_p_{r,'elec'} = \left(\sum_{s\_el}\left\{a_{r,s\_el}^{elec} \cdot \left(\frac{p\_p_{r,s\_el}}{tfp_{r,elec'}}\right)^{1-\sigma_r^{elec}}\right\}\right)^{\frac{1}{1-\sigma_r^{elec}}}$$

(16) Marginal user cost of gross production by capital vintage (top level production function)

$$tfp_{r,s\_el} \cdot \left(1-t_{r,s\_el,v}^{uvcv}\right) \cdot p\_xpv_{r,s\_el,v} =$$

$$\left(a_{r,s\_el,v}^{nnatr} \cdot \left(p\_xpv\_nnatr_{r,s\_el,v}\right)^{1-\sigma_{r,s\_el,v}^{natr}} + a_{r,s\_el,v}^{f} \cdot \left(\frac{p\_f_{r,s\_el}}{\lambda_{r,s\_el}^{ff}}\right)^{1-\sigma_{r,s\_el,v}^{natr}}\right)^{\frac{1}{1-\sigma_{r,s\_el,v}^{natr}}}$$

(17) Total demand for sector-specific natural resource factor for energy-producing sectors (both electricity and primary energy supply) (specific factor at top level)

$$ff_{r,natr} = \sum_{v}\left\{a_{r,natr,v}^{f} \cdot xpv_{r,natr,v} \cdot \left(tfp_{r,natr} \cdot \lambda_{r,natr}^{ff}\right)^{\sigma_{r,natr,v}^{natr}-1} \cdot \left(\frac{\left(1-t_{r,natr,v}^{uvcv}\right) \cdot p\_xpv_{r,natr,v}}{p\_f_{r,natr}}\right)^{\sigma_{r,natr,v}^{natr}}\right\}$$

(18) Gross production bundle for sectors with sector-specific natural resource factor at top level

$$xpv\_nnatr_{r,natr,v} = a_{r,natr,v}^{nnatr} \cdot xpv_{r,natr,v} \cdot \left(tfp_{r,natr}\right)^{\sigma_{r,natr,v}^{natr}-1} \cdot \left(\frac{\left(1-t_{r,natr,v}^{uvcv}\right) \cdot p\_xpv_{r,natr,v}}{p\_xpv\_nnatr_{r,natr,v}}\right)^{\sigma_{r,natr,v}^{natr}}$$

Variables: xpv_nnatr Intermediate aggregate in production bundle for energy sectors (production output bundle)

(19) Price of second level production bundles for electricity-producing sectors

$$p\_xpv\_nnatr_{r,s\_el,v} = \left(a_{r,s\_el,v}^{nd} \cdot \left(p\_nd_{r,s\_el}\right)^{1-\sigma_{r,s\_el,v}^{p}} + a_{r,s\_el,v}^{va} \cdot \left(p\_va_{r,s\_el,v}\right)^{1-\sigma_{r,s\_el,v}^{p}}\right)^{\frac{1}{1-\sigma_{r,s\_el,v}^{p}}}$$

(20) Aggregate bundle of intermediate demand for electricity-producing sectors

$$nd_{r,s\_el} = \sum_{v}\left\{a_{r,s\_el,v}^{nd} \cdot xpv\_nnatr_{r,s\_el,v} \cdot \left(\frac{p\_xpv\_nnatr_{r,s\_el,v}}{p\_nd_{r,s\_el,v}}\right)^{\sigma_{r,s\_el,v}^{p}}\right\}$$

(21) Value added bundle for electricity-producing sectors

$$va_{r,s\_el,v} = a^{va}_{r,s\_el,v} \cdot xpv\_nnatr_{r,s\_el,v} \cdot \left(\frac{p\_xpv\_nnatr_{r,s\_el,v}}{p\_va_{r,s\_el,v}} \right)^{\sigma^{p}_{r,s\_el,v}}$$

(22) Price of energy inputs in the electricity bundle

$$p\_xep_{r,s\_el,v} = \left(a^{ep}_{r,'elec',s\_el,v} \cdot \left[\frac{p\_xap_{r,'elec',s\_el}}{\lambda^{ep}_{r,'elec',s\_el,v}} \right]^{1-\sigma^{ELY}_{r,s\_el,v}} + a^{fossil}_{r,s\_el,v} \cdot \left(p\_xep^{fossil}_{r,s\_el,v} \right)^{1-\sigma^{ELY}_{r,s\_el,v}} \right)^{\frac{1}{1-\sigma^{ELY}_{r,s\_el,v}}}$$

3.3 Foreign Trade

World trade in ENV-Linkages 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. At the second nest, agents optimally allocate demand for the aggregate import good across the range of trading partners.

Box 3. Foreign trade equations

(23) Aggregate price of domestically produced and imported goods and services (Armington formulation)

$$p\_xa_{r,i} = \left[\left(a^{d}_{r,i} \cdot p\_p_{r,i} \right)^{1-\sigma^{m}_{r,i}} + \left(a^{m}_{r,i} \cdot p\_xim_{r,i} \right)^{1-\sigma^{m}_{r,i}} \right]^{\frac{1}{1-\sigma^{m}_{r,i}}}$$

(24) Imports

$$xim_{r,i} = a^{m}_{r,i} \cdot xa_{r,i} \cdot \left(\frac{p\_xa_{r,i}}{p\_xim_{r,i}} \right)^{\sigma^{m}_{r,i}}$$

Variables: *xa* Aggregate demand by domestic and foreign agents
xim Total imports

(25) Domestic price index of aggregate imports

$$p\_xim_{r,i} = \left[\sum_{rp} \left\{ a^{mw}_{rp,r,i} \cdot p\_m_{rp,r,i}{}^{1-\sigma^{w}_{r,i}} \right\} \right]^{\frac{1}{1-\sigma^{w}_{r,i}}}$$

(26) Import demand by region r from region rp

$$wtf_{rp,r,i} = a^{mw}_{rp,r,i} \cdot xim_{r,i} \cdot \left(\lambda^{trade}_{rp,r,i} \right)^{\sigma^{w}_{r,i}-1} \cdot \left(\frac{p\_xim_{r,i}}{p\_m_{rp,r,i}} \right)^{\sigma^{w}_{r,i}}$$

Variables: *wtf* Bilateral international trade flow

(27) Price index of aggregated exports

$$xex_{r,i} = \sum_{rp} \left\{ wtf_{r,rp,i} \right\}$$

Variables: *xex* Aggregated exports

(28) Export Price FOB

$$p\_e_{r,rp,i} = p\_p_{r,i}$$

(29) International transport and trade services (ITTS)

$$xwmarg \cdot wp\_marg = \sum_{i} \left\{ trd\_marg_{r,rp,i} \cdot wtf_{r,rp,i} \cdot wp\_e_{r,rp,i} \right\}$$

$$xtmarg_r = a_r^{t\_marg} \cdot xwmarg \cdot \left(\frac{wp\_marg}{p\_tmarg_r} \right)^{\omega^t}$$

$$wpmarg = \sum_{r} \left\{ a_r^{t\_marg} \cdot p\_tmarg_r^{\omega^t} \right\}^{\frac{1}{1-\omega^t}}$$

$$p\_tmarg_r = \sum_{transport} \left\{ a_{r,transport}^{marg} \cdot pp_{r,transport} \right\}$$

$$xmarg_{r,transport} = a\_marg_r^{transport} \cdot xtmarg_r$$

Variables: *xwmarg* Global demand of ITTS
xtmarg Regional supply of ITTS
xmarg Regional supply of ITTS by transport mode

3.4 Government and environmental policy

Government collects income taxes, indirect taxes on intermediate and final consumption as well as possible carbon taxes, production taxes, tariffs, and export taxes. It may also provide 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. 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 changes in 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.

Several types of environmental policies can be simulated with ENV-Linkages; the equations given in the Box 4 are just an example. The model features are particularly suitable for simulating carbon pricing policies. A price on carbon can be simulated through an emission trading scheme (national or international) or carbon taxes. The model is flexible in the choice of the regions, sectors and gases on which a carbon price is imposed. The implementation of the emissions trading can also reflect different levels of international collaboration: carbon markets can be implemented individually by the different regions of linked between all or a subset of regions. The model can also be used to analyse the implementation of carbon offsets or of policies such as the Clean Development Mechanism of the Kyoto Protocol and to see how this affects the emissions trading schemes in place. The model can also be used to analyse other policies linked to climate change issues, such as Border Carbon Adjustments (BCAs), removal or implementation of sectoral subsidies, and direct regulation such as a ban on new nuclear power plants.

The policies investigated with ENV-Linkages do not have to be directly linked to climate change issues. The model can in general be used to analyse changes in various fiscal measures ranging from export subsidies and import tariffs, to sectoral or regional subsidies or income taxes as well as policies affecting the costs of primary factors, such as the wage taxes. Other regulatory measures can also be mimicked in ENV-Linkages, for instance the adoption of measures that aim at increasing energy efficiency.

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.

Box 4. Government and environmental policy equations

(30) Government budget constraint

$$sav_r^g = Grev_r - \left(p\_fd_r^{'gov'} \cdot fdvol_r^{'gov'} + PIO\_xa_r \cdot trg_r + PIO\_xc_r \cdot ssp_r \right)$$

Variables: sav^g Government savings (budget surplus)
$Grev$ Government revenues from tax collection minus expenditures on subsidies (endogenous)

(31) Endogenous domestic or international emission trading scheme or carbon tax

$$emis_r^{target} \geq \sum_{e,i} \left\{ emc_{r,e,i}^{tot\_p} \cdot xap_{r,e,i} \right\} + \sum_{e} \left\{ emc_{r,e}^{tot\_c} \cdot xac_{r,e} \right\} + \sum_{GHG,i} \left\{ emis_{r,GHG,i}^{PROD} \right\}$$

$$emis_{TP}^{target} \geq \sum_{r \in TP,e,i} \left\{ emc_{r,e,i}^{tot\_p} \cdot xap_{r,e,i} \right\} + \sum_{r \in TP,e} \left\{ emc_{r,e}^{tot\_c} \cdot xac_{r,e} \right\} + \sum_{r \in TP,GHG,i} \left\{ emis_{r,GHG,i}^{PROD} \right\}$$

Variables: $emis^{target}$ Cap on total economy-wide emission level (policy variable)

(32) Output subsidy to polluters faced with environmental policy ("grandfathering")

$$t_{r,i,v}^{uvcv} \cdot p\_xp_{r,i} \cdot xp_{r,i} = t\_carbon_{r,GHG,i}^{di} \cdot \sum_{e} \left\{ emc_{r,e,i}^{tot\_p} \cdot xap_{r,e,i} \right\}$$
$$+ t\_carbon_{r,GHG,i}^{di} \cdot \sum_{GHG} \left\{ emis_{r,GHG,i}^{PROD} \right\}$$
$$+ p_r^{CDM} \cdot \left(permits_{r,i}^{CDM} - \sum_{pdt\_emi} \left\{ emc_{r,pdt\_emi,i}^{tot\_p} \cdot xap_{r,pdt\_emi,i} \right\} - \sum_{GHG} \left\{ emis_{r,GHG,i}^{PROD} \right\} \right)$$

Variables: $permits^{CDM}$ International offset permits allocated to host sector

3.5 Price normalisation and market equilibrium

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 export 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, foreign investment flows can be interpreted as the quantity of foreign saving used to purchase the average bundle of OECD manufacturing exports.

The domestic producer price of the good *j* in the model is defined as a composite index of the average variable cost and the costs of the non-CO_2 GHGs bundle, plus production taxes. The aggregate market prices of a good *i* (PA) is calculated as a composite index of domestic producer prices and import prices. Then the prices of final or intermediary demands are market prices (PA) plus agent-specific *ad-valorem* taxes.

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

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.

Box 5. Market equilibrium equations

(33) Definition of total absorption (sum of internal demands)

$$xa_{r,i} = \sum_{vs} \left\{ xap_{r,i,vs} \right\} + xac_{r,i} + \sum_{f} \left\{ xaf_{r,i,f} \right\}$$

(34) Determination of domestic demand

$$xd_{r,i} = a^{d}_{r,i} \cdot xa_{r,i} \cdot \left(\frac{p\_xa_{r,i}}{p\_p_{r,i}} \right)^{\sigma^{m}_{r,i}}$$

Variables: xd Domestic demand

(35) Equilibrium on produced goods and services markets

$$xp_{r,i} = xd_{r,i} + xex_{r,i} + xmarg_{r,i}$$

(36) Equilibrium on sector-specific land markets

$$td_{r,i} = ts_{r,i}$$

(37) Equilibrium on sector-specific production factor markets

$$fs_{r,i} = ff_{r,i}$$

(38) Equilibrium on labour market

$$labs_{r} = \sum_{i} \left\{ labd_{r,i} \right\}$$

(39) Equilibrium on capital market

$$kaps_r = \sum_{i,v} \left\{ kapdv_{r,i,v} \right\}$$

(40) Definition of consumption price index (Laspeyres)

$$PIO\_xc_r = \frac{\sum_i \left\{ xac^0_{r,i} \cdot \left(p\_xac_{r,i} + emc^{tot\_c}_{r,i} \cdot p\_carbon^{dm}_{r,i} \right) \right\}}{\sum_i \left\{ xac^0_{r,i} \cdot p\_xac^o_{r,i} \right\}}$$

(41) Definition of *numéraire*: index of OECD manufactured goods prices

$$p = \frac{\sum_{manu,oecd,rp} \left\{ wp\_e_{oecd,rp,manu} \cdot wtf^0_{oecd,rp,manu} \right\}}{\sum_{manu,oecd,rp} \left\{ wp\_e^0_{oecd,rp,manu} \cdot wtf^0_{oecd,rp,manu} \right\}}$$

Variables: wtf^0 Benchmark levels of international trade flows

3.6 Dynamic behaviour

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. The dynamics also depend on exogenous drivers like population growth, autonomous energy efficiency or sector specific autonomous labour efficiency improvements, *et cetera*.

Investment

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 and government consume a bundle of final goods, 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 government and investment expenditures of this good.

Capital accumulation and sectoral allocation of capital

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).[3]

[3] 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.

The putty/semi-putty specification

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.

Box 6. Dynamic behaviour equations

(42) Aggregate rate of return of capital

$$\sum_{i,v}\left\{kapdv_{r,i,v}\right\} = krat_r \cdot kstock_r$$

Variables: *kstock* Total stock of physical capital

(43) Determination of old sectoral capital supply

$$xpv_{r,i,'old'} \cdot kxrat_{r,i} = Min\left\{xp_{r,i} \cdot kxrat_{r,i}, kaps^0_{r,i}\right\}$$

$$\frac{kapdv_{r,i,'old'}}{xpv_{r,i,'old'}} \le kxrat_r \; ; \qquad rrat_{r,i} \le \left(\frac{kxrat_{r,i} \cdot xp_{r,i}}{kaps^0_{r,i}}\right)^{\frac{1}{InvElas_{r,i}}}$$

$$p\_rent_{r,i,'old'} = rrat_{r,i} \cdot trent_r$$

Variables: *kxrat* Capital to output ratio
kaps^0 Capital stock installed in the beginning of the period

(44) Determination of aggregate capital stock

$$kstock_r = \left(1 - depr_r\right) \cdot kstock_r^{lag} + fdvol_r^{'inv'}$$

Variables: *kstock*^{lag} Total stock of physical capital in previous period
depr Depreciation rate

(45) Determination of aggregate investment expenditure

$$p\_fd_r^{'inv'} \cdot fdvol_r^{'inv'} = sav_r^h + sav_r^g + p \cdot sav_r^f + depr_r \cdot p\_fd_r^{'inv'} \cdot kstock_r$$

Variables: *sav*^{f} Foreign 'savings' (opposite of current account surplus)

4. Calibration of the ENV-Linkages model

There are different ways in which dynamic models can be calibrated. A relatively simple approach, which is often used in more stylized analyses, is to assume that the economy is on a steady-state growth path, and thus the different factors of production, especially labour and capital, grow at a common rate. This provides a smooth evolution of the main model variables over time, but depends on the crucial assumption that the base year is on the steady-state path (or, in somewhat more elaborate alternatives, the economy is expected to converge rapidly towards a steady-state). The alternative calibration method used in ENV-Linkages is considerably more complex, but has the major advantage that it does not depend on a steady-state assumption, and is able to produce realistic patterns of the major variables over the model horizon.

The process of calibrating the ENV-Linkages model is broken down into three stages. First, a number of parameters are calibrated, given some elasticity values, to represent the data for historical year 2004 as an initial economic equilibrium. This process is referred to as the static calibration. Second, the 2004 equilibrium is updated to a reference year for the model baseline (currently 2007) by simulating the model dynamically to match historical trends over the period 2004-2007; static calibration is performed again for the reference year with price re-normalisation in order to express all variables in constant 2007 real USD. This step is important, as it ensures that the basis for the simulations is a relatively recent year. Third, the baseline projection for the model horizon 2008-2050 is based on conditional convergence assumptions about labour productivity and other socio-economic drivers (demographic trends, future trends in energy prices and energy efficiency improvements), using the methodology of the OECD Economics Department (for more information see Duval and de la Maisonneuve, 2009). These convergence assumptions are used to identify the evolution of key economic and environmental variables. The baseline projection is then obtained by running the model dynamically over the period 2007-2050, keeping these key variables exogenous but letting the model parameters adjust endogenously. Thus, the model parameters are calibrated using the structural relations of the model (production functions, household preferences, etc.) to mimic the evolution of the key variables over time. It should be emphasised that when the policy simulations are performed on this calibrated baseline, the model parameters are exogenously fixed, while the model variables are fully endogenous. For instance, while GDP is exogenous in the baseline projection in non-oil producing countries[4], it becomes fully endogenous in policy simulations.

The baseline assumes continuation of the European Union Emission Trading Scheme (EU-ETS) until 2020, but no further new climate policies, but does include other government policies for instance on energy policy as included in the energy projections of the IEA (2012).[5] It thus provides a benchmark against which policy scenarios aimed at achieving emission cuts can be assessed.

Static calibration of the model

The core of the static calibration is formed by the set of comprehensive input-output tables that describe how economic activities in the different sectors are linked to each other, and linked to economic activity in other regions. This set of mutually consistent accounting matrices is based upon the database GTAP. This 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 in Narayanan and Walmsley (2008). For the model version described here, the GTAP version 7.1 is used. As the model calibration is updated roughly every two years, later model versions will use the most recent data, including newer version of GTAP if available.

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

4 In oil-producing countries, GDP in the baseline projection is determined endogenously depending on the endogenous supplies of fossil fuels.

5 The EU Emission Trading System is simulated over the period 2006-2020, assuming a permits price that will rise gradually from 5 US$ in 2008 to 25 US$ in 2012-2020.

resources, etc). Table 1 reports some key elasticities used in the current version of the model. Use of these parameters was illustrated in Figure 1, as well as by the equations in Section 3. Income elasticities of household demand as well as Armington elasticities are taken from the GTAP 7.1 database.

Table 1. Key parameter values in ENV-Linkages

Substitution between GHGs bundle and Net-of-GHGs output	σ^{GHG}	0.05 for agricultural sectors; 0.15 to 0.3 in some industrial emissions
Substitution between material inputs and VA plus energy	σ^{p}	0.1 for new capital in services and manufacturing; 0 for other sectors
Substitution between material inputs	σ^{n}	0.1 for services and manufacturing sectors; 0 for other sectors
Substitution between VA and Energy	σ^{V}	0.04 – 0.27 for old capital vintages and 0.3-2.0 for new vintages
Substitution between inputs feedstocks and land	σ^{f}	0.5
Substitution between Capital and Energy	σ^{E}	0 for old capital vintages, 0.1-0.95 for new vintages
Substitution between Capital and Specific Factor	σ^{k}	0.2 to 0.35
Elasticity between Electricity & Non-electricity energy inputs	σ^{ELY}	0.03 for old capital and 0.25 for new in electricity sector. 0.125 and 1 in other sector except fossil fuel where equals to 0
Elasticity between Coal & liquids bundle	σ^{Coa}	0.06 for old capital and 0.51 for except fossil fuel where equals to 0.
Elasticity between energy inputs in liquids bundle	$\sigma^{liquids}$	0.125 for old capital vintages, 1 for new vintages, but always 0 in the energy sectors, except for Electricity (0.06 and 0.51, respectively)
Elasticity of substitution between all energy goods in extraction sectors	σ^{ep}	0, except 0.25 for Gas production
Armington elasticity, domestic versus imports	σ^{X}	0.9 to 5 depending on the sector
Armington elasticity, import sources	σ^{W}	Same as σ^{X}
Armington elasticity, intermediate goods imports	σ^{m}	Same as σ^{X}
Armington elasticity, energy imports	σ^{EI}	Same as σ^{X}
Elasticity of Supply of Sector-Specific factor	ω^{f}	0 to 10 depending on the sector
Elasticity of transformation of Land	ω^{tl1}	0.11 to 0.21 depending on the region
Elasticity of transformation of Land	ω^{tl2}	0.19 to 0.35 depending on the region
Elasticity of transformation of Land	ω^{tl3}	0
Elasticity of Land Supply	leps	0 to 1.69 depending on the region
Elasticity of substitution of sector specific factor in non-fossil electricity	σ^{natr}	0.2 to 0.4 depending on the sector
Elasticity of substitution between electricity technology	σ^{elec}	5
Elasticity of substitution between food in the feed bundle	σ^{fd}	0.75
Elasticity of substitution between GHGs in the GHGs bundle	σ^{emi_prod}	0-0.05

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 2004 $US) of version 7.1 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).

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. The approach followed here considers only one single set of drivers while recognising that alternative sets may potentially generate somewhat different simulation results.[6] The baseline projection allows calculating the values of a number of parameters over time (such as energy efficiency gains), in order to reproduce the evolution of the drivers (such as energy demands; for more details see below). In any variants or policy simulations, these parameter values are kept constant while all other variables in the model, including some of the original drivers that are used to calibrate the baseline, are fully endogenous.[7]

The macroeconomic context of the baseline projection is based on projections by the OECD Economics Department. Further sectoral information is required to replicate these projections in ENV-Linkages:

- Sectoral labour productivity growth, controlled by calibration of technical progress coefficients embodied in labour;
- Autonomous efficiency gains for capital, land and specific natural resources; after 2015 efficiency gains for capital are calibrated in order to imply a constant efficiency capital to efficiency labour ratio;
- Autonomous efficiency gains of fertilizers in crops sectors and of the food bundle in livestock rearing;
- Supply of land and natural resources;
- 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, controlled by calibration of the Autonomous Energy Efficiency Improvements (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;
- Non-CO_2 GHGs emissions, controlled by calibration of technological parameters of the CES GHG bundle, by sector and type of GHGs emissions;
- Share of electricity by technology in total generation, controlled by potential supply of the specific resource factor.

Data used for dynamic calibration

Socio-economic variables such as population, apparent labour productivity or investment to GDP ratios are part of the underlying long-term ENV-Growth model described in Chateau et al. (2013). Convergence assumptions used in this scenario are based on real income comparisons expressed in purchasing power parity (PPP) and not in market exchange rates. In addition, the updated baseline projection incorporates the recent world economic recession that is simulated using negative productivity shocks.

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6 For instance, differences in projected energy prices in the baseline scenario may affect the economic costs of policy scenarios, although by a marginal extent. For more on sensitivity analysis to baseline scenario, see OECD (2006).

7 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.

AEEIs in energy use have been dynamically calibrated on the basis of elasticities for each kind of energy demand to GDP for 2007-2030, as projected in the IEA *World Energy Outlook* (2009, 2012). These elasticities are assumed to be constant after 2030, governing the long-term development of the AEEIs.

Non-CO_2 greenhouse gases also require calibration in the base year database. For this purpose, the price of these emissions is arbitrarily set equal to 0.5 USD per ton of CO_2 equivalent in the upper bundle of the gross output. Emissions by source reported in US EPA (2006a) are attributed to the sectors of ENV-linkages. It was not possible to attribute all emission sources to an economic activity described in the model.[8] For the period 2005-2020, the non-CO_2 emissions are calibrated on forecasts made by the US EPA by adjusting parameters 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-CO_2 GHGs emissions, where the trend assumed is taken from the OECD *Environmental Outlook* (2008).

The evolution of the international import prices of fossil fuels is also controlled for in the baseline scenario. During the period 2004-2009, the model reproduces the historical statistics reported by the IEA in its *World Energy Outlook* report. Over the rest of the model horizon (2010-2050), the crude oil potential reserves are calibrated to reproduce the exogenous trajectory of the international crude oil price assumed by the IEA.

In line with IEA projections, the evolution of the international price of natural gas closely follows that of the crude oil price. This is controlled for by adjusting natural gases resources in all producing regions. The historical and projected surge of the international coal price up to 2009 is introduced by controlling the supply of coal-producing regions.

From 2001-2014, current account balances as well as government savings are calibrated to match IMF (2010) historical data and projections. After 2014, 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). Depreciation rates for physical capital stock are also calibrated using data from IMF until 2012; for the period 2013-2020 we assume a convergence to the long-run depreciation rate used by Duval and de la Maisonneuve (2010), which is applied after 2020.

Dynamic calibration of household preferences

The parameters relative to household demands (see equations 1-3) need to be recalibrated dynamically in the baseline simulation. 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. Income elasticities of final demands of energy goods are calibrated to match IEA household energy demands (IEA, 2010b).

8. For instance, non-CO_2 emissions from the burning of savannas are not introduced. They correspond to less than 5% of the non-CO2 emissions reported by the US EPA.

Dynamic adjustment of world trade and output structures

In models like ENV-Linkages, which use the Armington specification 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.

Software and model solution

ENV-Linkages model is written in the General Algebraic Modeling System (GAMS) modelling language. GAM is particularly useful for numerical modelling of linear, nonlinear and mixed integer optimization systems. The software has a number of solvers that can be used for a particular problem and, in many cases, switching between solvers is straightforward. In the past this has proved useful since problems that don't solve with one solution algorithm may solve with another.

For economic problems, GAMS can be particularly useful since it allows problems to be written as mixed complementarity – which specifies inequalities that the solution must meet. This facilitates the solutions to problems involving budgets constraints or homogeneous products being produced by multiple sectors.

5. Recent policy applications

OECD Environmental Outlook to 2050

The ENV-Linkages model has played a key role in the analysis of the *Environmental Outlook to 2050* (OECD, 2012). Modelling analysis features elaborately in the Chapters on Socioeconomic developments and Climate change. More details on the Environmental Outlook to 2050 can be found on www.oecd.org/environment/outlookto2050.

The Socioeconomic developments chapter starts by describing current demographic trends and corresponding *Baseline* projections (notably for population growth/composition including ageing, and urbanisation). It then outlines economic trends and projections, including economic growth (GDP, consumption, sectoral composition) and its drivers, such as labour and capital. These trends are based on a gradual conditional convergence of income levels among countries. In its final section it explores two factors which directly link economic trends to environmental pressures: energy use (energy mix such as fossil fuels, renewables and nuclear) and land use (in particular agricultural land). The projected key socioeconomic developments under the *Environmental Outlook Baseline* scenario presented in this chapter serve as the basis for the environmental projections described in the other chapters of the *Outlook.* The chapter focuses on global projections for major world regions such as the group of OECD countries, emerging economies of Brazil, Russia, India, Indonesia, China and South Africa (the BRIICS) and the rest of the world, although the analysis is done at a more disaggregated level.

The Climate change chapter analyses the policy implications of the climate change challenge. Are current emission reduction pledges made in Copenhagen/Cancun enough to stabilise the climate and limit global average temperature increase to 2^{o}C? If not, what will the consequences be? What alternative growth pathways could achieve global average atmospheric concentration of greenhouse gases (GHG) at 450 ppm, the level needed to keep the temperature rise to 2^{o}C with a 50% chance? What policies are needed, and what will be the costs and benefits to the economy? How can the world adapt to global warming that is already occurring? To shed light on these questions, this chapter first looks at GHG emissions (including from land-use) and concentration, and temperature and precipitation changes under the *Environmental Outlook Baseline* scenario of "business-as-usual" (*i.e.* no new action) to 2050. It then takes stock of the state of climate policy today. Most countries use on a mix of policy instruments that include carbon pricing (carbon taxes, cap-and-trade emissions trading, fossil fuel subsidy reform), other energy efficiency policies, information-based approaches and innovation policy to foster clean technology. The transition to a low-carbon, climate-resilient development path requires financing, innovation and strategies that also address potential negative competitiveness and employment/job impacts. The chapter also looks at what further action is needed by comparing different mitigation scenarios (variants of 450 ppm and 550 ppm scenarios with differences in: technology options, *e.g.* carbon capture and storage (CCS), nuclear phase-out, biofuels; linking of carbon markets; permit allocation rules) against the *Baseline* to understand how the situation could be improved. A prudent response to climate change involves both mitigation policies to cut emissions, as well as timely adaptation policies to limit damage by the already changing climate. The modelling behind this chapter is done in collaboration between ENV-Linkages and the IMAGE suite of models of the Netherlands Environmental Assessment Agency, PBL.

Competitiveness and carbon leakage

The ENV-Linkages model has been used to analyse the competitiveness and carbon leakage impacts of different carbon market designs. Competitiveness impacts have been analysed considering both macroeconomic indicators, such as wealth, and sectoral indicators, such as output, exports and imports of key sectors. The environmental impact has been analysed considering emission levels as well as carbon leakage impacts, since high levels of carbon leakage risk compromising the effectiveness of a carbon pricing policy.

This work-stream has taken into consideration different designs in terms of coverage (i.e. number of countries participating, types of gases and sectors included), possibilities to link across national trading schemes and stringency of the carbon pricing policy. Dellink et al. (2013) find that indirect linking of carbon markets through a common offset system can be at least as powerful as direct linking in terms of reducing mitigation costs. The model was also used to investigate border carbon adjustments (BCAs) as possible response policy to address impacts of climate policies on competitiveness and carbon leakage (Burniaux *et al.*, 2013). The BCAs were modelled carbon-based import tariffs levied on non-acting countries and carbon-based export subsidies in support of domestic production in acting countries.

Lanzi et al. (2012) and OECD (2013) bring these two work-streams together and compare linking and BCAs. As part of this exercise, carbon leakage impacts have been calculated for the various scenarios. The model details in terms of regional and sectoral details for GHGs emissions are exploited to calculate, not only international carbon leakage, but also additional indirect emission changes. In particular this analysis considers a domestic carbon leakage effect, arising when sectors in acting countries are excluded from the policy causing emission increases in uncapped sectors, as higher production costs for capped sectors cause shifts in demand towards uncapped sectors. It also considers complementary emission reductions: when the policy is limited to CO_2, in acting countries there is a decrease in emissions of other GHGs, as they are largely linked to the same economic activities.

Fossil fuel subsidies

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 showing that removing fossil fuel subsidies in a number of non-OECD countries could reduce world GHG emissions by 10% in 2050 compared with their level in the absence such a reform (OECD, 2009). According with IEA estimates, total fossil fuel subsidies in 2008 amounted to USD 557 billion (IEA, OPEC, OECD, World Bank, 2010).

The ENV-Linkages model has been used to provide quantified estimates of the emission reduction and the 'real income' gains that can be achieved by removing fossil fuel subsidies (e.g. Burniaux and Chateau, 2011; Burniaux et al., 2011). This analysis only concerns consumer subsidies that are mostly present in non-OECD countries. While each form of consumer subsidies should ideally be modelled explicitly in order to quantify their impact, this approach was not feasible due to lack of data. Instead, the approach followed here is a simplified one usually referred to as the "price-gaps approach". This approach aims at summarizing various forms of consumer price regulations using one single indicator that is the observed price deviation between the domestic consumer price and a reference price considered as undistorted (usually the corresponding international price).

This analysis uses price gaps data that is the most recent and comprehensive in country coverage. Price gaps are estimated by the IEA for coal, refined oil products, natural gas and electricity for 37 countries, including 2 OECD countries (South Korea and Mexico). The price gaps estimated by the IEA for 2008 are introduced by calibration in the initial year of the model, 2007, and they are supposed to remain constant in percentage up to 2050. In simulations of generic subsidy reforms, these price gaps are gradually phased-out over the period 2013 to 2020.

In all reform simulations, the budgetary saving obtained from the subsidy removal is entirely refunded to households in a lump-sum manner. In other words, subsidies to the consumption of fossil fuel are then replaced by a direct 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.

Labour market implications of mitigation policies

In June 2009, Ministers requested the OECD Secretariat to develop a "Green Growth Strategy" with the aim of helping governments to identify policies to achieve environmentally sustainable growth. This means supporting continued economic growth while reducing pollution and greenhouse gas emissions, waste and inefficient use of natural resources, and at the same time addressing social implications of the transition to a green economy. The ENV-Linkages model contributes to this project in different ways*: i)* by giving insights on the magnitude and direction of labour reallocation resulting from mitigation policies across sectors; *ii)* by assessing the transitory costs associated with this labour reallocation; and, *iii)* by simulating policies aimed at creating new jobs, such as reducing the labour taxes. Improvement of the specification of the labour market in ENV-Linkages is, however, essential to provide robust insights into these issues

The model improvements made for this work are detailed in Chateau and Saint-Martin (2013). The calibration of these model extensions is, however, deemed not robust enough to be incorporated in the core version of the model. The extended labour market specification remains therefore optional for future projects.

Consequences of the Copenhagen Accord / Cancún Agreement pledges

A first assessment of the economic and environmental implications of the emission pledges for 2020 made by countries in the Copenhagen Accord, and confirmed in the Cancún Agreement, is presented in Dellink et al. (2011). This analysis has also featured in the UNEP Emissions Gap report (UNEP, 2010). Updates of this analysis have been presented in UNEP (2011, 2012) and in the Environmental Outlook to 2050 (OECD, 2012).

Other improvements to the model

Given the varied needs of the OECD Environment Directorate, flexibility is deemed essential in building a general-purpose tool for environmental policy analysis. The objective is therefore to make ENV-Linkages as adaptable as possible to studying different policy issues within a relatively short time horizon. Some of the improvements that have been made in this area include:

- General purpose routines that extract data from various source databases: GTAP database, United Nations Population Prospects, IMF, US-EPA for non-CO_2 greenhouse gases, IEA databases for energy demands and CO_2 emissions associated to fuel combustion, economic baseline drivers such as productivity, labour force participation, etc.
- Development and maintenance of database routines that allow a source file including individual countries/regions to be maintained. The aggregation routines permit an easy shift between sectoral and regional aggregations of the model. The procedures automatically generate aggregated data that serve as preliminary projections of the baseline for a model simulation. A high degree of flexibility in the routines permits modification for different applications. Consistency across aggregations in model parameters and calibrations is largely automatic with only residual effort needed to make different aggregations largely equivalent from an economic perspective; *i.e.* that the sum of individual region responses to most policy are nearly equal to the whole of an aggregated region. Nonetheless, some simulation results would be aggregation dependent. For instance, “Armington trade-off” between goods of different /countries/regions would be affected by the retained aggregation.
- Flexibility has also been developed in changing the model’s structure. Some elements of the model may be added or removed in order to focus on specific issues while keeping the model tractable. For example, it is easy to change between an economy that follows a quasi-balanced growth path (where the capital to output ratio is fixed) versus one where it does not. The structure of the energy demand can be modified easily too. In the model currently used, the energy bundle consists of several nests implying different degree of substitution between specific energy sources. International trade shares may be made to evolve over time rather than just respond to price changes – so globalisation can be factored in. Other areas have also been made to be more flexible. The importance of these changes is that the model can be re-specified on relatively short notice to study issues of interest for policy from alternative perspectives.
- The dynamic calibration of the model has been made more flexible by directly linking to the underlying ENV-Growth model. In the construction of a baseline scenario (*e.g.* the central projection made on the basis of a set of socio-economic drivers and used as a benchmark for subsequent policy simulations) some trends may be exogenously determined, or left as part of the solution of the model simulation.

6. Foreseen model developments and applications

The CIRCLE project

The CIRCLE project aims at identifying how feedbacks from poor environmental quality, climatic change and natural resource scarcity affect economic growth (for more details, see OECD, 2013). The CIRCLE project will also compare these costs of inaction with the benefits of action for environmental and other policies. Over a series of model developments during this and next biennia, the project could provide assessments of the economic impacts of a selected number of major environmental and resource scarcity issues. CIRCLE will generate reference projections for economic growth which reflect the costs of policy inaction in these areas insofar as these are adequately measurable. Such reference projections would be more appropriate starting points for future OECD projections of economic growth, as well as for assessments of the economics of environmental policies, as they are able to include not only costs but also benefits of policy action. This would allow a more informative evaluation of policies, and a comparison of the costs and benefits involved.

The environmental challenges investigated largely coincide with those addressed by the *Environmental Outlook to 2050*. The modelling work in CIRCLE will initially focus on climate change, local air pollution and the land-water-energy nexus. In the future, further modelling work on water, biodiversity and ecosystem services and resource scarcity could be considered.

- For climate change, the ENV-Linkages model will be expanded with a simple climate module that imputes the consequences for radiative forcing and global average temperature change resulting from the emission pathway projected in the model. Next, a number of sectoral adjustments to productivity and other relevant model parameters will be specified to reflect the impact of climate change damages on the economy.
- For local air pollution, the first step is to link economic activities to emissions of the main air pollutants. Then, attention will be paid to the specification of the associated marginal abatement costs for these pollutants. Finally, options to represent economic implications of health impacts from air pollution in the model will be investigated.
- For the resource nexus, the ENV-Linkages model will be linked to PBL's IMAGE model, but in contrast to the joint modelling work for the Outlook, this linking will go both ways: outputs from IMAGE in terms of the bottlenecks that result from biophysical scarcities will be used to adjust specific parameters in ENV-Linkages, analogous to the specification of the climate damages.

Distributional impacts of climate-related policies

The modelling team has also started a project to assess the distributional consequences of climate-related policies. The project will combine insights from ENV-Linkages with household level data on income and expenditures to shed light on the distributional impacts of green growth policies, including climate mitigation and energy policies. The enhanced modelling framework could for instance be used to investigate to which extent market-based environmental policies, such as environmental taxes, that can contribute to growth objectives (e.g. fiscal consolidation), can also be made consistent with equity goals. There may be scope to rebalance current consolidation efforts in favour of more equity and greening of the fiscal system.

For this project, for a limited number of case studies, the output of ENV-Linkages will be coupled to country-specific budget survey databases. Furthermore, several possibilities to improve the specification of ENV-Linkages are also currently under consideration. These could include distinguishing different skill levels for labour, urban and rural households, and, if sufficient data is available, different household groups may be specified directly in the model.

REFERENCES

ENV-LINKAGES PUBLICATIONS

Burniaux, J. and J. Chateau (2008), "An Overview of the OECD ENV-Linkages Model", *OECD Economics Department Working Papers*, No. 653, OECD Publishing, Paris, http://dx.doi.org/10.1787/230123880460.

Burniaux, J.M., et al. (2008), "The Economics of Climate Change Mitigation: Policies and Options for the Future", *OECD Economics Department Working Papers*, No. 658, OECD Publishing, Paris, http://dx.doi.org/10.1787/228868001868.

Burniaux, J.M., et al. (2009), "The Economics of Climate Change Mitigation: How to Build the Necessary Global Action in a Cost-Effective Manner", *OECD Economics Department Working Papers*, No. 701, OECD Publishing, Paris, http://dx.doi.org/10.1787/224074334782.

Burniaux, J.M. and J. Chateau (2011), "Mitigation Potential of Removing Fossil Fuel Subsidies: A General Equilibrium Assessment", *OECD Economics Department Working Papers*, No. 853, OECD Publishing, Paris, http://dx.doi.org/10.1787/5kgdx1jr2plp-en.

Burniaux, J.M., J. Chateau and J. Sauvage (2011), "The Trade Effects of Phasing Out Fossil-Fuel Consumption Subsidies", *OECD Trade and Environment Working Papers*, No. 2011/05, OECD Publishing, Paris, http://dx.doi.org/10.1787/5kg6lql8wk7b-en.

Burniaux J.M., J. Chateau, and R. Duval (2013), "Is there a case for carbon-based border tax adjustment? An applied general equilibrium analysis", Applied Economics, No 45:16, 2231-2240. www.tandfonline.com/doi/full/10.1080/00036846.2012.659346#.U0a-N-Kktgk.

Chateau, J., C. Rebolledo and R. Dellink (2011), "An Economic Projection to 2050: The OECD "ENV-Linkages" Model Baseline", *OECD Environment Working Papers*, No. 41, OECD Publishing, Paris, http://dx.doi.org/10.1787/5kg0ndkjvfhf-en.

Chateau, J., and A. Saint-Martin (2013), "Employment impacts of climate change mitigation policies in OECD: a general equilibrium perspective", International Economics, http://dx.doi.org/10.1016/j.inteco.2013.08.001.

Dellink, R., G. Briner and C. Clapp (2011), "The Copenhagen Accord / Cancun Agreements emissions pledges for 2020: exploring economic and environmental impacts", Climate Change Economics, Vol. 2(1), pp. 53-78. www.worldscientific.com/doi/abs/10.1142/S2010007811000206.

Dellink, R. et al. (2014), "Towards global carbon pricing: Direct and indirect linking of carbon markets", *OECD Journal: Economic Studies*, Vol. 2013/1, Paris, http://dx.doi.org/10.1787/eco_studies-2013-5k421kk9j3vb.

IEA, OPEC, OECD, World Bank (2010), "Analysis of the Scope of Energy Subsidies and Suggestions for the G-20 initiative", Joint Report prepared for submission to the G-20 Meeting of the Finance Ministers and Central Bank Governors, Busan (Korea), 5 June 2010, 26 May 2010. www.learningace.com/doc/1344509/353049d0aabe87a4f01869c2972069ad/g20.

Lanzi, E., J. Chateau and R. Dellink (2012), "Alternative approaches for levelling carbon prices in a world with fragmented carbon markets", Energy Economics, Vol. 34, pp. S240-S250. http://dx.doi.org/10.1016/j.eneco.2012.08.016.

Lanzi, E., et al. (2013), "Addressing Competitiveness and Carbon Leakage Impacts Arising from Multiple Carbon Markets: A Modelling Assessment", *OECD Environment Working Papers*, No. 58, OECD Publishing, Paris, http://dx.doi.org/10.1787/5k40ggjj7z8v-en.

OECD (2006), “Sensitivity analysis in ENV-Linkages”, [ENV/EPOC/GSP(2006)6], OECD, Paris, France.

OECD (2008), *OECD Environmental Outlook to 2030*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264040519-en.

OECD (2009), *The Economics of Climate Change Mitigation: Policies and Options for Global Action beyond 2012*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264073616-en.

OECD (2012), “*OECD Environmental Outlook to 2050: The Consequences of Inaction”*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264122246-en.

OECD (2013), "CIRCLE: Assessing environmental feedbacks on economic growth and the benefits (and trade-offs) of policy action: Scoping paper", [OECD ENV/EPOC(2013)15], OECD, Paris, France.

OTHER REFERENCES

Armington, P. (1969), "A Theory of Demand for Products Distinguished by Place of Production", IMF Staff Papers, Vol. 16, pp. 159-178. www.jstor.org/stable/3866403?origin=pubexport.

Arnberg, S. and T. B. Bjorner (2007), "Substitution between energy, capital and labour within industrial companies: A micro panel data analysis", Resource and Energy Economics, 2007, vol. 29, no. 2, pp. 122-136. dx.doi.org/10.1016/j.reseneeco.2006.01.001.

Burniaux, J.M. (2000), "A Multi-Gas Assessment of the Kyoto Protocol", *OECD Economics Department Working Papers*, No. 270, OECD Publishing, Paris, http://dx.doi.org/10.1787/540631321683.

Burniaux, J.M., G. Nicoletti and J. Oliveira Martins (1992), “GREEN: A Global Model for Quantifying the Costs of Policies to Curb CO_2 Emissions”, OECD Economic Studies, 19 (Winter 1992). www.oecd.org/eco/growth/35044127.pdf.

Dowrick, S., Y. Dunlop, and J. Quiggin (2003), "Social Indicators and Comparisons of Living Standards", Journal of Development Economics, 2003, Vol. 70. dx.doi.org/10.1016/S0304-3878(02)00107-4.

Duval, R. and C. de la Maisonneuve (2009), "Long-Run GDP Growth Framework and Scenarios for the World Economy", *OECD Economics Department Working Papers*, No. 663, OECD Publishing, Paris, http://dx.doi.org/10.1787/227205684023.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin, and H.D. Jacoby (2002), "Modeling Non-CO2 Greenhouse Gas Abatement", Environmental Modeling and Assessment, Vol. 8, No. 3, pp. 175-86. download.springer.com/static/pdf/19/art%253A10.1023%252FA%253A1025576926029.pdf?auth66=1397404259_e046124779f85342a8e64312e6a1831a&ext=.pdf.

International Energy Agency (IEA) (2004),*Prospects for CO2 Capture and Storage*, Energy Technology Analysis, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264108820-en.

IEA (2009), *World Energy Outlook 2009*, OECD Publishing, Paris, http://dx.doi.org/10.1787/weo-2009-en.

IEA (2012), *World Energy Outlook 2012*, OECD Publishing, Paris, http://dx.doi.org/10.1787/weo-2012-en.

IEA (2010a), Projected Costs of Generating Electricity, IEA, Paris. www.iea.org/textbase/npsum/eleccost2010SUm.pdf.

IEA (2010b), "IEA statistics", "Oil Information", "Coal Information" and "Natural Gas information", Paris.

IMF (2010), "World Econonomic Outlook Database", www.imf.org/external/pubs/ft/weo/2010/02/weodata/index.aspx.

Krugman, P. (1989), "Differences in Income Elasticities and Trends in Real Exchange Rates", European Economic Review, Vol. 33, No. 5. cdn.elsevier.com/assets/pdf_file/0003/105267/Differences_in_income_elasticities.pdf.

Lee, H-L., (2008), "The Combustion-based CO2 Emissions for the GTAP Version 7 database", GTAP Working Paper 4470, Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana, USA. sequestration.mit.edu/pdf/2006_McFarland_Herzog_EnergyEconomics.pdf.

McFarland, J.R. and H.J. Herzog (2006), "Incorporating carbon capture and storage technologies in integrated assessment models", Energy Economics 28, 632–652. sequestration.mit.edu/pdf/2006_McFarland_Herzog_EnergyEconomics.pdf.

Narayanan , B. and T.L. Walmsley (eds) (2008) Global Trade, Assistance, and Production: The GTAP 7 Data Base, Center for Global Trade Analysis, Purdue University.

OECD (2001), *OECD Environmental Outlook*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264188563-en.

OECD (2000), *Agricultural Policies in OECD Countries 2000: Monitoring and Evaluation*, OECD Publishing, Paris, http://dx.doi.org/10.1787/agr_oecd-2000-en.

OECD (2005), *Trade and Structural Adjustment*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264064591-en.

PBL (2010), The IMAGE model suite, ENV/EPOC(2010)15, Paris.

UNEP (2010), The emissions gap report: Are the Copenhagen Accord pledges sufficient to limit global warming to 2°C or 1.5°C?, UNEP, Geneva. www.unep.org/publications/ebooks/emissionsgapreport/pdfs/The_EMISSIONS_GAP_REPORT.pdf.

UNEP, 2011, Bridging the emissions gap: A UNEP Synthesis Report, UNEP, Geneva. www.unep.org/publications/ebooks/bridgingemissionsgap/.

UNEP, 2012, The emissions gap report 2012: A UNEP Synthesis Report, UNEP, Geneva. www.unep.org/publications/ebooks/emissionsgap2012/.

US EPA (2006a), "Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020", United States Environmental Protection Agency, Washington DC, June 2006 Revised. www.epa.gov/outreach/pdfs/global_emissions.pdf.

US EPA (2006b), "Global Mitigation of Non-CO2 Greenhouse Gases", United States Environmental Protection Agency, Washington DC, June 2006. nepis.epa.gov/Adobe/PDF/2000ZL5G.PDF.

Van der Mensbrugghe, D. (2005), "Linkage Technical Reference Document Version 6.0", Development Prospects Group, The World Bank, Washington DC, January 2005. Accessible at www.worldbank.org/prospects/linkagemodel.

Weyant, J. and F. de la Chesnaye (eds.) (2006), "Multigas Mitigation and Climate Change", Energy Journal. econpapers.repec.org/article/aenjournl/2006se_5fweyant-a01.htm.