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CGE model PLACE

MINISTRY OF FINANCE
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CENTER FOR CLIMATE POLICY ANALYSIS

CGE model PLACE

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Contents

Introduction

PLACE[1] is a static multi-region, multi-sector computable general equilibrium (CGE) model designed to assess the economic impact of energy and climate policies. Policies are typically analyzed using a comparative static approach, in which a situation with policy interference is compared to a situation without policy interference (often termed "baseline" or "business-as-usual"). Based on general equilibrium theory, PLACE incorporates micro-economic mechanisms within a comprehensive macro-economic framework, which distinguishes it from other large-scale economic models such as multivariate econometric models and input output analysis. The particular strengths of the CGE approach is the scope for quantifying distributional impacts of policies and the ability to reflect complex sectoral adjustments.

The PLACE model was developed by the members of the Center for Climate Policy Analysis (Polish acronym – CAK) working together with World Bank staff and consultants. The Center was established based on the joint letter of intent of May 7, 2013, between the Minister of Economy, Minister of Environment and Minister of Finance of the Republic of Poland and the World Bank on cooperation in creating an analytical toolbox for analyses dealing with the impact of climate and energy policy. The aim is for the toolbox to include transparent economic and sectoral models based on transparent assumptions, approaches and data, which will respond to climate and energy policy questions formulated by governmental institutions in Poland. PLACE originates from the ROCA model developed by Christoph Böhringer and Thomas Rutherford in 2011 as part of the World Bank project on the report *Transition to a Low-emissions Economy in Poland* (World Bank, 2011).

This document constitutes technical documentation of the PLACE model and aims to present the underlying algebra and data sources that were used at different stages during the model's development. It is structured as follows. In chapter 1, we lay out the model logic and data sources. Section 1.1 presents a non-technical model summary. Section 1.2 describes the GTAP database and other complementary data sources used to parameterize the model. Chapter 2 offers a detailed technical description of the model: we first present the underlying algebra and then discuss model calibration methods. Chapter 3 of the documentation describes the baseline assumptions and presents illustrative policy analyses that have been conducted with the model to date.

[1] PLACE stands for the Polish Laboratory for Analysis of Climate and Energy Policy.

1. Overview of model logic and data

1.1 Non-technical model summary

PLACE is a computable general equilibrium (CGE) model. CGE models have become a standard tool for economy-wide policy regulation impact analysis. The fundamental paradigm is that economic agents behave rationally and optimize their choices – e.g., to maximize profits (firms) or consumption utility (households), subject to constraints – e.g., technological restrictions (firms) or budgetary limits (households). In the CGE model, agents interact on markets where prices are determined so that the supply of good and factors equals demand. This enables market supply and demand functions to be derived from optimizing the behavior of economic agents. The CGE model solves for values in prices, activity levels, and income for agents so that the fundamental equilibrium conditions (non-excessive profits, market clearance, and income balance) are satisfied.

CGE models commonly adopt nested *constant elasticity of substitution* (CES) functions to describe technological options in production and preferences in consumption. The specific nesting of inputs and the choice of substitution elasticities may critically depend on the assumption about the model horizon and the availability of econometric estimates (see chapters 2.1 and 2.2.1). Given a wider range of reasonable nesting structures and elasticity values, CGE model analysis should include sensitivity analysis on these dimensions to test the robustness of policy insights and policy conclusions.

Box 1. Constant elasticity of substitution production function (CES)

Constant elasticity of substitution functions are commonly used in CGE modeling to describe the technological options in production. A basic property is that the elasticity of substitution (loosely speaking, the ease with which one production factor can be substituted for another) does not change. In the other words, the percentage change in the ratio of marginal productivity of production inputs in reaction to the percentage change in the relation between these inputs is constant, regardless of how many inputs were initially employed. The basic CES production function for two inputs has the following form:

$$F(x, y) = (\theta x^{\rho} + (1-\theta)y^{\rho})^{1/\rho}$$

where $\sigma = 1/(1-\rho)$ is the parameter of substitution.

There are two general conditions that have to be met by functional forms of production function to ensure the existence of the equilibrium in the general equilibrium model (Shoven, Whalley, 1994):

- The resulting demand for the intermediate inputs and production factors must conform to Walras' Law, which implies that the aggregate values of excess demand across all markets must equal zero, irrespective of whether the economy is in general equilibrium. This implies that if positive excess demand exists in one market, negative excess demand must exist in another market. Thus, if all markets but one are in equilibrium, then that last market must also be in equilibrium.
- The functional forms must be continuous and homogeneous of degree one (i.e., multiplying all inputs by a certain factor will cause output to increase by the same factor), which is equivalent to the property of constant returns to scale.

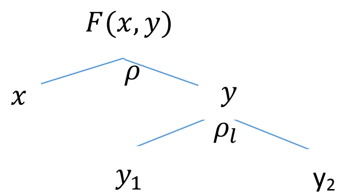
The concept of the "nested CES" function is crucial to understanding CGE modeling. In this concept, a range of different inputs enter the production function in a hierarchical manner – inputs at "higher" level are the CES functions of inputs at the "lower" level. For instance, we can define y, which was used in the previous equation, as:

$$y = F(y_1, y_2) = (\vartheta y_1^{\rho_l} + (1-\vartheta)y_2^{\rho_l})^{1/\rho_l}$$

If this function is substituted for y, we reach a nested CES function with two nests:

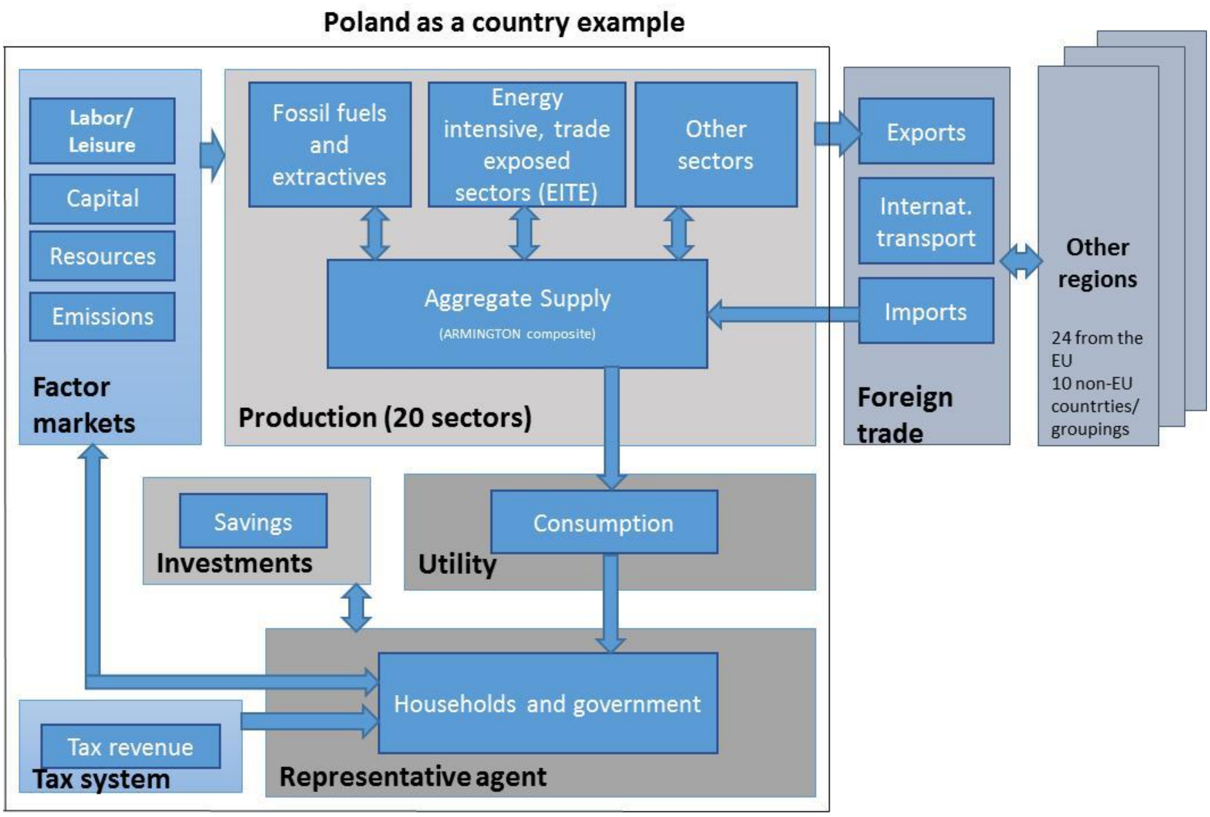
$$F(x, y) = (\theta x^{\rho} + (1-\theta)((\vartheta y_1^{\rho_l} + (1-\vartheta)y_2^{\rho_l})^{1/\rho_l})^{\rho})^{1/\rho}$$

This can be illustrated schematically as follows (ρ_l and ρ denote elasticities in particular nests).



Source: Center for Climate Policy Analysis.

Figure 1. PLACE model – schematic overview



Source: Center for Climate Policy Analysis.

The interactions between different agents in the model are presented in Figure 1. We distinguish two categories of production:

- Production of goods as characterized by the input-output data for sectors (industries). Firms employ production factors and intermediate inputs to produce goods. Production decisions are based on relative prices, including the respective taxes and subsidies. Goods enter both the domestic and export markets – thus we implicitly assume infinite elasticity of transformation between goods produced for domestic and export markets.
- Production of composite Armington goods from domestic and imported goods subject to a constant elasticity of substitution (so-called Armington elasticities). The Armington composite enters the intermediate demand and final demand categories (private consumption, public consumption, and investment).

On the consumption side, the model distinguishes between a representative household and the government in each region.

The **representative household** owns factors of production – time that may be devoted to leisure and labor, capital, land and other resources (as a rule natural resources, see 1.2.1). The household receives labor income and remuneration from other resources (factors). It also receives transfers from the government. Disposable income is spent on consumption and investment (i.e., future consumption).

The **government** receives income from taxes (minus subsidies) (see 2.1.3), which is spent on the provision of public goods (public consumption) and transfers to households.

PLACE is comparative-static, but the policy simulations refer to the future state of the economy, which is achieved using the procedure of dynamic re-calibration. It requires the use of external projections. The recalibration is made using the external projections from the EU Reference scenario (European Commission, 2013) based on the PRIMES model, used by the EC.

The PLACE model has been developed with the primary objective of assessing the economic impacts of energy and climate policies. To date, the PLACE model has been used to analyze the following topics:

- the economic impacts of the EU 2030 climate and energy policy package;
- the economic effects of the proposed changes in energy taxation on Poland and other EU regions through 2030;
- the burden-sharing proposals under the EU 2030 climate and energy policy package.

Further details on the analysis of these policy issues using the PLACE model can be found in chapter 3.2 of this documentation.

The model is static and a comparative static framework is used to assess the economic effects of particular policies. In such a framework, the model is calibrated in line with the external economic projections for 2030, and the values predicted by the model constitute baseline scenario. In the policy scenario, some policy parameters (e.g. tax rates) or external assumptions are changed/shocked and the model is recalculated in order to obtain values of macroeconomic variables in the alternative scenario. The difference between the values in the alternative scenario and the baseline envisages the policy impact of the shocks.

The PLACE model is comparable in its class to other multi-sector, multi-region computable general equilibrium (CGE) models used for the impact assessment of climate policies. Such models provide counterfactual ex-ante comparisons, assessing the outcomes of policy reforms with what would have happened had they not been undertaken. They reflect comprehensive interactions on product and factor markets and are able to quantify the economic effects of policy shocks. The paper by Böhringer et al. (2012) summarizes twelve[2] multi-sector, multi-region models which could be compared to the PLACE model.

1.2 Data – GTAP and other data sources

1.2.1 GTAP

Since 1990, the Global Trade Analysis Project (GTAP) has been providing global input-output databases of the same name with detailed information on country-specific consumption and

[2] These models are: BCR, CEPE, DART, CVO, EC-MS-MR, ENVLINKAGES, FF, MINES, PACE, SNOW, WEG_CENTER, and WORLDSCAN.

production patterns and flows (Hertel et al., 2012, Rutherford 2012).[3] Beyond the core database, GTAP offers additional satellite data such as information on non-CO_2 greenhouse gas emissions (GTAP-NCO2), global land use (GTAP-AEZ), or labor migration (GMig2). The GTAP database to date features several base years (1990, 1992, 1995, 1997, 2001, 2004 and 2007) for up to 5 production factors, 57 sectors and 129 regions.

Aggregations of the database by factor, sector and region can be flexibly chosen to reflect the requirements of the specific policy issues to be considered in the model-based CGE analysis. Given that PLACE primarily focuses on EU climate and energy policy, the sector aggregation adopted so far for PLACE applications explicitly distinguishes primary/secondary energy goods as well as emission- and energy-intensive (non-energy) industries (EITE), while the regional dimension treats almost all of the 28 EU countries separately (see Table 1). The production factors are kept as in GTAP, with capital, resources, land and labor distinguished by skilled and unskilled workforce.

Regional aggregation

Table 1 presents the regional aggregation of the PLACE model. The detailed representation of the EU countries reflects the focus on analyzing EU policies. Outside the EU, the largest greenhouse gas emitters as well as all the major fossil fuel suppliers are distinguished.

Table 1. Country aggregation in the standard PLACE model

	Country code	GTAP country/region names
EU – 28	AUT	Austria
	BEL	Belgium + Luxembourg
	BGR	Bulgaria
	CZE	Czech Republic
	DEU	Germany
	DNK	Denmark
	ESP	Spain
	EST	Estonia
	FIN	Finland
	FRA	France + Malta
	GBR	United Kingdom
	GRC	Greece + Cyprus
	HRV	Croatia
	HUN	Hungary
	IRL	Ireland
	ITA	Italy
	LTU	Lithuania
	LVA	Latvia
	NLD	Netherlands
	POL	Poland
	PRT	Portugal
	ROM	Romania

[3] The core database also includes data on energy use and energy-related CO_2 emissions.

	SVK	Slovakia
	SVN	Slovenia
	SWE	Sweden
	EFT	EFTA countries involved in EU ETS: Norway, Liechtenstein, Iceland
	OPE	OPEC: Saudi Arabia, Ecuador, Venezuela, Nigeria, United Arab Emirates, Islamic Republic of Iran, Kuwait, Qatar, Rest of North Africa (Algeria, Libyan Arab Jamahiriya, Western Sahara), South Central Africa (Angola, Democratic Republic of the Congo)
	RUS	Russian Federation
	USA	United States of America + Canada
	BRA	Brazil
	JPN	Japan
	CHN	China
	IND	India
	AUS	Australia + New Zealand
	RWW	Rest of the World (remaining GTAP 8 regions)

Source: Center for Climate Policy Analysis.

Sectoral aggregation

In the standard PLACE model, we distinguish 20 sectors reflecting their relevance for climate and energy policy analysis. There are 5 primary energy goods (coal, gas, crude oil, biofuels and biomass) and 3 secondary energy carriers (electricity generation, heat (including gas distribution) and refined oil products). According to the GTAP classification, refined oil production does not just include different oil products but also coke and nuclear fuels (note that uranium mining is included in "other mining"). The GTAP database does not explicitly feature supplies of biofuels and biomass. We follow Taheripour et al. (2008a,b, 2011) in attributing biofuel and biomass supply across the 6 original GTAP sectors.

The decomposition of non-energy sectors aims to explicitly represent emission- and energy-intensive (non-energy) industries covered under the EU Emissions Trading System (EU ETS). We can distinguish 6 non-energy ETS sectors (chemical, non-metallic minerals, iron and steel, non-ferrous metals, pulp & paper, air transport). Table 2 summarizes the sectoral disaggregation in the standard PLACE model version.

Table 2. Sectoral disaggregation of the PLACE model

	Abbrev.	Sectors	ETS	EITE
ENERGY SECTORS				
1	COL	Coal (mining and agglomeration of hard coal, lignite and peat)	**X**	
2	CRU	Crude oil (extraction of crude petroleum, service activities excluding surveying)	**X**	
3	GAS	Primary gas production (extraction of natural gas, service activities excluding surveying)	**X**	
4	GDT	Gas manufacture and distribution (distribution of gaseous fuels through networks, production of town gas)	**X**	
5	OIL	Refined products (coke oven products, refined petroleum products, nuclear fuels)	**X**	**X**
6	ELE	Electricity and heating (production, collection and distribution)	**X**	
NON-ENERGY SECTORS				
7	FRS	Forestry (forestry, logging, and related services)		
8	BIO	Biofuels agriculture (paddy rice, wheat, other grains, oilseeds, sugar cane and beat, vegetable oils)		
9	AGR	Rest of agriculture and fishing (vegetables and fruit, plant fibers, other crops, cattle, other animal products, raw milk, wool, fishing)		
10	FOO	Food industry (beverages, tobacco, cattle meat, other meat, milk, processed rice, sugar, other food)		
11	CHM	Chemical industry (basic chemicals, rubber and plastics, other chemicals)	**X**	**X**
12	NMM	Non-metallic minerals (cement, lime, ceramic, glass, gypsum, plaster, gravel, concrete)	**X**	**X**
13	ISI	Iron and steel industry (basic production and casting)	**X**	**X**
14	NEM	Non-ferrous metals (production and casting of: copper, aluminum, zinc, lead, gold, silver)	**X**	**X**
15	PPP	Paper–pulp–print (including publishing, printing)	**X**	**X**
16	CON	Construction (of houses, factories, offices, and roads)		
17	OTH	Other manufacturing (textiles, clothing, leather, lumber, fabricated metal products, motor vehicles, other transport equipment, electronic equipment, other machinery, recycling, other mining: metal ores, uranium, precious stones)		
18	SRV	Services (water distribution, trade, hotels and restaurants, communications, financial intermediation, insurance, real estate, recreational, cultural, and sporting activities, public administration and defense, social security, health and social work, sewage and refuse disposal, sanitation, dwellings)		
19	ATR	Air transport	**X**	
20	TRN	Other transport (water and land transport, travel agencies)		

Source: Center for Climate Policy Analysis.

1.2.2 CO_2 emissions

The GTAP database covers only CO_2 emissions from burning fuels. We use the following data sources to include process emissions in the PLACE model:

- For the EU28 and EFTA, we draw on the European Environmental Agency (EEA), which provides information on process emissions for the following sectors: cement production, lime production, chemical industry, iron and steel production, ferroalloys production, aluminum production and production of other metals.

- For all other countries, we extract information on CO_2 process emissions from the Emission Database for Global Atmospheric Research (EDGAR).

Energy-related CO_2 emissions are proportional to the use of fossil fuels, with CO_2 coefficients (emission per unit of energy) differentiated by fuels. In contrast, process-related CO_2 emissions are assumed to be proportional to sector output.

1.2.3 Non-CO_2 emissions

GTAP comprises the following non-CO_2 GHGs: methane (CH_4), nitrous oxide (N_2O) and F-gases.

The following sources of non-CO_2 emissions are distinguished:

- input-related emissions by firms;
- consumption-related emissions by households;
- output-related emissions by firms;
- endowment-related emissions (from capital and land use) by firms.

Non-CO_2 emissions are assumed to be proportional to the respective input (consumption), output, or endowment.

Labor market

Unemployment rates for the EU28 and Norway are taken directly from Eurostat (2013a). For other countries, data are taken (if available) from the World Bank (2013) or (otherwise) from the IMF (2012b). Finally, the unemployment rates for individual countries were aggregated to GTAP regions, taking into account United Nations (2012) data on population in productive age, which allows the total number of unemployed to be calculated for all countries. Unemployment rates for GTAP regions are then calculated as the total of unemployed divided by the total of the labor force.

In addition, we include data on replacement rates. The replacement rate is defined as the ratio of the average unemployment benefit to the average wage in the economy that can be earned by an unemployed person. For EU and OECD countries, the replacement rate data (as of 2012) is taken from OECD (2015). Croatia and Cyprus are attributed the estimates for Slovenia and Greece respectively due to the lack of data. For Argentina, Brazil and China, we use the World Bank (2013), IMF (2012b) and United Nations (2014) databases, as well as national sources. For all other regions, either the replacement ratios of neighboring countries or zero values (meaning zero benefits in a given region) are attributed.

Allocation of emission permits in the EU ETS

To reflect the provisions of the EU ETS, we include the free allocation of emission permits to ETS sectors on the basis of their emissions in 2007 using data from European Environmental Agency (EEA 2013).

2. Technical description

2.1 Algebraic model structure

CGE models build on general equilibrium theory, which combines the behavioral assumptions for rational economic agents with analysis of equilibrium conditions. There are three classes of (inequality) conditions associated with a standard Arrow-Debreu general equilibrium describing a competitive market economy: (i) exhaustion of product (zero profit) conditions for producers, (ii) market clearance for all goods and factors, and (iii) income expenditure balances for all households. Zero profit conditions determine production activity levels, market clearance conditions determine price levels, and income expenditure balances identify income levels. In equilibrium, each variable is linked to one condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition, and an income level to the income expenditure constraint. The standard competitive setting can be complemented by price restrictions and quantity constraints to reflect market imperfections (e.g., monopoly power, labor market rigidities, or R&D spill-over effects).

The structure of production, consumption, government, etc., in each region is similar; only the parameters differ. As a result, country subscripts will be omitted in the following sections.

2.1.1 Producer

Producers are assumed to minimize the costs of production subject to technological constraints as characterized by their production function. Each producer represents one sector in given country and chooses the optimal amount of primary production factors, intermediate inputs and output. The company's decision-making process can be viewed in two stages. In the first of these, the firm chooses production inputs (primary production factors and intermediate consumption) so that the chosen value minimizes the total costs given that a particular amount of output is produced, subject to production function constraint ($Y_{i,r} = f(A_{i,j,r}, K_{i,r}, LH_{i,r}, LL_{i,r}, R_{i,r})$, where $A_{i,j,r}$ is the amount of intermediate input and $K_{i,r}, LH_{i,r}, LL_{i,r}, R_{i,r}$ are the amounts of primary production factors as described in Table 3).

Table 3. Primary production factors.

Symbol	Primary production factor
$\boldsymbol{K_{i,r}}$	Capital
$\boldsymbol{LH_{i,r}}$	Skilled labor
$\boldsymbol{LL_{i,r}}$	Unskilled labor
$\boldsymbol{R_{i,r}}$	Natural resources and land

The amount of output to be produced is established in the following stage, given the output price, which is exogenous from the firm's perspective. Consequently, the optimization problem for a firm in sector i and region r is as follows:

$$\max_{A_{i,j,r},K_{i,r},LH_{i,r},LL_{i,r},R_{i,r},Y_{i,r}} \Pi_{i,r} = Y_{i,r}p_{i,r} - C_{i,r}\left(Y_{i,r}, p^A_{j,r}, w_{f,r}\right)$$
$$\text{s.t.} \quad Y_{i,r} = f(A_{i,j,r}, K_{i,r}, LH_{i,r}, LL_{i,r}, R_{i,r})$$

Where $\Pi_{i,r}$ denotes the firm's profit, $p_{i,r}$ the exogenous price of a domestically produced good, and $C_{i,r}$ is the cost function, depending on the price of the intermediate good ($p^A_{j,r}$), the price of production factors ($w_{f,r}, f \in \{K, LH, LL, R\}$), and the amount of output that is produced ($Y_{i,r}$). The cost functions result from the first stage of the optimization process, where the amount of intermediate inputs and production factors to be deployed is set.

Box 2. Euler's theorem

Euler's theorem states that if a function is homogenous of order n, so $f(tx_1,\dots,tx_N) = t^n f(x_1,\dots,x_N)$, then $\sum_{i=1..N} \frac{\partial f}{\partial x_i} x_i = n f(x_1,\dots,x_N)$.

Constant returns to scale in the CGE modeling framework mean that the production function is homogenous of order one. As the necessary profit maximization condition implies that marginal productivity of production factors equal their price, we have $\frac{\partial f}{\partial x_i} = p_i$ for all production factors and intermediate inputs. Consequently, $\frac{\sum_{i=1..N} p_i x_i}{f(x_1,\dots,x_N)} = 1$, so the unit production costs are equal to 1.

Source: Center for Climate Policy Analysis.

A CES production function that exhibits constant returns to scale is used as standard in the CGE model. In line with Euler's theorem, this implies that unit costs of production equal the price of products. The result implies the "zero-profit" condition and the corresponding (complementary) variable is output. As per Shephard's lemma, demand for the intermediate inputs and production factors can be calculated as the derivative of the cost function with respect to input price. Consequently, we have:

$$A_{i,j,r} = \frac{\partial C_{i,r}}{\partial p^A_{j,r}} = Y_{i,r} \frac{\partial c_{i,r}}{\partial p^A_{j,r}}$$

for intermediate inputs, and:

$$F_{f,i,r} = \frac{\partial C_{i,r}}{\partial w_{f,r}} = Y_{i,r} \frac{\partial c_{i,r}}{\partial w_{f,r}}, f \in \{K, LH, LL, R\}$$

for production factors. These demand functions appear in market clearing conditions, where supply is either provided by households (factors) or production firms (intermediate inputs). Our model includes the three hierarchical (nested) CES production functions described below.

Production function for industrial and commercial sectors

Production functions in the model are built in a hierarchical manner. This means that the decision about production levels is taken sequentially at each "nest" of the production function. Process emissions are introduced at the top level, since they are proportional to the given sector's product.

$$EM\_PROC_{g,i,r} = \alpha_{g,i,r} Y_{i,r}, g \in \{CO_2, CH_4, N_2O, FGAS\}$$

$$\begin{bmatrix} process \\ emissions \end{bmatrix} = \begin{bmatrix} emission \\ coefficient \end{bmatrix} \cdot [output]$$

The decision about the employment of intermediate inputs, natural resources, and capital-labor and energy is made at the second level. At this stage, the substitution possibilities are defined by CES functions:

$$Y = f(M \ \ , A_R, Q_{klle}) = \left(\beta_A M_i^{\rho_{klem}} + \beta_R A_R^{\rho_{klem}} + \beta_{klle} Q_{klle}^{\rho_{klem}}\right)^{1/\rho_{klem}}$$

$$[output] = CES\left[materials, \begin{matrix} natural \\ resources \end{matrix}, \begin{matrix} production \\ factors \end{matrix}\right]$$

Where $M_{i,r}$ represents the intermediate input (or materials) bundle, A_R denotes natural resources and land used for production, and Q_{klle} is the amount of the capital-labor-energy bundle. The quantities of the production factors bundle and materials are decided at this stage.

Materials comprise intermediate goods that enter the bundle in a fixed quantity (Leontief production function). It is therefore impossible to substitute materials originated from one sector with materials taken from another sector. Technically, this can be denoted as:

$$M = g(A_j) = \min(A_j)$$

$$\begin{bmatrix} materials \\ composite \end{bmatrix} = Leontief \begin{bmatrix} materials \\ from\ sectors \end{bmatrix}$$

Moreover, the optimal mix between value-added composite Q_{klab} and energy bundle Q_{ener} is given by another CES process, which describes the trade-off possibilities between the energy bundle and capital- labor:

$$Q_{klle} = f(Q_{ener}, Q_{klab}) = \left(\beta_{ener} Q_{ener}{}^{\rho_{klle}} + \beta_{klab} Q_{klab}{}^{\rho_{klle}}\right)^{1/\rho_{kllle}}$$

$$\begin{bmatrix} quantity \\ of\ production \\ factors \end{bmatrix} = CES \begin{bmatrix} all \\ factor \\ inputs \end{bmatrix}$$

The elasticity of substitution between these inputs is equal to $\sigma_{klle} = 1/(1-\rho_{klle})$.

The decision about the optimal energy mix is made at the next stage. This decision is also sequential: first the decision as to whether the energy should be taken from electricity or fossil fuels is made. At this stage, the production process can also be described as a CES function with elasticity $\sigma_{ener} = 1/(1-\rho_{ener})$:

$$Q_{ener} = f(A_{ELE}, Q_{fuel}) = \left(\beta_{ELE} A_{ELE}{}^{\rho_{ener}} + \beta_{fuel} Q_{fuel}{}^{\rho_{ener}}\right)^{1/\rho_{ener}}$$

$$\begin{bmatrix} quantity \\ of\ aggregate \\ energy\ inputs \end{bmatrix} = CES \begin{bmatrix} electricity & fossil\ fuels \\ consumption' & consumption \end{bmatrix}$$

Fossil fuel consumption is a bundle of oil, gas and coal. In this case, the decision-making process has two stages: firstly, agents decide whether they will use coal or other fossil fuels. The decision is again described by a CES production function with elasticity $\sigma_{fuel} = 1/(1-\rho_{fuel})$:

$$Q_{fuel} = f(Q_{col}, Q_{nsol}) = \left(\beta_{col} Q_{col}{}^{\rho_{fuel}} + \beta_{nsol} Q_{nsol}{}^{\rho_{fuel}}\right)^{1/\rho_{fuel}}$$

$$\begin{bmatrix} fossil\ fuels \\ consumption \end{bmatrix} = CES \begin{bmatrix} coal & gas\ and\ oil \\ consumption' & consumption \end{bmatrix}$$

Secondly, the choice between oil and gas is modeled. This is also a CES function with elasticity $\sigma_{nsol} = 1/(1-\rho_{nsol})$:

$$Q_{nsol} = f(A_{oil}, Q_{gas}) = \left(\beta_{oil} A_{oil}{}^{\rho_{nsol}} + \beta_{gas} Q_{gas}{}^{\rho_{nsol}}\right)^{1/\rho_{nsol}}$$

$$\begin{bmatrix} gas\ and\ oil \\ consumption \end{bmatrix} = CES \begin{bmatrix} oil & gas \\ consumption' & consumption \end{bmatrix}$$

The ratio of gas consumption to gas distribution is fixed, meaning that a constant amount of gas distribution is needed for each unit of gas used in the production process. Consequently, we have:

$$Q_{gas} = g(A_{gas}, A_{gdt}) = \min(A_{gas}, A_{gdt})$$

$$\begin{bmatrix} gas\ and\ oil \\ consumption \end{bmatrix} = Leontief \begin{bmatrix} gas & gas \\ consumption, & distribution \end{bmatrix}$$

Energy- related emissions must be included to gain a full picture of energy-related inputs. These emissions enter the production function in fixed proportions, so they are calculated as a product of the emission coefficient and respective energy consumption:

$$EM_i = \alpha_i A_i, \qquad i \in \{COL, GAS, OIL\}$$

$$\begin{bmatrix} energy - related \\ emissions \end{bmatrix} = \begin{bmatrix} emission \\ coefficient \end{bmatrix} \cdot \begin{bmatrix} energy \\ consumption \end{bmatrix}$$

In parallel, the decision about the employment of labor and capital is taken. At this stage, the representative firm decides how much capital and labor should be employed. As before, a CES production function is used with elasticity between the capital and labor components equal to $\sigma_{klab} = 1/(1 - \rho_{klab})$:

$$Q_{klab} = f(K, Q_L) = \left(\beta_K K^{\rho_{klab}} + \beta_L Q_L^{\rho_{klab}}\right)^{1/\rho_{klab}}$$

$$\begin{bmatrix} capital - labor \\ bundle \end{bmatrix} = CES \begin{bmatrix} capital, & labor \\ & aggregate \end{bmatrix}$$

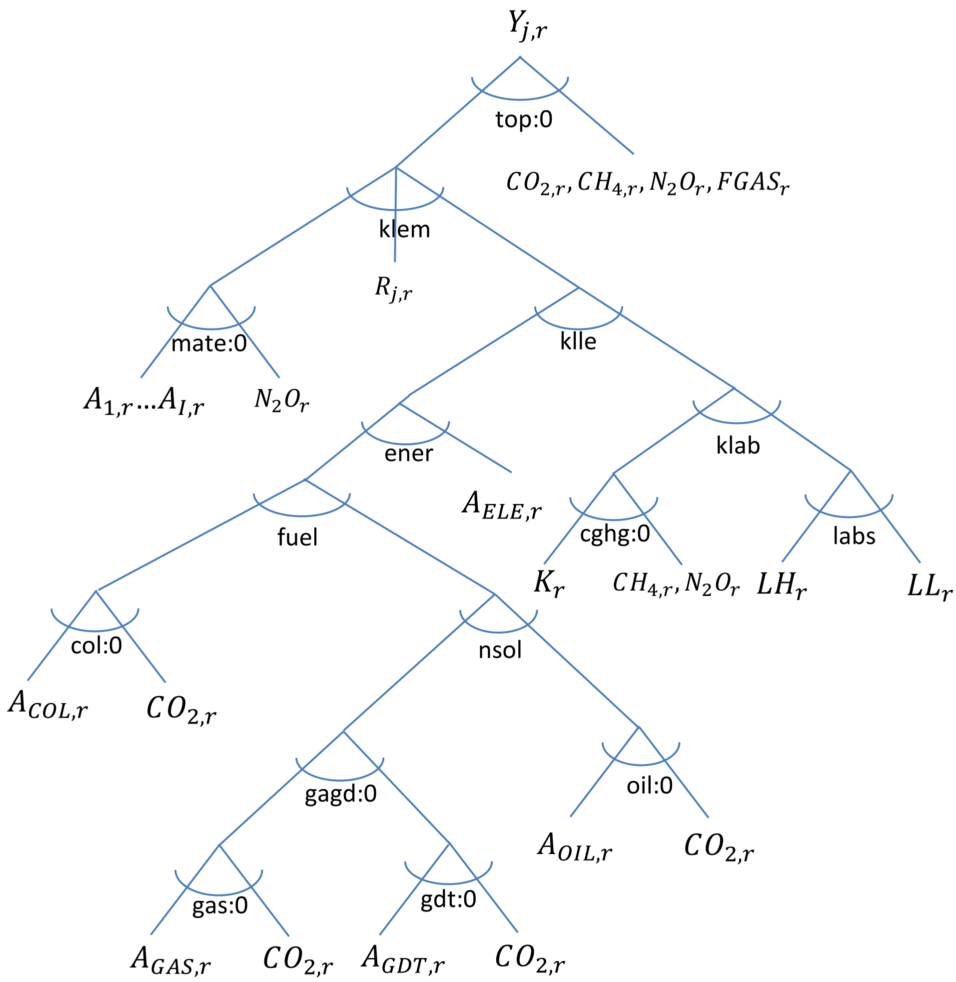
In this case, aggregate labor is a CES function of high-skilled and low-skilled employees. This reflects the possibility to substitute between low-skilled and high-skilled employers, as they can be educated, etc. The possibility to substitute between two types of employees is reflected by $\sigma_{labs} = 1/(1 - \rho_{labs})$:

$$Q_L = f(LH, LL) = \left(\beta_{LH} LH^{\rho_{labs}} + \beta_{LL} LL^{\rho_{labs}}\right)^{1/\rho_{labs}}$$

$$\begin{bmatrix} labor \\ aggregate \end{bmatrix} = CES \begin{bmatrix} low\ skilled & high\ skilled \\ labor, & labor \end{bmatrix}$$

In conclusion, the production structure for industrial and commercial sectors can be depicted schematically in Figure 2. The elasticities for each nest are described in chapter 2.2.1.

Figure 2. CES production technology for industrial and commercial sectors.

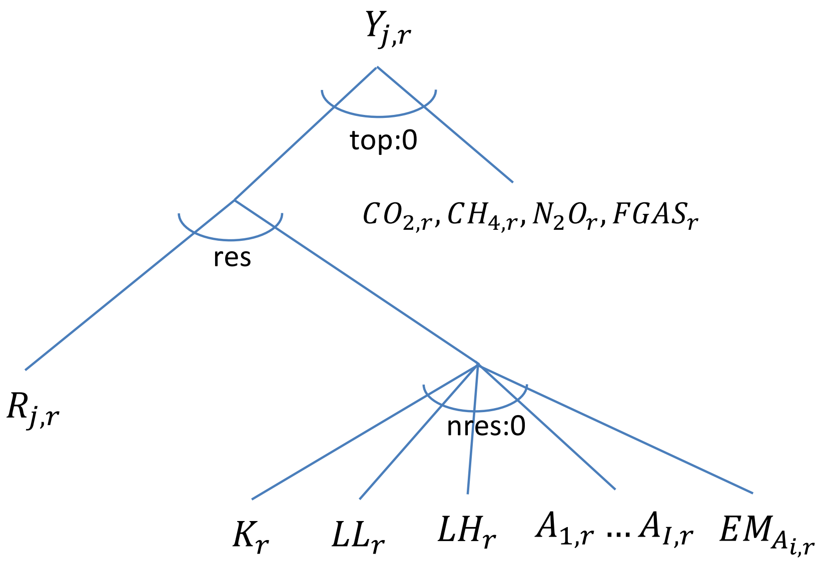


Source: Center for Climate Policy Analysis.

Production function for resource extraction sectors (CRU, GAS, COL)

We decided to formulate different production functions for natural resource extraction sectors to reflect the crucial role of natural resources in their output. The production structure for resource extraction sectors is simpler, since the only substitution possibility is between natural resources and other inputs. It is therefore impossible to substitute between capital and labor or between production inputs. Figure 5 shows the production structure for the natural resource extraction sectors: *CRU, GAS, COL*.

Figure 3. Nested Leontief and CES production technology for natural resource sectors related to energy (CRU, GAS and COL) using the GTAP database



Source: Center for Climate Policy Analysis.

Aside from process emissions that are introduced in a similar manner to other sectors, there is only one substitution possibility – between resources and other inputs (both intermediate inputs and production factors). This substitution possibility is reflected in the nest *res*. The sector's output is therefore equal to the CES composite of natural resources and production inputs, which exhibits an elasticity of substitution equal to $\sigma_{res} = 1/(1-\rho_{res})$:

$$Y = f(R, IN) = \left(\beta_R R^{\rho_{res}} + \beta_{IN} IN^{\rho_{res}}\right)^{1/\rho_{res}}$$

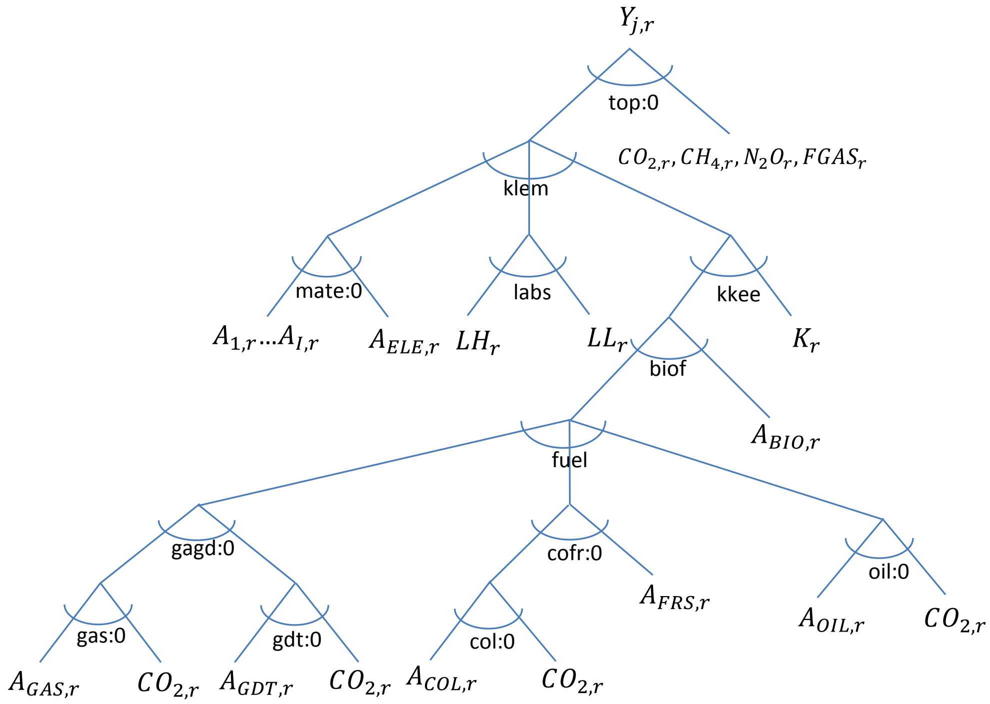
$$[output] = CES\begin{bmatrix} natural & production \\ resources' & inputs \end{bmatrix}$$

Production inputs – both factors (excluding natural resources) and intermediate goods – enter the production inputs bundle in fixed proportions. Assuming CES function for the *res* nest means that if the amount of natural resources is decreased there is a need to employ capital, labor, land and intermediate goods.

Production function for the electricity, transportation, gas distribution and refined fuels sectors

We decided to adopt a different production structure for the energy-intensive sectors to reflect the fact that the forestry and agriculture sectors provide biomass for combustion. The main difference is that it is possible to substitute between biofuels (sector BIO) and fossil fuels in the nest *biof*. In addition, it was assumed that the forestry sector's input to the production function can be substituted by coal – the substitution is implemented as a CES function in the nest *cofr*.

Figure 4. Graphical representation of Leontief and CES production functions



Source: Center for Climate Policy Analysis.

2.1.2 Consumer

Similarly as with the production process that is decided by firms, the consumer maximizes utility subject to budgetary constraints. The consumer's utility is derived from consumption and leisure, i.e., time that is not devoted to labor. There is a limited substitution possibility between leisure and consumption, which is reflected in the CES utility function. Consequently, the consumer optimization problem is:

$$\max_{LE,C} U = (\beta LE^{\rho} + (1-\beta)C^{\rho})^{1/\rho}$$

$$s.t.\ \ P_c C + P_L LE = P_K K + P_L(L + LE) + P_R R + P_c trf$$

$$max \begin{bmatrix} households \\ utility \end{bmatrix} = CES[consumption, leisure]$$

$$\text{s.t.} \begin{bmatrix} households \\ expenditure \end{bmatrix} = \begin{bmatrix} households \\ income \end{bmatrix}$$

Where LE denote leisure demand, C – consumption of goods, P_C – gross consumer price index, trf – public and foreign transfers. The solution to the above problem gives uncompensated demand functions for the consumption bundle and leisure.

Elasticity of substitution σ_L between consumption and leisure is calibrated in such a way that the labor supply response to a variation in real wages is consistent with an external estimate of wage elasticity of labor supply (for the empirical value used in PLACE see section 2.2.1). Assume that ε is the uncompensated elasticity of labor supply LS with respect to the net of tax wage, then the elasticity of substitution σ_L between consumption and leisure may be calculated using the following formula (compare Rutherford, 1998, p. 106):

$$\sigma_L = \left(\frac{\varepsilon}{\zeta - 1} - \theta + \frac{\overline{LS} + \overline{LE}}{\overline{P_C}\,\overline{C} + \overline{P_L}\,\overline{LE}} \right) \cdot \frac{1}{1-\theta}.$$

where the bar over a symbol denotes its benchmark equilibrium value, θ represents leisure value share in (leisure-augmented) consumption, and $\zeta \equiv \left(\overline{LS} + \overline{LE}\right) / \overline{LS}$; note that in PLACE unemployment is excluded from labor supply (see section 2.1.6).

The consumer's decisions about the consumption of particular goods can be viewed as a process that is similar to the choice of production inputs for firms. It can therefore be described by a combination of Leontief function and nested CES functions presented in Figure 6. The decision about consuming energy and non-energy products is made at the first (top) level. It is impossible to substitute between energy and non-energy goods in the adopted setting, so households always spend a fixed percentage on their consumption of energy products.

$$Q_{klem} = f(g(A_i), Q_{ener}) = \min(g(A_i), Q_{ener})$$

$$\begin{bmatrix} household \\ consumption \end{bmatrix} = Leontief \begin{bmatrix} energy & non-energy \\ goods\ , & goods \end{bmatrix}$$

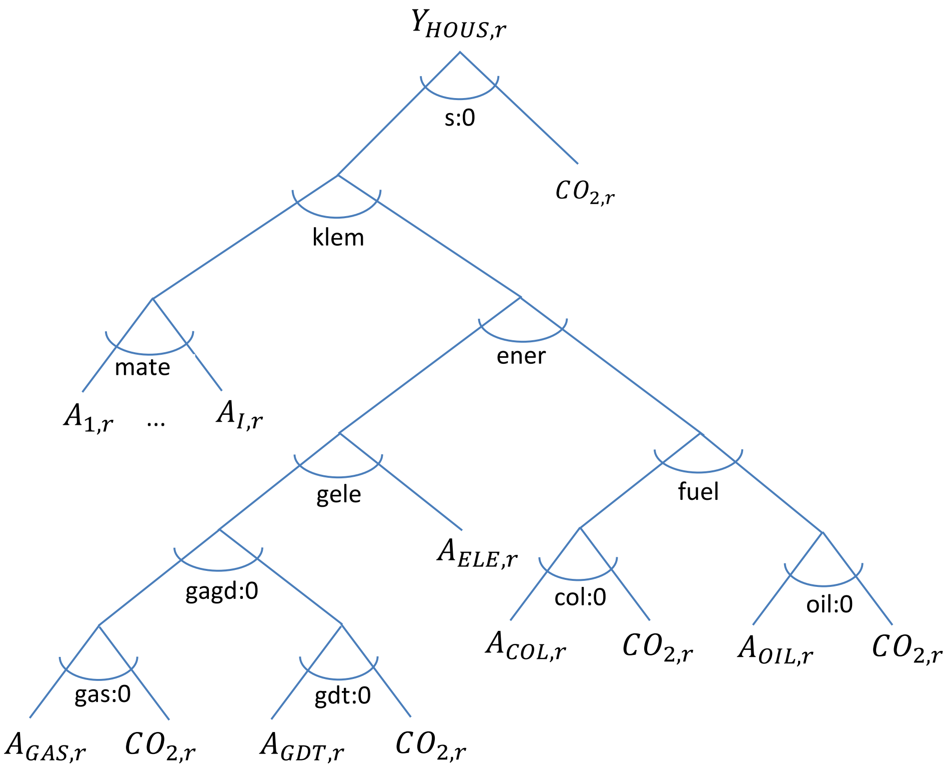
It is possible for different non-energy products to be substituted in the current version of the model. The elasticity is set to $\sigma = 1$, which means that the consumer good is a Cobb-Douglas bundle of different non-energy goods. Consequently, the choice between non-energy consumption is as follows:

$$g(A_i) = \prod_{i \in \{non-energy\ sectors\}} A_i^{\alpha_i}$$

$$\begin{bmatrix} aggregate \\ consuption\ of \\ non-energy \end{bmatrix} = Cobb-Douglas \begin{bmatrix} non-energy \\ sector\ goods \end{bmatrix}$$

The consumption structure for energy goods is somewhat more complicated. At the first stage, the consumer decides whether to use the gas-electricity bundle or other fossil fuels (namely coal and oil). In the next step, the consumer decides whether to consume electricity or gas and makes a choice between oil and coal. Similarly to the production function, consumption emissions are also linked to both the consumption of energy and aggregate consumption levels, and the consumption of gas (GAS sector) requires a constant amount of gas distribution. Figure 6 provides a schematic depiction of the consumption decision.

Figure 5. Nested Leontief and CES consumption structure for households using the GTAP database



Source: Center for Climate Policy Analysis.

2.1.3 Government

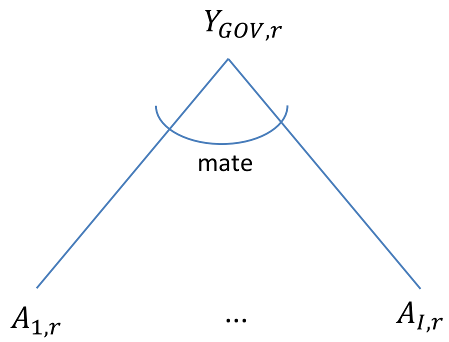
The government collects taxes, makes and receives transfer payments, and purchases goods and services. Government expenditures are interpreted as government consumption (including public consumption). This is described as the Leontief demand function (Figure 6):

$$Y_{GOV} = Q_{MATE} = g(A_i) = \min(A_1, \dots, A_I)$$

$$\begin{bmatrix} aggregate \\ public \\ consumption \end{bmatrix} = Leontief \begin{bmatrix} services \\ and \\ products \end{bmatrix}$$

The commodity structure of government consumption is therefore fixed in real terms.

Figure 6. Nested Leontief consumption structure for government using the GTAP database



Source: Center for Climate Policy Analysis.

Total government revenue in each region is a sum of revenues from taxes and emission permits. The model is able to simulate green tax reform. The equal yield constraint required by the green tax reform implies constant government consumption and revenue. The following taxes are incorporated in the model (sectors, as usual, are indexed with i):

- taxes on labor: $TL_i = \sum_L t_{L,i} P_L L_{L,i}$, where P_L denotes a net wage, $t_{L,i}$– the tax rate on labor (taxes for high-skilled and low-skilled workers are defined separately).
- taxes on capital: $TK_i = t_{K,i} P_K K_i$, where P_K denotes a net price on capital, $t_{K,i}$– the aggregate tax rate on capital.
- taxes on natural resources and land: $TR_i = t_R P_R R_{R,i}$, where P_R denotes a net price on $R_{R,i}$, t_R- tax rate on R_R.
- taxes on products: $TA_i = t_{IM,i} P_{IM,i} M_i + t_{D,i} P_{D,i} D_i$, where $P_{D,i}$ denotes the supplier price of the Armington composite's domestic component, $P_{IM,i}$ – the price of the Armington composite's imported component, $t_{IM,i}$ and $t_{D,i}$ – the tax rates on imported and domestic components, respectively.
- taxes on domestic production: $TY_i = t_{Y,i} P_{Y,i} Y_i$, where $P_{Y,i}$ denotes the producer price of domestic output Y_i, and $t_{Y,i}$- the tax rate on product Y_i .
- import tariffs: $TM_i = t_{M,i}(1 - t_{X,i}) P_{M,i} M_i$, where $P_{M,i}$denotes the producer price of imported products, and M_i, $t_{M,i}$ – the tax rate on imported products M_i.
- taxes on exported products: $TX_i = t_{X,i} P_{X,i} X_i$, where P_X denotes the producer price of exported products X_i, and $t_{X,i}$ – the tax rate on exported products X_i.

  taxes on pollution emissions: $TEM_i = \sum_{EM}(t_{EM} + P_{EM}) EM_i$, where P_{EM} denotes the price of emission permits for greenhouse gases, and EM-t_{EM} – the tax rate on pollution emissions. EM_i is measured in US dollars per ton.

All taxes are reported net of subsidies. Thus the government tax revenue across the whole economy in each region is a sum of net tax revenue collected from each agent:

$$I_{GOV} = \sum_i TL_i + TK_i + TR_i + TY_i + TA_i + TM_i + TX_i + TEM_i$$

$$\begin{bmatrix} government \\ revenue \end{bmatrix} = \begin{bmatrix} taxes\ on \\ primary \\ factors \end{bmatrix} + \begin{bmatrix} taxes \\ on \\ production \end{bmatrix} + \begin{bmatrix} taxes \\ on \\ products \end{bmatrix} + \begin{bmatrix} import \\ tariffs \end{bmatrix} + \begin{bmatrix} export \\ tax \end{bmatrix} + \begin{bmatrix} emission \\ tax\ and \\ permits \end{bmatrix}$$

where subscript *i* denotes the various sectors in the economy. Thus, only taxes are explicitly modeled on the revenue side in this framework. The government balance imposes equality between revenue and the sum of current expenditures:

$$I_{GOV} = Y_{GOV} + S_{GOV}$$

$$\begin{bmatrix} government \\ revenue \end{bmatrix} = \begin{bmatrix} government \\ consumption \end{bmatrix} + \begin{bmatrix} net\ transfers \\ to\ domestic \\ institutions \end{bmatrix}$$

where S_{GOV} denotes the actual transfers from the government *plus* government investments *plus* other government expenditure (e.g., interest on debt) *minus* other government revenue (e.g., property income) *minus* the government deficit. Public investments are covered by S_{GOV}.

Government consumption is fixed in absolute terms in the current setting of the model. Consequently, each increase in government revenue (over consumption expenditure) is "automatically" transferred to households and used for consumption purposes. The same is done with revenue from emission allowances.

As a default, government consumption is fixed in level (in real terms) in policy scenarios, while this assumption can be modified in the model. Since policy-induced deviations from the baseline solution analyzed in CAK reports are relatively small (see section 3.2), the assumption of fixed level of government consumption seems to be sensible; moreover, it makes calculation of welfare effects more transparent (one does not need to consider welfare effects related to changes in the public provision of goods). When recalibrating the model to external projections of the world economy, we assume that government consumption grows at the same rate as GDP. Government expenditures are by default equal to government income (from taxes and emission permits), so there is no government deficit in the model. Since transfers are adjusted accordingly, government accounts match.

2.1.4 Investment

The product composition of investment outlays (gross fixed capital formation) is assumed to be fixed, i.e., investment demand is represented by the Leontief function:

$$Y_{INV} = g(A_i) = \min(A_1, \dots, A_I)$$

$$\begin{bmatrix} aggregate \\ investment \end{bmatrix} = Leontief \begin{bmatrix} investment \\ goods \end{bmatrix}$$

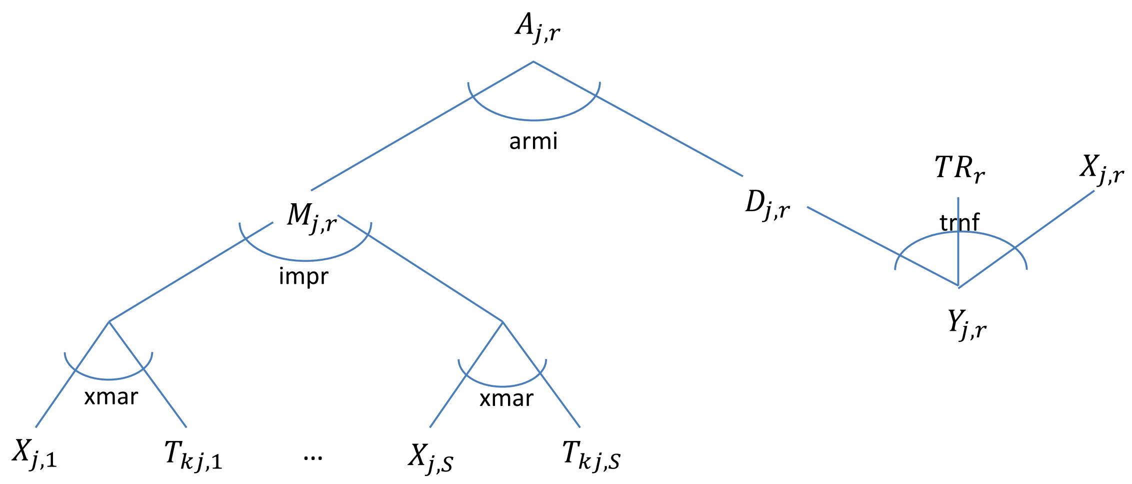
There is one representative investor in each region to represent all producers, households, and the government. In the static version of the PLACE model, aggregate investment is either exogenous or follows the movements in long-term capital stock, i.e., the percentage change in investment is equal to the percentage change in capital stock (which is consistent with the steady-state closure assumption). In both cases, domestic savings adjust to facilitate a given amount of investment..

Linking investment to the movements of capital stock is possible in PLACE, but it has not been used so far. Under this option, aggregate capital stock adjusts to keep the rate of return constant; aggregate investment change proportionally to capital stock, which is consistent with the steady state assumption.

2.1.5 International trade

The formulation of international trade in the model is based on the standard CGE assumption of product differentiation by origin. Intermediate goods and consumer goods are bundles of domestic and imported goods. The nesting structure of international trade is depicted in Figure 7.

Figure 7. Nested CES structure for trade using the GTAP database



Source: Center for Climate Policy Analysis.

An imported good that is linked to a domestic product ($M_{j,r}$) is modeled in two stages. Firstly, the goods that are imported to sector *j* from different countries are linked in fixed proportion to the international transport services attributed to these goods. In the other words, the cost of transporting good *j* from country *s* to country *r* is strictly proportional to the amount of good that is transported (and is route-specific). Consequently, the production function at this stage is as follows:

$$X_{j,s} = g(X_{j,s}, T_{r,j,s}) = \min(X_{j,s}, T_{r,j,s})$$

$$[imported\ good] = Leontief[physical\ product, transport\ costs]$$

At the next stage, goods from sector *j* originating from different countries are linked together to build the imported goods bundle using the CES function. The elasticity of substitution between goods imported from different countries varies across sectors (products) but not across regions. In addition, there are no complicated nesting structures that would reflect the fact that it is easier to substitute agricultural products from Ecuador with agricultural output from Mexico than with crops originating from Norway. However, such extensions could be introduced in subsequent versions of the model. Formally, the production function of an imported good for sector *j* in country r is as follows:

$$M_{j,r} = f(X_{j,1,r} \dots X_{j,S,r}) = (\sum_{s \epsilon \{1..S\}} \beta_{j,s,r} X_{j,s,r}^{\rho})^{1/\rho}$$

$$\begin{bmatrix} aggregate \\ imported \\ sector\ good \end{bmatrix} = CES \begin{bmatrix} goods\ imported \\ from \\ different\ countries \end{bmatrix}$$

At the highest stage, aggregate imported goods are linked to domestic production using the Armington aggregate. Armington aggregate is the name for an aggregate that uses a CES function. As with the other equations, a good that is consumed on the domestic market is thus created using CES function. Similarly to other goods that are produced using CES functions, we can describe the 'production' (or aggregation) process of a good used for the domestic production or consumption as follows:

$$A_{j,r} = f(M_{j,r}, D_{j,r},) = (\beta_{j,r} D_{j,r}^{\rho_{IM}} + (1-\beta_{j,r}) M_{j,r}^{\rho_{IM}})^{1/\rho_{IM}}$$
$$\begin{bmatrix} goods\ used \\ in\ domestic \\ production \end{bmatrix} = CES \begin{bmatrix} domestic & aggregate \\ sector & , \ imported \\ good & sector\ good \end{bmatrix}$$

In the current model version, each sector supplies a homogenous commodity, and the split of supply between domestic and foreign markets is only driven by relative domestic to foreign demand.

2.1.6 Labor market

A market clearing condition is a convenient starting point to describe the labor market:

$$TIME = L + UN + LE$$

$$\begin{bmatrix} exogenous \\ time \\ endownment \end{bmatrix} = \begin{bmatrix} endogenous \\ labor \\ demand \end{bmatrix} + \begin{bmatrix} endogenous \\ unemployment \end{bmatrix} + \begin{bmatrix} endogenous \\ leisure \end{bmatrix}$$

Changes in labor demand (*L = LH + LL*) arise in the model as a result of changes in the output of individual industries and changes in the price of labor relative to the prices of other production factors. Involuntary unemployment UN is determined as follows:

$$UN = UR \cdot TIME$$
$$\begin{bmatrix} unemployment \\ level \end{bmatrix} = \begin{bmatrix} unemployment \\ rate \end{bmatrix} \cdot \begin{bmatrix} time \\ endownment \end{bmatrix}$$

where UR is the unemployment rate, and $LS = TIME - UN - LE$ is the endogenous labor supply.

Since time endowment, specifically the leisure part, is not directly observable, we determine it based on the approach suggested by Ballard (2000), using external estimate of income elasticity of labor supply, η (for more details see Boeters and Savard, 2012). The calibrated parameter is the ratio of labor supply augmented by leisure time to labor supply alone: $\zeta \equiv \left(\overline{LS} + \overline{LE}\right) / \overline{LS}$ Boeters and Savard (2012) show that ζ can be approximated as:

$$\zeta \approx \frac{1}{1+\eta}.$$

The above formula is valid for small values of η, such as $\eta = -0.1$ adopted following Ballard (2000).

The labor market clearing condition is $LS = L$. We can determine the unemployment rate through the wage curve, which postulates that the real gross wages are negatively related to the unemployment rate[4]:

[4] The explanation of this fact is based on the efficiency wage concept - the lower the unemployment rate, the higher the wages that have to be offered by employers in order to prevent employees from seeking another job. Regions with higher unemployment have lower wages due to the increased competition for jobs.

$$\frac{P_L}{P_C} = f(UR)$$

$$\begin{bmatrix} real \\ wage \end{bmatrix} = \begin{bmatrix} function\,of \\ unemployment \end{bmatrix}$$

where $\frac{P_L}{P_C}$ denotes the real gross wage based on consumer price index P_C. The elasticity describes the marginal change in the level of real wages following a change in the unemployment rate. In order to implement the wage curve in a CGE model, scaling parameters for the benchmark equilibrium are required:

$$\frac{P_L / \overline{P}_L}{P_C / \overline{P}_C} = \frac{UR^{\sigma_U}}{\overline{UR}^{\sigma_U}}$$

$$\begin{bmatrix} relative \\ real \\ wage \end{bmatrix} = \begin{bmatrix} function\ of \\ relative \\ unemployment \end{bmatrix}$$

where benchmark variables are denoted with a "bar" symbol; the parameter $\sigma_U < 0$ reflects the elasticity of real wages with respect to the unemployment rate. This formula is applied for each labor type and each region.

The inclusion of the wage curve reflects to some extent the adjustment costs associated with the transformation of labor market because of climate policy measures. Also, introduction of "voluntary unemployment" was motivated by the need of endogenous adjustment of labor supply in model simulations.

The final element of the labor market clearing equation is leisure LE. This is introduced in order to facilitate endogenous labor supply (i.e., labor supply responding to changes in real wages and non-labor income).

2.1.7 Emissions

Energy use and emissions are of crucial importance in a model that aims to analyze climate policies. PLACE follows the standard CGE model specification of greenhouse gas emissions. Emissions are related in constant proportion to fuel combustion in sectors. In addition, process emissions are in fixed proportion to output. This setting implies that the only way to reduce emissions is either through reducing fuel use or reducing output. In other words, abatement options such as filters to reduce emissions without affecting either fuel consumption or output are not explicitly modeled (although they are implicitly captured through substitution of fuels for capital). On a technical level, the emission constraint is modeled as an endowment of government in emission allowances, both in the ETS and in the non-ETS sectors. Each agent that emits greenhouse gases requires pollution permits, creating demand for emissions. The carbon price is the result of market clearing.

2.1.8 Free allowances

By default, free allowances are modeled as an output-based subsidy. Free allowances are allocated to the energy intensive industries that are exposed to the risk of carbon leakage (European Commission, 2010). The modeling of free allocation as an implicit output subsidy is consistent with the assumption that competitive firms are granted free allowances in proportion to their actual output. This mechanism effectively decreases the purchase price and increases product output compared to the full auctioning situation. There is also the option for unconditional free allocation (grandfathering) or full auctioning to be modeled.

In our model, the firms receive an output subsidy that equalizes the cost of emission allowances, which, in turn, are proportional to the output. In other words, the user price that is paid by the consumer is equal to $P_{i,r}(1-\gamma_{i,r})$, where γ is set such that:

$$\gamma_{i,r} \cdot P_{i,r} \cdot Y_{i,r} = P_{ETS} \cdot eua_{i,r}$$

$$\begin{bmatrix} gamma \\ coefficient \end{bmatrix} \cdot \begin{bmatrix} price\ of \\ product \end{bmatrix} \cdot [output] = \begin{bmatrix} price\ of \\ ETS\ emission \\ allowance \end{bmatrix} \cdot \begin{bmatrix} emissions \\ that\ are\ to\ be \\ rebated \end{bmatrix}$$

Consequently, the total amount of the rebate received by a given sector is equal to the cost of emission allowances that are needed to produce a given output.

2.1.9 Closures in the model

Government closure

Public consumption is fixed in real terms in the current version of the model. Also, the tax rates are kept constant. In the current version, the government deficit is not modeled explicitly, hence the government revenues are equal to the government expenditures, which are constituted by the government consumption and transfers:

$$I_{GOV} = Y_{GOV} + S_{GOV}$$

$$\begin{bmatrix} government \\ revenue \end{bmatrix} = \begin{bmatrix} government \\ consumption \end{bmatrix} + \begin{bmatrix} net\ transfers \\ to\ domestic \\ agents \end{bmatrix}$$

Investment closure

Investment is modeled in the same manner as the government consumption – it is fixed in real terms. Therefore, savings rate needs to adjust endogenously as a result of policy changes. Such a setting was adopted to ensure proper estimates of welfare effects resulting from an introduction of policy measures. In the static framework, the economy does not benefit from increase of investment, as additional capital stock is used only in the next period. However, in the recalibration process, investment changes at a same rate as GDP. Hence, the investment closure is following:

$$P_{INV} \cdot Y_{INV} = S \cdot (P_K K + P_L(L+LE) + P_R R + P_c trf)$$

$$\begin{bmatrix} price\ of \\ investment \end{bmatrix} \cdot \begin{bmatrix} real \\ investment \end{bmatrix} = \begin{bmatrix} savings \\ rate \end{bmatrix} \cdot \begin{bmatrix} households \\ income \end{bmatrix}$$

$$s.t. Y_{INV} = \overline{Y_{INV}}$$

$$s.t. \begin{bmatrix} real \\ investment \end{bmatrix} = \begin{bmatrix} steady\ state\ value\ of \\ real\ investment \end{bmatrix}$$

2.2 Model recalibration and solving

Data for the base year are taken from the GTAP, and the recalibration procedure is mainly related to values for 2030. In this chapter, we elaborate more on the sources of elasticity parameters and the technical details of the recalibration and solving procedure, while the next chapter is devoted in its entirety to construction of the baseline. The choice of elasticities of substitution between different production inputs is made on the basis of literature and expert knowledge.

2.2.1 Elasticity parameters

The benchmark CGE model solution reflects the state of an economy in a base year under the assumption that the general equilibrium conditions are met. The CGE model parameters are calibrated, meaning that they result from a mathematical procedure to solve non-linear equations given the base year data. One example of calibrated parameter are shares (e.g., the share of capital earnings in total cost of production). However, some parameters (like elasticities) need to be taken from exogenous sources (i.e., they must be determined outside the model). Exogenous parameters typically take the form of elasticities: price elasticities, income elasticities, and elasticities of substitution. The simulation results of CGE models are highly dependent on the assumed elasticity values.

Elasticities of substitution

Despite their critical importance for simulation results, estimated elasticities of substitution are fairly seldom found in the papers published in the reviewed journals. There are very few papers presenting estimation results for the elasticities of substitution labor between the capital and energy composites (K-E nest), between the capital-energy and labor-materials composites (KE-LM nest), or other combinations (KL-EM nest, KEL-M nest, or KLE-M nest). Where the substitutability between capital and labor is concerned, there is a controversy in the literature as to whether these two inputs are substitutes or complements (see Apostolakis, 1990; Thompson and Taylor, 1995).

We adopt the elasticities of substitution values from Koesler and Schymura (2012) as our initial values. In the case of interfuel substitution, we adopt a uniform substitution elasticity value of 0.75 as it seems to be a reasonable assumption and empirical evidence is very scarce. Trade elasticities are taken from Neméth et al. (2011). Since Neméth et al. (2011) showed insignificant long-term Armington elasticity of substitution values for energy-intensive manufacturing in these sectors, we have adopted the estimated elasticities values for total manufacturing.

The assumed values for elasticity of substitution applied in our model are presented in Table 4. There are 26 types of nests in the CES structure (see Sections 2.1-2.4) for 20 sectors:

gas – nest of natural gas and related CO_2 emissions
cru – nest of crude oil and related CO_2 emissions
oil – nest of refined oil and related CO_2 emissions
col – nest of coal and related CO_2 emissions
gdt – nest of gas distribution and related CO_2 emissions
gagd – nest of natural gas and distribution of gas
crol – nest of crude oil and refined oil
cofr – nest of coal and forestry
oibi – nest of refined oil and biofuels
biof – nest of fuels and biofuels
nsol – nest of natural gas, crude oil, and refined oil-biofuels composite
fuel – nest of fuels
ener – nest of fuels and electricity
gele – nest of natural gas and electricity
labs – nest of skilled and unskilled labor
klab – nest of capital and labor
klle – nest of energy and capital-labor composite
kkee – nest of capital and fuels
klma – nest of materials and capital-labor composite

mate – nest of materials
klem – nest of material and energy and value-added
armi – nest of domestic and imported goods (Armington nest)
impr – nest of imported goods from different regions
n2o – nest of output-related N_2O emissions
ch4 – nest of output-related CH_4 emissions
fgs – nest of output-related F-gas emissions.

For the *gas, gdt, cru, oil, col* nests we assume a zero elasticity of substitution value since CO_2 emissions are proportional to the consumption of non-renewable fuels. The same rule applies to the *n2o, ch4, fgs* nests – sectoral output is assumed to be proportional to non-CO_2 emissions. For the *gagd* nest we also assume zero elasticity of substitution, thus treating distribution services as complementary to gas supply. In line with the assumption that materials used in the production process should be complementary, we assume zero elasticity values for the *mate* nest. We also assume zero elasticity values at the top-level *klem* nest. For the *fuel* nest in the ELE sector, we adopt a substitution elasticity value of 0.75. For *klma* nest in the industrial sectors we take the values from McKibbin and Wilcoxen (1999).

For the *klab*, *klle* and *kkee* nests we assume elasticities of substitution in line with Koesler and Schymura (2012), but where the estimated elasticity emerged as insignificant or was unavailable from this source, we replace it with the appropriate elasticity value from Baccianti (2013). Accordingly, we use Baccianti's elasticity values for the OIL sector (*klab* nest), the AGR, BIO, FRS, and GDT sectors (*klle* nest), and the ELE sector (*kkee* nest). The elasticity of substitution between skilled and unskilled labor (*labs* nest) is based on Behar (2010) and Leon-Ledesma (2012). The above nesting structure with assumed elasticity values for the *klle* and *labs* nests implies easier substitution between skilled and unskilled labor than between capital and skilled labor. This is in line with the weak empirical evidence for capital-skill complementarity (see e.g., Kovak, 2011).

For households, we assume that the level of elasticities of substitution between energy carriers is similar to the SRV sector. Expenditures on non-energy goods are characterized by fixed value shares, which corresponds to the unit elasticity of substitution.

Labor-related elasticities

We set the uncompensated wage elasticities of labor supply at 0.2, following Bargain et al (2012). In light of the available evidence, income elasticity of labor supply is set to –0.1 following Ballard (2000). Following the authors of the wage curve concept, Blanchflower and Oswald (1995, 2005), the elasticity of real wages with respect to the unemployment rate is –0.1. This is a robust finding across countries and time periods. We chose it as a default value.

Table 4. Values for elasticities of substitution in the PLACE model

Nests / Sectors	Gas	gdt	cru	Oil	col	Gag	Crol	Cofr	Oibi	Biof	nsol	Fuel	Ener	Gele	Labs	klab	klle	kkee	klma	mate	klem	armi	impr	n20	ch4	fgs
COL	0	0	0	0	0	0	-	0.75	-	-	-	-	0.75	-	2.0	1.3	-	-	1.7	0	0.3-2.9	1.1	2.2	0	0	0
CRU	0	0	0	0	0	0	-	0.75	-	-	-	-	0.75	-	2.0	1.3	-	-	0.5	0	0.9-1.8	0	2.2	0	0	0
GAS	0	0	0	0	0	0	-	0.75	-	-	-	-	0.75	-	2.0	1.3	-	-	0.5	0	0.7-1.7	1.1	2.2	0	0	0
GDT	0	0	0	0	0	0	-	0.75	0.75	-	0.75	0.75	0.75	-	2.0	0.3	0.3	-	-	0	0	0.9	4.4	0	0	0
OIL	0	0	0	0	0	0	-	0.75	0.75	-	0.75	0.75	0.75	-	2.0	0.8	0.5	-	-	0	0	0.9	4.4	0	0	0
ELE	0	0	0	0	0	0	0.75	0.75	-	0.75	-	0.75	-	-	2.0	-	-	0.4	-	0	0	1.9	2.1	0	0	0
FRS	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.4	0.3	-	-	0	0.02-0.1	3.6	4.2	0	0	0
BIO	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.4	0.3	-	-	0	0.01-0.2	3.6	4.2	0	0	0
AGR	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.4	0.3	-	-	0	0.01-0.3	3.6	4.2	0	0	0
FOO	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	0.9	2.4	0	0	0
CHM	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	2.3	4.4	0	0	0
NMM	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	2.3	4.4	0	0	0
ISI	0	0	0	0	0	0	-	-		-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	2.3	4.4	0	0	0
NEM	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	2.3	4.4	0	0	0
PPP	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	2.3	4.4	0	0	0
CON	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0	0.9	2.4	0	0	0
OTH	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.8	-	-	0	0-0.2	0.9	2.4	0	0	0
SRV	0	0	0	0	0	0	-	-	-	-	0.75	0.75	0.75	-	2.0	0.5	0.7	-	-	0	0	0.9	2.4	0	0	0
ATR	0	0	0	0	0	0	-	0.75	0.75	-	0.75	0.75	0.75	-	2.0	0.6	0.7	-	-	0	0	2.3	4.4	0	0	0
TRN	0	0	0	0	0	0	-	0.75	0.75	-	0.75	0.75	0.75	-	2.0	0.6	0.7	-	-	0	0	0.9	2.4	0	0	0
HOUS	-	-	-	-	-	0	-	-	-	-	-	0.75	0.75	0.75	-	-	-	-	-	1	0	-	-	0	0	0
GOV	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	0	-	-	0	0	0

technical restrictions, assumed values, McKibbin, Wilcoxen (1999), Koesler, Schymura (2012), Baccianti (2013), Behar (2010); Leon-Ledesma (2012), Neméth et al. (2011)

Source: Center for Climate Policy Analysis.

2.2.2 Recalibration procedure

While we know the initial values of share parameters (see chapter 1) and the values of elasticities of substitution, we also know the initial values of model variables. Each flow that is represented in the underlying social accounting matrix (in our case the GTAP database) can be modeled by model variables, making it fairly straightforward to assign the initial values to model variables. This is performed implicitly by MPSGE software.

The recalibration procedure, which is performed iteratively, aims to adjust the model variables to their expected future values (the procedure to obtain these values is described in section 3.1). In the current version of the model, the several variables are adjusted to match the expected future paths. These are:

- Economic growth (GDP by country);
- Global fuel prices used in energy production;
- Energy demand.
- EU ETS allowance price (optional)

The recalibration reflecting GDP's expansion is needed as it would be naïve to assume that each region will grow in the same rate up to 2030. The same is true for fuel prices as IEA projects rising prices of oil, gas and coal in the next 20 years. Also, the recalibrated model follows an exogenous path of energy demand instead of the exogenously rescaled energy efficiency improvement. The procedure applied keeps the energy demand as close as possible to the EC projections made in the energy model PRIMES. This step is needed to assure the comparability of model projections to the impact assessments prepared by the European Commission. Also, as PRIMES model is an engineering model based on the bottom up assumptions about different technologies, it is believed to approximate the future changes in energy efficiency in a robust manner.

The recalibration procedure comprises two steps.

Firstly, the model is forward-projected to GDP growth rates and international fuel prices. For this, we scale all endowments with the GDP growth rate (index). At the same time, we take the fossil fuel supply functions (which are Leontief at this point) and scale the resource-specific factor to be in line with the projected fossil fuel prices. In other words, there is some endowment in natural resources that can be rescaled to match the expected future fossil fuel prices and which can somehow be interpreted as natural resources that are present in the ground and are used to produce energy. In the current version of the model, the growth rates are uniform across sectors and follow changes in GDP. In such a manner, adopting additional assumptions about growth rates for about 20 sectors in each region was avoided. However, there are plans to differentiate them to some extent in the future version of the PLACE model.

The second step involves an iterative targeting of energy demands in the (production) cost and (consumption) expenditure functions. As a result, we change the reference quantities and reference prices (i.e., we change technologies and preferences) to reach the projected energy demands. The rationale behind these changes is that we can expect developments in production technology that will improve efficiency. The key method used to minimize rebound effects[5] is to readjust where cost

[5] Rebound effect is the extent to which the estimated energy savings enabled by the enhancement in energy efficiency are reduced by the behavioral response (i.e. higher consumption) to the increase in efficiency – see Gavankar and Geyer (2010).

changes for energy inputs are compensated through cost adjustments for other inputs. This is done at each step along the isocost line. In other words, in addition to the decrease in energy demand, the demand for other inputs is also lower, meaning that there is no substitution between energy and other inputs. In our GTAP-WEO projection, we employ growth indices for energy demands by fuel, demand sector, and region (see chapter 3). This implies that we miss the eventual phasing-in of "new" energy demands that do not have a basis in the base-year (where the input output fields are equal to zero). This procedure is described in detail in Böhringer et al. (2009). See also Appendix A for the procedure used to calibrate demand with a fixed factor.

3. Implementation of the baseline and policy scenarios

3.1 Baseline scenario

In order to be used as the starting point in the simulation of public policy, the business-as-usual (BAU) scenario should refer to most probable state of affairs in the future. The BAU scenario is used as a reference against which alternative scenarios are compared. In the PLACE model, we use the following data to prepare the baseline scenario:

- GDP projections,
- unemployment rate projections,
- primary energy demand/energy-related CO_2 emission projections,
- process-related CO_2 emissions and non-CO_2 emission projections,
- fossil fuel price projections.

We use forecasts issued by several institutions, mainly due to data gaps, inconsistency, and quality. These are:

- the International Energy Agency for energy projection,
- the OECD and IMF for GDP projection,
- the European Commission for GDP and energy projection.

However, different data sources were used to calibrate model to the projected future state. Forecasts from *World Energy Outlook 2012* and *PRIMES 2013 Reference* scenario were adopted for this purpose, as they provided the best compromise between consistency and precision. The data sources for projections are summarized in Table 5.

Table 5. Data sources for the forecast to calibrate the model to 2030.

Regions	*GDP*	*Energy demand*	*Fuel prices*
Non-EU	WEO 2012	WEO 2012	WEO 2012
EU	PRIMES 2013	PRIMES 2013	WEO 2012
Poland	PRIMES 2013	PRIMES 2013	WEO 2012

Source: Center for Climate Policy Analysis.

3.1.1 GDP projections

The OECD provides a complete forecast for all model regions. However, the European Commission uses its own forecasts to design European policy. To ensure consistency with European Commission analysis, we decided to use multiple data sources (different for EU and non-EU countries) to model GDP growth rates in the BAU scenario. For the EU28 countries, we use real GDP growth rates calculated on the basis of the GDP levels (at constant 2010 EUR exchange rate) used in the PRIMES model (NTUA 2013). Additional GDP data for 2007-2010 were taken from Eurostat (2013b) for the purposes of calculating GDP growth rates relative to 2007.

For the non-EU countries, we intended to use projections as close as possible to the WEO 2012 to be consistent with the energy scenarios. However, economic development is not simulated by the World Energy Model. Instead, it uses projections by the OECD (2012a), IMF (2012a), and other forecasting institutions, as well as IEA's assessment of growth in labor supply and productivity (IEA 2012a, p. 36). Unfortunately, no data for GDP projections consistent with WEO 2012 are publically available. We therefore use publically available long-term OECD projections up to 2060 (OECD 2012b):

- For non-EU countries that appear individually in the model, we use real GDP growth rates calculated on the basis of levels in constant 2005 PPPs that are available from the OECD (2012b).
- For the USA region, we calculated GDP growth using OECD data (OECD 2012b) for the United States and Canada.
- For the AUS region, we calculated GDP growth using OECD data (OECD 2012b) for Australia and New Zealand.
- For the EFTA region, we calculated GDP growth using OECD data (OECD 2012b) for Norway and Iceland.
- For the OPEC region, GDP growth was calculated using total non-OECD data excluding Brazil, China, India, Indonesia, Russia, and South Africa due to the lack of data for the remaining countries.

GDP growth for the Rest of the World region was calculated using aggregated data for Mexico, South Africa, Chile, Korea, and Israel due to the lack of data for the remaining countries.

Since we computed GDP in 2030 by multiplying the indices taken from the OECD by the base year GDP, it is of crucial importance to select the correct benchmark that would resemble GTAP data as close as possible. GDP in 2007, measured in constant 2005 USD, is taken from Eurostat (2013b) for EU countries, and from the OECD (2013b) for other countries that appear individually in our model and for the EFTA region (except for Liechtenstein). For the remaining regions, the benchmark GDP in the PLACE model was calculated based on the IMF (2012b) database using data for countries that constitute a region.

3.1.2 Unemployment rate projections

Unemployment rate projections for the EU (excluding Croatia) are available from the European Commission (2011) up to 2060 and are published in the *Ageing Report*. The projections for Croatia were calculated based on projected unemployment rate changes for the entire New Member States group (EU12). For all other countries, projections up to 2017 were prepared in a similar way (based on IMF (2012b) data) as the World Bank only provides historical data. Projections beyond 2017 were constructed on the basis of unemployment rate changes for the entire EU27, as given in the Ageing Report. Finally, the unemployment rates for individual countries were aggregated to GTAP regions, taking into account historical data and United Nations (2012) projections of population in productive age, which enabled us to calculate the total number of unemployed for all countries. Unemployment rates for the GTAP regions were then calculated as the (total) number of unemployed divided by the (total) labor force.

3.1.3 Energy demand and energy-related CO_2 emission projections

The energy demand projections are differentiated regionally. The energy demand path for non-EU regions is based on the WEO 2012 *Current Policies* scenario (IEA 2012a). The assumptions concerning policy implementation for this scenario are similar to the PRIMES *2013 Reference* scenario, i.e., they are only based on the policies formally enacted or adopted up to mid-2012. Historical energy balances for 2007 are taken from previous WEO release (IEA 2009) and Energy Balances (EB) (IEA 2010a,b). Due to the different dimension (fuels, sectors, regions) between energy balances in WEO and in our model (which is based on input-output tables), we performed the following procedure to map datasets:

1. Mapping fuels and sectors from PRIMES into GTAP/PLACE format;
2. Mapping regions from IEA EB into GTAP format;
3. Mapping regions from IEA WEO into GTAP format;
4. Mapping regions from GTAP into PLACE model format;

5. Mapping fuels and sectors from IEA WEO into PLACE model format.

The first two steps only take into account historical data (i.e., 2007), while the other steps consider both historical and projected data. Details of the mapping are presented in Appendix C. CO_2 emission projections were based on future energy use, which is derived from the fixed emission intensity coefficient from GTAP 2007.

For the EU28 countries, energy demand projections were derived from the PRIMES Reference scenario 2013 (European Commission 2013b). The following procedure was performed:

1. Energy demand was generated based on 2007 data and growth rates from the PRIMES database. At this stage, it was essential to map production sectors and emission sources between PRIMES and GTAP in detail;
2. CO_2 emissions for future periods were generated based on energy demand projections and emission intensity coefficients as of GTAP 2007.
3. CO_2 emissions were scaled to match PRIMES data;
4. Energy demand was scaled so as to maintain the emission intensity coefficient as of GTAP 2007.

The emission intensity of energy coefficients was maintained as they appear in GTAP data from 2007 due to the fact that energy-related CO_2 emissions (which are a by-product of fuel combustion) are set in a fixed proportion to energy use. The scaling procedure aimed at matching emission levels from PRIMES was essential to credibly reflect the reduction targets proposed by the European Commission. Although the energy consumption was adjusted, the values remained at the GTAP levels since changing them would unbalance the input-output matrix provided by GTAP and create inconsistency between the intermediate inputs that were used to calibrate the model.

3.1.4 Process-related CO_2 emission projections

The baseline process emissions path for the EU28 countries was constructed based on projections of non-energy related CO_2 emissions from the PRIMES database (European Commission 2013b). A country-specific, uniform growth rate for this category was applied to process emissions in all model sectors. For the EFTA region, projections were based on applying the GDP process emission intensity growth rate across the entire EU28. Projections for other non-EU regions were prepared in a similar way. In the case of EU countries, emissions were additionally scaled in order to match levels from PRIMES. This was essential to credibly reflect the emissions reduction targets proposed by the European Commission.

3.1.5 Non-CO_2 emission projections

Projections of non-CO_2 emissions were obtained by calculating non-CO_2 emission growth rates from the GAINS database (European Commission 2013b) for EU regions and from the U.S. Environmental Protection Agency (EPA 2014) for non-EU regions. These growth rates were subsequently applied to 2007 data. In this step, it was necessary to map production sectors and emission sources between GAINS/EPA and GTAP in detail. In the case of EU countries, emissions were additionally scaled in order to match levels from GAINS. This was essential to credibly reflect the European Commission's proposed emission reduction targets.

3.1.6 Fuel price projections

We apply global market prices for primary fuels in the PLACE model. This means that the same price is used for all regions**.** We took fuel prices from the IEA (2012) using the *Current Policies Scenario* to rely on international energy institution and to maintain conformity with the energy demand projection for non-EU countries. The paths for each form of energy, presented in Table 6, reflect IEA judgment of the prices that would be needed to encourage sufficient investment in supply to meet projected WEO demand. Data for 2040 and 2050 have been extrapolated based on the trends provided by the IEA (2012). For the sake of comparison, we also present analogous fuel prices from the PRIMES *2013 Reference Scenario*.

Table 6. Fuel price index in real terms (2007=100)[6]

	IEA WEO *2012 Current Policies Scenario*			
	2020	*2030*	*2040*	*2050*
Crude oil	172	189	199*	209*
Natural gas	161	177	184*	191*
Coal	147	156	162*	168*
	PRIMES *2013 Reference Scenario*			
	2020	*2030*	*2040*	*2050*
Crude oil	150	158	174	187
Natural gas	168	176	176	172
Coal	165	175	197	228

Source: Center for Climate Policy Analysis *based on European Commission (2012), IEA (2009) and IEA (2012). According to personal communications with DG Energy at the European Commission, PRIMES use data from IEA statistics and the Energy Market Observatory System & Modeling framework*.
*Own extrapolations.

The average OECD steam coal import price was used by the IEA as a general proxy for international coal prices. The crude oil price reflects the average crude oil import price trends, where the mounting cost of producing oil from new sources (as existed fields are depleting) are considered by the IEA in order to satisfy the increasing demand. For natural gas, the IEA provides a price projection for the three main regional markets (U.S.A., Europe, and Japan), because there are considerable differences in pricing mechanisms for gas, limited arbitrage options, cost of transport, and local gas market conditions. The IEA assumes that gas prices in North America will remain the lowest due to abundant supplies of relatively low-cost unconventional gas. In Europe, there is a growing reliance on gas imports from more distant sources. There is an increased reliance on local supplies of unconventional gas and spot purchases of liquefied natural gas in Asia. Globally, the IEA assumes that natural gas prices broadly follow oil price trends, but this assumption do not apply to the U.S.A.

3.2 Policy scenarios and exemplary analysis using the PLACE model

Three reports were prepared using the model in the period to April 2015. The first report (CAK, 2014a) analyzed and described the impact of the European Commission's proposed regulations, regarding mainly emission reduction, on Poland's economy and other EU regions. In the second report (CAK 2014b) we analyzed the impact of the green tax reform on economic development. In the third report, we explored the influence of different burden-sharing rules (CAK, 2015).

[6] Price indices are expressed in real terms, i.e., price levels were expressed in terms of prices in one common year (base year) – in this case, 2010.

3.2.1 Impact of the proposed 2030 climate and energy policy framework on Poland and other EU regions (CAK, 2014a)

The first report prepared using the PLACE CGE model was aimed at assessing the impact of the 2030 climate and energy policy framework on Poland and other EU regions. Using the model, we found that comparatively higher costs are in store for the EU's more dynamically growing economies and countries where the share of power- and energy-intensive sectors (EITE) is relatively high (especially if their energy mix relies on high-carbon fuels). Poland and most of the New Member States (EU13, NMS) meet both criteria. In addition, the losses for the energy-intensive sectors in Poland are more dramatic than in other EU countries.

Under the Central scenario, the EU as a whole loses 0.45% in terms of welfare (0.4% in terms of GDP), while Poland is at the extreme with a 1.5% welfare loss and 1.0% GDP loss. If compared to the other baseline scenarios with possibly more realistic (higher) economic growth assumptions for the NMS, the welfare loss for the EU as a whole would amount to nearly 0.8% (0.6% in terms of GDP) and for Poland 2.6% (1.7% in terms of GDP). In addition, the losses for energy-intensive sectors in Poland are more dramatic than in other EU country groupings of results for 2030.

Furthermore, the pattern of real household consumption is mostly comparable with GDP, although consumption suffers more. Along with GDP, the results for real household consumption are reported as more appropriate measures of the welfare impacts of climate policies. Consumption is affected by climate policies both directly (increased share of disposable income spent on energy) and indirectly (higher cost of energy intensive products, lower income due to decreased economic activity). The details and findings can be found in CAK (2014a).

3.2.2 Green tax reform (CAK, 2014b)

In this report, the analysis comprises four alternative simulation scenarios. All scenarios assume the same policy shock, i.e., fuel-, sector-, and region-specific changes in effective 'pre-reform' excise tax rates as of 2012 to the 'post-reform' levels, in line with the analyzed reform. The scenarios are differentiated in two dimensions (as presented in Table 1): baseline (business as usual – BAU) choice and tax revenue recycling option.

Table 7. Policy scenarios modeled in CAK, 2014b

	Tax revenue recycling options	
Baseline (BAU)	Lump-sum transfer to households	Reduction in labor taxes
2007 (backward-looking)	**Tax_LUMP_2007**	**Tax_LABR_2007**
2030, REF2013 (forward-looking)	**Tax_LUMP_2030**	**Tax_LABR_2030**

Source: CAK (2014b).

Given the time schedule for the implementation of excise reform, the forward-looking (2030) baseline is the natural default. However, this baseline implies considerable decarbonisation until 2030 (32.4% GHG emissions reduction compared to 1990), based on the implementation of the currently adopted climate and energy policies. However, due to the fall in the energy demand, the role of fuel taxes diminishes in time along this baseline, and the effects of tax reform are likely to be less pronounced in 2030 than perceived today. To highlight this issue, as well as to address the problem of various uncertainties inherent in the REF2013 baseline, we contrast the results for 2030 with the hypothetical effects of imposing excise on the economies' structures as represented in 2007 (the backward-looking baseline).

Two means of using the extra tax revenues were considered. Under the LUMP option, any additional tax revenues generated as a result of the reform (going beyond the tax revenues the government needs to finance the provision of public goods) are transferred as a lump sum to households. Under the LABR option, the increase in tax revenues is offset by a reduction in labor taxation, in line with the “double-dividend” hypothesis and the “environmental tax reform”. Both recycling variants assume fixed budget balance and fixed real government consumption. A detailed description of both the construction and results of the scenarios can be found in CAK (2014b).

3.2.3 Burden sharing (CAK, 2015)

In the third report based on the model PLACE, we analyzed the impact of different burden-sharing rules on the economies of European countries. We took into consideration several burden-sharing options based on Böhringer et al. (2014). The ex-ante allocation rules define “fairness” in emission permit allocation from the perspective of economic, social, or environmental conditions that exist in different regions prior to implementation of the considered emission mitigation policy.

The sovereignty (*PastEmissions* scenario) criterion takes into account the current or past flow of emissions as a basis for the allocation of emission permits. Implementing the sovereignty rule implies equal relative cuts in emissions by all regions, such that:

$$E_r = (1-t) \cdot E_r^0,$$

$$\begin{bmatrix} permit \\ allocation \\ in\ region\ r \end{bmatrix} = \begin{bmatrix} 1 - reduction\ target, \\ fraction\ of\ target \\ emissions \end{bmatrix} \cdot \begin{bmatrix} benchmark \\ emissions \\ in\ region\ r \end{bmatrix}$$

The total number of allowances allocated to a country is given by its past emissions diminished by a fraction (target) t.

The egalitarian (Population scenario) criterion assumes that all individuals have equal rights to pollute the atmosphere. Hence, emission permits are allocated on an equal per capita basis. In the egalitarian criterion, the total quantity of permits is multiplied by weights (i.e., share of the overall EU population) to result in total emission permits allocated to a given country. An egalitarian rule could be represented by the following functional form:

$$E_r = (1-t) \cdot \frac{P_r}{\sum_r P_r} \cdot \sum_r E_r^0,$$

$$\begin{bmatrix} permit \\ allocation \\ in\ region\ r \end{bmatrix} = \begin{bmatrix} 1 - reduction\ target, \\ fraction\ of\ target \\ emissions \end{bmatrix} \cdot \begin{bmatrix} weight\ based\ on \\ population \\ in\ benchmark\ year \end{bmatrix} \cdot \begin{bmatrix} total\ emissions \\ in\ benchmark \\ year \end{bmatrix}$$

where in addition, P_r denotes the population in region *r*.

Income inequalities across the EU Member States imply that different countries have different abilities to pay for emission reductions (ability to pay). Under this criterion, more emissions permits are allocated proportionally to regions with a lower GDP *per capita.* This burden-sharing rule is represented by the following functional form:

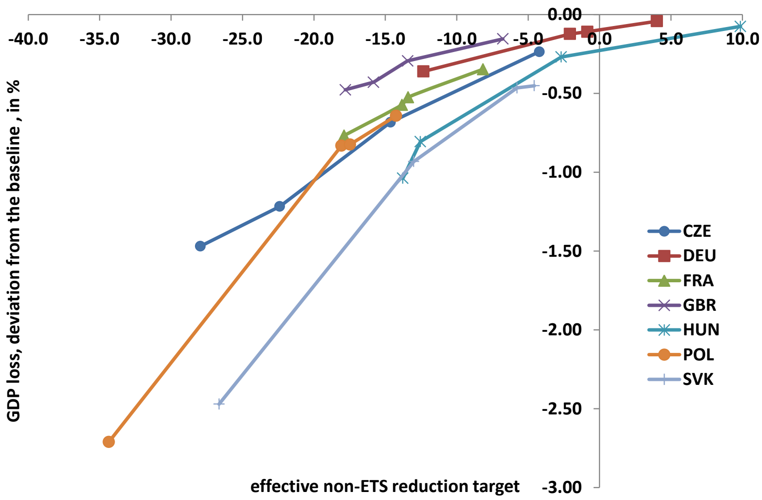
$$E_r = E_r^0 - t \cdot \frac{Y_r^0 E_r^0}{\sum_r Y_r^0 E_r^0} \cdot \sum_r E_r^0$$

$$\begin{bmatrix} permit \\ allocation \\ in\ region\ r \end{bmatrix} = \begin{bmatrix} past\ (benchmark) \\ emissions \\ in\ region\ r \end{bmatrix} - \begin{bmatrix} reduction \\ target \end{bmatrix} \cdot \begin{bmatrix} weight \\ based\ on\ GDP \\ per\ capita \\ in\ benchmark\ year \end{bmatrix} \cdot \begin{bmatrix} total\ emissions \\ in\ benchmark \\ year \end{bmatrix}$$

where Y_r^0 denotes GDP *per capita* in the base year.

Using the model PLACE, we reached the unsurprising conclusion that the higher the effective abatement targets, the bigger the consumption or GDP loss for the respective country. Figure 7 illustrates how the GDP loss depends on the stringency of the effective abatement target in the non-ETS sectors. The line for Poland is steeper than for the other countries, which means that Poland's GDP is relatively more sensitive to GHG abatement in non-ETS sectors, indicating more limited potential for cheap abatement in the non-ETS segments of the economy (mainly transport and agriculture).

Figure 7. GDP loss vs. effective emission change in non-ETS in ex-ante scenarios



Source: CAK (2015).

Moreover, The variation of GDP or consumption losses resulting from the introduction of different burden-sharing rules follows the variation in non-ETS targets and allocation of EU ETS allowances. Compared to the Central+ scenario, consumption and GDP losses in Poland are higher in the PastEmissions and Population scenarios, while they are lower for the InverseGDP criterion (Table 8-Table 9).

Table 8. Impact of different ex-ante scenarios on consumption, deviation from the baseline in percent

	Central+	Inverse GDP	Past Emissions	Population
HRV	-3,43	0,16	-5,77	0,68
POL	-2,38	-1,83	-5,72	-3,50
FIN	-1,57	-2,73	-1,63	-2,38
EST	-1,45	-1,69	-4,36	-4,72
PRT	-1,31	0,14	-0,93	0,19
ESP	-1,19	-1,48	-2,18	-1,03
SVN	-1,08	-1,42	-3,01	-2,70
ITA	-1,04	-0,95	-0,95	-0,73
NLD	-0,94	-1,43	-0,80	-1,72
DEU	-0,92	-0,67	-0,44	-0,75
LVA	-0,90	-1,07	-2,23	0,03
SVK	-0,90	0,15	-3,22	-1,17
IRL	-0,84	-4,60	-1,48	-8,66
DNK	-0,83	-2,43	-0,83	-1,48
FRA	-0,81	-0,88	-0,49	-0,83
SWE	-0,76	-1,97	-0,77	-0,23
CZE	-0,72	0,37	-2,15	-3,97
HUN	-0,72	0,22	-1,30	0,33
GBR	-0,69	-1,01	-0,40	-0,81
BGR	-0,67	-0,48	-3,77	-3,73
AUT	-0,65	-1,26	-0,71	-1,82
ROM	-0,65	-0,05	-2,68	-0,67
BEL	-0,46	-1,55	-0,79	-3,37
GRC	-0,43	0,25	0,02	-0,39
LTU	-0,42	-0,15	-1,27	0,09

Table 9. Impact of different ex-ante scenarios on GDP, deviation from the baseline in percent

	Central+	Inverse GDP	Past Emissions	Population
HRV	-2,48	-0,27	-4,08	-0,23
EST	-1,95	-1,35	-2,70	-1,20
BGR	-1,84	-1,33	-2,34	-1,55
POL	-1,79	-1,60	-3,64	-1,79
SVK	-1,37	-0,90	-2,89	-0,86
PRT	-1,29	-0,19	-0,90	-0,18
CZE	-1,18	-0,75	-1,68	-1,90
ROM	-1,15	-0,63	-2,13	-0,64
HUN	-1,04	-0,30	-1,26	-0,49
SVN	-1,03	-1,45	-2,56	-2,44
LVA	-1,00	-0,77	-1,84	-0,52
ESP	-0,92	-1,17	-1,58	-0,86
GRC	-0,82	-0,17	-0,18	-0,21
FIN	-0,81	-1,36	-0,83	-1,13
LTU	-0,79	-0,54	-1,25	-0,46
ITA	-0,78	-0,73	-0,75	-0,66
BEL	-0,70	-1,84	-1,17	-3,57
DEU	-0,61	-0,37	-0,28	-0,35
FRA	-0,61	-0,66	-0,43	-0,85
DNK	-0,60	-1,50	-0,58	-1,08
AUT	-0,54	-1,10	-0,72	-1,64
IRL	-0,48	-2,20	-0,84	-4,25
SWE	-0,43	-1,13	-0,49	-0,24
GBR	-0,43	-0,61	-0,28	-0,56
NLD	-0,36	-0,74	-0,42	-0,99

Source: CAK (2015).

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APPENDIX A: Calibration of supply with a fixed factor

We tried to find a relationship between elasticity of substitution, elasticity of supply, and the value share parameter in order to match benchmark profits.

CASE I: two factors

Consider output as a function of labor (L) and fixed capital (K) inputs: $Y = f(\overline{K}, L)$. We then have a CES unit cost function that, in equilibrium, defines the price of output (classic form):

$$P = C(P_K, P_L) = \left(\beta^{\sigma} P_K^{\ 1-\sigma} + (1-\beta)^{\sigma} P_L^{\ 1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{A1}$$

where P_L is the given wage rate[7], P_K is the residual return on fixed capital[8], β is a share parameter, and σ is an elasticity of substitution. It complies with Hicks' definition of the elasticity of substitution (see Broadstock et al., 2007, pp.78-79). For example, $\sigma = 0.5$ implies that if P_L / P_K increases by 1%, then the cost minimizing K/L ratio rises by approximately 0.5%. However, care must be taken when using literature results for elasticities of substitution, as these are often based on different definitions (Allen-Uzawa or Morishima elasticities), which only coincide with Hicks elasticity in simple special cases (e.g., a non-nested CES function). If, for example, Allen-Uzawa elasticities are estimated for a nested CES production structure, the results will not refer to σ directly (see e.g., Broadstock et al. 2007, pp.54-57).

Associated demand functions:

$$K(P_K, P_L, Y) = Y\left(\frac{\beta C(P_K, P_L)}{P_K}\right)^{\sigma}$$

$$L(P_K, P_L, Y) = Y\left(\frac{(1-\beta) C(P_K, P_L)}{P_K}\right)^{\sigma}$$

We can invert the capital demand function to determine β :

$$\beta = \frac{\overline{P}_K \left(\dfrac{\overline{K}}{\overline{Y}}\right)^{\frac{1}{\sigma}}}{\overline{C}}, \text{ where } \overline{C} = \frac{\overline{P}_K \overline{K} + \overline{P}_L \overline{L}}{\overline{Y}}$$

The bar symbol represents benchmark levels. We can obtain the calibrated share form (see Rutherford 2002 and Böhringer at. al 2003) of the unit cost function by substituting β into (A1):

[7] Fixed price is related to the perfect elastic supply curve, i.e., supply adjusts to clear the market (long-term closure). Thus the short-term effect of changes in the economy implies price change (supply is not able to adjust so fast), but in the next step (long term) the supply is adjusted to the new fixed market price.

[8] When supply is fixed, then its price adjusts to clear the market (short-term closure). This means that increased demand for capital implies a short-term increase in its price (because of the fixed supply of capital and the decreasing marginal productivity of labor). In the long term, it is usually assumed that the supply of capital adjusts while retaining a fixed price (rate of return).

$$P = C(P_K, P_L) = \overline{C}\left(\theta \left(\frac{P_K}{\overline{P}_K} \right)^{1-\sigma} + (1-\theta) \left(\frac{P_L}{\overline{P}_L} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \quad \text{(A2)}$$

where θ is value share parameter:

$$\theta = \frac{\overline{P}_K \overline{K}}{\overline{P}_K \overline{K} + \overline{P}_L \overline{L}} \text{ , } \beta = \theta \left(\frac{\overline{Y}}{\overline{K}} \right)^{\rho} \text{ , } \rho = \frac{\sigma - 1}{\sigma}$$

Associated demand functions in a calibrated-share form:

$$K(P_K, P_L, Y) = \overline{K} \frac{Y}{\overline{Y}} \left(\frac{\overline{P}_K C}{P_K \overline{C}} \right)^{\sigma}$$

$$L(P_K, P_L, Y) = \overline{L} \frac{Y}{\overline{Y}} \left(\frac{\overline{P}_L C}{P_L \overline{C}} \right)^{\sigma}$$

Setting benchmark prices $(\bar{p}_K, \bar{p}_L)$ equal to unit and $\overline{C} = 1$, we have simplified calibrated share form:

$$P = C(P_K, P_L) = \left(\theta P_K^{1-\sigma} + (1-\theta) P_L^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \quad \text{(A3a)}$$

Since the capital is fixed, we have the following relationship between output, supply of the fixed factor, and the return on the fixed factor (by Shepard's lemma):

$$Y \frac{\partial C(P_K, P_L)}{\partial P_K} = \overline{K}$$

Next, we calculate the optimal price of capital:

$$Y \frac{1}{1-\sigma} \left(\theta P_K^{1-\sigma} + (1-\theta) P_L^{1-\sigma} \right)^{\frac{1}{1-\sigma} - 1} \theta (1-\sigma) P_K^{-\sigma} = \overline{K}$$

$$Y \left(\theta P_K^{1-\sigma} + (1-\theta) P_L^{1-\sigma} \right)^{\frac{\sigma}{1-\sigma}} \theta P_K^{-\sigma} = \overline{K}$$

$$P_K^{\sigma} = \frac{Y P^{\sigma} \theta}{\overline{K}}$$

$$P_K = P \left(\frac{\theta Y}{\overline{K}} \right)^{\frac{1}{\sigma}}$$

Substituting P_K into the cost function (3a), we have:

$$P^{1-\sigma} = \left(\theta P_K^{1-\sigma} + (1-\theta) P_L^{1-\sigma} \right)$$

$$P^{1-\sigma} = \theta P^{1-\sigma}\left(\frac{\theta Y}{\overline{K}}\right)^{\frac{1-\sigma}{\sigma}} + P_L^{1-\sigma}$$

$$1 = \theta^{\frac{1}{\sigma}}\left(\frac{Y}{\overline{K}}\right)^{\frac{1-\sigma}{\sigma}} + (1-\theta)\left(\frac{P_L}{P}\right)^{1-\sigma}$$

$$\frac{Y}{\overline{K}}\theta^{\frac{1}{1-\sigma}} = \left(1-(1-\theta)\left(\frac{P_L}{P}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}$$

$$Y = \overline{K}\theta^{\frac{1}{\sigma-1}}\left(1-(1-\theta)\left(\frac{P_L}{P}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}$$

The calibration problem consists of finding the values of θ and σ, for which elasticity of supply (η) is at benchmark point:

$$\eta = \frac{\partial Y}{\partial(P/P_L)} \cdot \frac{P/P_L}{Y}$$

Differentiating *Y* with respect to relative price of output (P/P_L):

$$\eta = \frac{\overline{K}\theta^{\frac{1}{\sigma-1}}\left(1-(1-\theta)\left(\frac{P}{P_L}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}-1}\frac{\sigma}{1-\sigma}\left(-(1-\theta)\right)(\sigma-1)\left(\frac{P}{P_L}\right)^{\sigma-2}\left(\frac{P}{P_L}\right)}{\overline{K}\theta^{\frac{1}{\sigma-1}}\left(1-(1-\theta)\left(\frac{P}{P_L}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}}$$

$$\eta = \left(1-(1-\theta)\left(\frac{P}{P_L}\right)^{1-\sigma}\right)^{-1}(1-\theta)\sigma\left(\frac{P}{P_L}\right)^{\sigma-2}$$

and setting all prices equal to the unit at the benchmark, we obtain:

$$\eta = \frac{\sigma(1-\theta)}{\theta} \qquad \text{(A4a)}$$

CASE II: three factors

Next, we consider output as a function of labor, capital, and fixed natural resource (R) inputs: $Y = f(K, L, \bar{R})$. In this case, the cost function in a calibrated share form is:

$$C(P_K, P_L, P_R) = \left(\theta_K P_K^{1-\sigma} + \theta_L P_L^{1-\sigma} + (1-\theta_K-\theta_L) P_R^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \qquad \text{(A3b)}$$

where P_K and P_L are exogenous prices, and P_R is the residual return to the fixed factor.

Since R is fixed, we have:

$$Y \frac{\partial C(P_K, P_L, P_R)}{\partial P_R} = \bar{R}$$

Next, we calculate the optimal price of natural resources:

$$Y \frac{1}{1-\sigma} \left(\theta_K P_K^{1-\sigma} + \theta_L P_L^{1-\sigma} + (1-\theta_K-\theta_L) P_R^{1-\sigma}\right)^{\frac{1}{1-\sigma}-1} (1-\theta_K-\theta_L)(1-\sigma) P_R^{-\sigma} = \bar{R}$$

$$YP^{\sigma}(1-\theta_K-\theta_L) P_R^{-\sigma} = \bar{R}$$

$$P_R^{\sigma} = \frac{YP^{\sigma}(1-\theta_K-\theta_L)}{\bar{R}}$$

$$P_R = P\left(\frac{Y(1-\theta_K-\theta_L)}{\bar{R}}\right)^{\frac{1}{\sigma}}$$

Substituting P_R into the cost function (A3b), we obtain:

$$P^{1-\sigma} = \theta_K P_K^{1-\sigma} + \theta_L P_L^{1-\sigma} + (1-\theta_K-\theta_L) P_R^{1-\sigma}$$

$$P^{1-\sigma} = \theta_K P_K^{1-\sigma} + \theta_L P_L^{1-\sigma} + (1-\theta_K-\theta_L) P^{1-\sigma}\left(\frac{Y(1-\theta_K-\theta_L)}{\bar{R}}\right)^{\frac{1-\sigma}{\sigma}}$$

$$\frac{Y}{\bar{R}}(1-\theta_K-\theta_L)^{\frac{1}{1-\sigma}} = \left(1-\theta_K\left(\frac{p_K}{P}\right)^{1-\sigma} - \theta_L\left(\frac{p_L}{P}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}$$

$$Y = \bar{R}(1-\theta_K-\theta_L)^{\frac{1}{\sigma-1}}\left(1-\theta_K\left(\frac{P_K}{P}\right)^{1-\sigma} - \theta_L\left(\frac{P_L}{P}\right)^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}$$

Next, we calculate the elasticity of supply:

$$\eta = \frac{dY}{dP} \cdot \frac{P}{Y} = \frac{\partial Y}{\partial (P/P_K)} \cdot \frac{P/P_K}{Y} + \frac{\partial Y}{\partial (P/P_L)} \cdot \frac{P/P_L}{Y}$$

$$\eta = \frac{\sigma \cdot \theta_K}{1-\theta_K-\theta_L} + \frac{\sigma \cdot \theta_L}{1-\theta_K-\theta_L}$$

$$\eta = \frac{\sigma \cdot (\theta_K+\theta_L)}{1-\theta_K-\theta_L} = \frac{\sigma(1-\theta_R)}{\theta_R} \quad \text{(A4b)}$$

Thus we can use elasticity of substitution σ and supply elasticity η to estimate the value share of fixed factor θ_R:

$$\theta_R = 1-\theta_K-\theta_L = \frac{\sigma}{\sigma+\eta}$$

We can see from (A4a) and (A4b) that no matter how many variable factors we have in the production function, the relationship between the value share parameter of the fixed factor and the elasticities is the same.

CASE III: three factors with nesting CES function

Assuming the production function is given as a nested CES function:

$$Y = f(A, f(K, L, \bar{R}))$$

where two different nests are represented by Leontief function $f(.)$ and CES function $f(.) = Q_{VA}$ with an elasticity of substitution between K, L, R equal to σ. Parameter $\bar{R}$ is a constant production factor. The CES unit cost function defines the price of output in equilibrium similar to the following formula (3b):

$$P_{VA} = C(P_K, P_L, P_R) = \left(\beta_K{}^{\sigma} P_K{}^{1-\sigma} + \beta_L{}^{\sigma} P_L{}^{1-\sigma} + (1-\beta_K-\beta_L)^{\sigma} P_R{}^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \quad \text{(A1c)}$$

where P_L is the fixed wage rate, P_K is the fixed return to capital (exogenous prices), and P_R is the residual return to the fixed factor. Associated demand function for natural resources:

$$\bar{R}(P_K, P_L, P_R, Q_{VA}) = Q_{VA}\left(\frac{(1-\beta_K-\beta_L)C}{P_R}\right)^{\sigma}$$

In order to determine the relationship between supply elasticity and elasticity of substitution, we need to linearize the above demand function:

$$\log \bar{R} = \log Q_{VA} + \sigma(\log C - \log P_R + \log(1-\beta_K-\beta_L))$$

and differentiate it:

$$\Delta\log \bar{R} = \Delta \log Q_{VA} + \sigma(\Delta \log C - \Delta \log P_R + \Delta \log(1-\beta_K-\beta_L))$$

where $\Delta\log(1-\beta_K-\beta_L)=0$ and $\Delta\log\bar{R}=0$ because $\beta_K, \beta_L, \bar{R}$ are constant.

We can describe the above relationship as:

$$0 = q_{VA} + \sigma\,(p_{VA} - p_R\,)$$

where p_i and q_i denote corresponding relative log differentials:

$$p_i = \frac{\Delta\, P_i}{P_i} \approx \Delta\log P_i\,, \qquad q_i = \frac{\Delta\, Q_i}{Q_i} \approx\ \Delta\log Q_i, y = \frac{\Delta Y}{Y} \approx \Delta\log Y$$

Total output $f(A, Q_{VA})$ is a Leontief function, so percentage changes in inputs cause the same percentage changes in output:

$$y = q_{VA} = q_A$$

The desired relationship between percentage changes in the quantity of natural resources and output is equal:

$$y - \sigma\,(p_R - p_{VA}\,) = 0 \tag{A2c}$$

Lemma 1:

θ_{ij} denotes the value share of input j in the cost of output i:

$$\theta_{i,j} = \frac{P_j Q_j}{P_i Q_i}$$

where $i, j \in \{K, L, R, A, VA, O\}$. For example $\theta_{VA,R}$ is a value share of R in VA.

If prices of inputs other than natural resources are constant, then price changes p_{VA} and p_O exclusively depend on changes of p_R and p_{VA} respectively:

$$p_R\theta_{VA,R} = p_{VA} \tag{A3c}$$

$$p_{VA}\theta_{Y,VA} = p$$

Proof:

Take the total differential of the cost function (1c):

$$dP_{VA} = \frac{\partial P_{VA}}{\partial P_R} = (\beta_K^{\sigma} P_K^{1-\sigma} + \beta_L^{\sigma} P_L^{1-\sigma}\,(1-\beta_K-\beta_L\,)^{\sigma}) P_R^{1-\sigma})^{\frac{\sigma}{1-\sigma}} \frac{1}{1-\sigma} \beta_R^{\sigma}(1-\sigma) P_R^{-\sigma} dP_R$$

$$dP_{VA} = P^{\sigma} \beta_R^{\sigma} P_R^{-\sigma} dP_R$$

Next, divide the equation above by P_{VA}:

$$\frac{dP_{VA}}{P_{VA}} = \frac{(1-\beta_K-\beta_L)^{\sigma}P_R^{1-\sigma}}{P_{VA}{}^{1-\sigma}}\frac{dP_R}{P_R} = \frac{(1-\beta_K-\beta_L)^{\sigma}P_R^{1-\sigma}}{(\beta_K^{\sigma}P_K^{1-\sigma}+\beta_L^{\sigma}P_L^{1-\sigma}\,(1-\beta_K-\beta_L\,)^{\sigma})P_R^{1-\sigma})}\frac{dP_R}{P_R}$$

(L1)

The value share parameter of natural resources in the value-added is equal:

$$\theta_{VA,R} = \frac{\bar{R}P_R}{\bar{K}P_K+\bar{L}P_L+\bar{R}P_R} = \frac{Y\left(\frac{(1-\beta_K-\beta_L)P^{\sigma}}{P_R^{\sigma}}\right)P_R}{Y\left(\frac{\beta_K P}{P_K}\right)^{\sigma}P_K+Y\left(\frac{\beta_L P}{P_L}\right)^{\sigma}P_L+Y\left(\frac{(1-\beta_K-\beta_L)P}{P_R}\right)^{\sigma}P_R}$$

$$\theta_{VA,R} = \frac{(1-\beta_K-\beta_L)^{\sigma}P_R^{1-\sigma}}{(\beta_K^{\sigma}P_K^{1-\sigma}+\beta_L^{\sigma}P_L^{1-\sigma}\,(1-\beta_K-\beta_L\,)^{\sigma})P_R^{1-\sigma})}$$

(L2)

Inserting (L2) into (L1):

$$\frac{dP_{VA}}{P_{VA}} = \theta_{VA,R}\frac{dP_R}{P_R}$$

This gives us the formula (A3c):

$$p_{VA} = \theta_{VA,R}\cdot p_R$$

Substituting (A2c) with (A3c) we have:

$$y = \sigma\,(p_R - p_{VA}\,) = \sigma\left(\frac{p_{VA}}{\theta_{VA,R}} - \frac{p}{\theta_{Y,VA}}\right) = \sigma\left(\frac{p}{\theta_{Y,VA}\,\theta_{VA,R}} - \frac{p}{\theta_{Y,VA}}\right)$$

$$y = \sigma\left(\frac{1}{\theta_{Y,R}} - \frac{1}{\theta_{Y,VA}}\right)p = \sigma\frac{1-\theta_{VA,R}}{\theta_R}p$$

Then the elasticity of supply is equal:

$$\eta_S = \frac{\Delta\log Y}{\Delta\log P} = \frac{y}{p} = \sigma\left(\theta_{Y,R}^{-1}+\theta_{Y,VA}^{-1}\right) = \sigma(\theta_R^{-1}+\theta_{VA}^{-1}) \quad \text{(A4c)}$$

APPENDIX B: Mapping of IEA WEO into GTAP

Due to the different dimension (fuels, sectors, regions) between energy balances in WEO and our model (which is based on input-output tables), we have performed the following procedure to map datasets:

1. Mapping fuels and sectors from IEA EB into IEA WEO format;
2. Mapping regions from IEA EB into GTAP format;
3. Mapping regions from IEA WEO into GTAP format;
4. Mapping regions from GTAP into PLACE model format;
5. Mapping fuels and sectors from IEA WEO into PLACE model format.

The first two steps only take into account historical data (i.e., 2007), while the other steps consider both historical and projected data. We present a brief description of each step below.

B.1. Mapping fuels and sectors from IEA EB into IEA WEO format

Historical energy balances in the IEA EB contain data on the supply and consumption of coal, oil, gas, electricity, heat, and renewables for 34 OECD countries and over 100 non-OECD countries. This format differs considerably from forecasted WEO balances despite the fact that both balances are sourced from IEA. Thus in the first step, we created WEO format (fuels and sectors) for 2007 for each country present in the IEA EB 2007 database, and then applied that format to the WEO projections. A scheme of balance transformation from EB to WEO is presented in Table 20 (transfer from “blue” to “green”).

Table 20. Mapping fuels and sectors from IEA Energy Balances into IEA WEO balances and into GTAP database.

	IEA Energy Balance 2007	Fuels →			Coal, Peat	Crude	Oil	Gas		Nuclear fuels	Hydro	Bioenergy,	Geothermal, Wind, Solar, etc.	Electricity	Heat
	Demand categories ↓	IEA WEO balance			Coal	Oil		Gas		Nuclear fuels	Hydro	Bioenergy, Biofuels	Other renewables	Electricity	Heat
			EB + WEO		COL	CRU	OIL	GAS	GDT	Nuc	Ren	Bio	Ren	ELE	
TPES	Total Primary Energy Supply	TPED		GTAP	COL	CRU	OIL	GAS	GDT	No such energy in GTAP database				ELE	
Transformation processes	Main activity and auto producer electricity, CHP, and heat plants, Heat pumps, Electric boilers, Chemical heat for electricity production	Power generation	ELE	ELE	EWG	EG	EWG	EWG	G	EW	EW	EW	EW		
	Gas works, Coke ovens, Patent fuel plants, BKB plants	Other energy sector	Coke	OIL	G			G	G						
	Blast furnaces			Iron & steel	G			G	G						
	Oil refineries, Petrochemical plants, Coal liquefaction plants		Oil	OIL	EG	EG	EG	EG	G					G	E
	Other transformation, Own use, Distribution losses		ELE	ELE										EWG	E
			OIL	OIL	G	EG	EG	G	G			E	E		
			GAS	GAS	G	EG	G	G	G			E	E		
				GDT	G	EG	G	EG	G			E	E		
	Industry	Industry	Industry	Industry	EWG	EG	EWG	EWG	G			EW	EW	EWG	E

	Transport	Transport	Transport	Transport	EWG	EG	EWG	EG	G			EW	EW	EWG	E
	Residential	Buildings	Service	Srv, G, C	EWG	EG	EWG	EG	G			EW	EW	EWG	E
	Non-energy use	Other	Non-energy use	All sectors	EW	E	E	E	G			E	E	EW	E
	Agriculture		Agriculture	Agriculture	EW	E	E	E	G			E	E	EW	E

E means that the item is available in the IEA Energy Balance, W – in IEA WEO, and G – in the GTAP database.

Cells shaded gray denote that no such use exists.

In energy balances, primary energy carriers are used either as an input in transformation processes into other energy carries or as a final consumer. There are two types of energy users in a balance: energy industries and final users. The first type covers mainly electricity and heat producers. Other important transformations are crude to oil products and coking coal to coke. The transformation of crude oil into oil products is not shown in the WEO format, probably because crude oil is chiefly transferred to refineries (such data would be of little use to WEO). Neither is the transformation from coking coal to coke shown in WEO because coke is a part of coal. However, energy loss in these processes, as well as distribution loss and own use, are presented in the WEO balance as other energy sector (OES). Since that sector only has information on electricity input in WEO, we have disaggregated inputs in the OES for 2007 into other fuels based on information from EB. The transformation of primary into secondary energy carriers are presented in WEO as positive values, but in EB as negative and positive values. In order to convert transformation process from the EB into the WEO format, we must aggregate only those categories in EB that have negative values.

The second type of energy users are those that consume fuels directly: industry (IND), transport (TRA), buildings (BUI), and other (OTH). In WEO, inputs for the transport sector are not consistently presented in new (IEA 2012a) and previous (IEA 2009) issues – namely, electricity is aggregated with other fuels for 2007. Thus in transportation sector, other fuels are disaggregated into coal, gas, and electricity based on EB. Another inconsistency between WEO issues is related to other users. The "other" sector in IEA (2012) covers non-energy use of fuels and energy use in the agriculture sector, but in previous IEA (2009) issue, agriculture was a part of the buildings sector. We ignore this inconsistency.

To summarize, the growth path is based on the reference year 2007 taken from previous issue of WEO (IEA 2009), with some exceptions where EB (IEA 2010a,b) is applied. The exceptions are the categories absent in (IEA 2009): electricity in TRA, disaggregated other fuels in OES, and disaggregated fuels in OTH. We could use EB instead of WEO for the reference period if it were possible to match both balances precisely. As a result of our mapping, we get EB historical dataset for WEO aggregation of fuels and sectors. We will call this EB_WEO.

B.2. Mapping regions from EB_WEO into GTAP format

We subsequently assigned each country in EB to the GTAP region classification. The difference between IEA energy balances is presented in Table 21, where data for WEO comes from IEA (2009), and data for EB_WEO are based on our calculations using IEA (2010a,b) and mapping from the previous step. The category EB_WEO_GTAP is related to EB data, where some regions were dropped if there was no regional match between EB_WEO and the GTAP dataset.

The biggest difference (19%) between WEO and EB_WEO comes from electricity and heat use in the other energy sector, because WEO aggregates heat with other fuels. There are also differences in renewables use in buildings (14%) and biofuels in transport (5%), but it is irrelevant taking into account the small differences in absolute terms. The difference between WEO and EB_WEO_GTAP comes from international transport (16%), since GTAP does not include international bunkers.

As a result of mapping, we get EB_WEO historical data for GTAP regional aggregation. We will call this EB_WEO_GTAP.

Table 10. Comparison of global energy demand for 2007 (ktoe)

	fuel	ELE	OES	IND	BUI		TRA	OTH	Total*
WEO	Biofuels	84	NA	189	806		34		1176
	Coal	2167	NA	581	110		NA	NA	3184
	Electricity/Heat		287**	716	947		NA		1950
	Gas	988	NA	460	613		NA	NA	2512
	Nuclear	709							709
	Oil	284	NA	320	453		2161	NA	4093
	Renewables	325	NA	NA	12				339
	Other fuels		925				101	770	1796
WEO Total		4557	1212	2266	2941		2296	770	14042
EB_WEO	Biofuels	86	63	192	810		32		1183
	Coal	2169	297	588	114		4	32	3203
	Electricity/Heat		344	718	944		23		2029
	Gas	991	287	453	603		76	132	2543
	Nuclear	709							709
	Oil	281	267	332	454		2176	592	4101
	Renewables	331	0	0	14				346
EEB Total		4568	1257	2284	2938		2311	756	14114
EB_WEO_GTAP	Biofuels	86	56	184	739		32		1097
	Coal	2166	295	577	111		4	32	3184
	Electricity/Heat		341	715	939		23		2018
	Gas	986	282	449	603		76	123	2519
	Nuclear	709							709
	Oil	273	227	330	449		1816	591	3687
	Renewables	328	0	0	14				342
EB_GTAP Total		4548	1201	2256	2854		1951	746	13556
Percentage difference compared to WEO									
		ELE	OES	IND	BUI		TRA	OTH	Total
EB_WEO	Biofuels	2%	NA	1%	0%		-5%		1%
	Coal	0%	NA	1%	3%		NA	NA	1%
	Electricity/Heat		19%	0%	0%		NA		4%
	Gas	0%	NA	-1%	-2%		NA	NA	1%
	Nuclear	0%							0%
	Oil	-1%	NA	4%	0%		1%	NA	0%
	Renewables	2%	NA	NA	14%				2%
EB Total		0%	4%	1%	0%		1%	-2%	1%
EB_WEO_GTAP	Biofuels	2%	NA	-2%	-8%		-5%		-7%
	Coal	0%	NA	-1%	1%		NA	NA	0%
	Electricity/Heat		19%	0%	-1%		NA		3%
	Gas	0%	NA	-2%	-2%		NA	NA	0%
	Nuclear	0%							0%
	Oil	-4%	NA	3%	-1%		-16%	NA	-10%
	Renewables	1%	NA	NA	14%				1%
EB_GTAP Total		0%	-1%	0%	-3%		-15%	-3%	-3%

NA – not available.

* The sum of the columns is not equal to Total (total primary energy demand) for the WEO balance, because other fuels are not disaggregated.
** Only electricity.

B.3. Mapping regions from IEA WEO into GTAP format

The energy demand projection in WEO should be assigned to the regions represented in GTAP. For non-single country representation in WEO (such as OECD_Europe or Africa), it was assumed that each GTAP country covered by a given WEO region has the same growth path per fuel and sector as for the region as a whole. In order to achieve a single representation of different inputs (apart from electricity) in the other energy sector within the WEO projections, for this sector we assumed a similar growth path of demand for each input as the growth path of total demand for inputs excluding electricity. In order to achieve a single representation of other fuels in the transport sector within the WEO projection, we assumed that the growth path of demand for coal and gas is equal to the growth path of demand for other fuels. As a result of mapping, we get WEO projections for GTAP regional disaggregation. We call this WEO_GTAP.

B.4. Mapping regions from WEO_GTAP and EB_WEO_GTAP into PLACE model format

This part of procedure is straightforward – it simply aggregates GTAP regions in energy balances into the PLACE model dimension. As a result, we get projected and historical energy demand for PLACE regional disaggregation. We call this WEO_PLACE.

B.5. Mapping fuels and sectors from WEO_PLACE into PLACE model format

The previous steps led us to an energy demand projection in the following dimensions:

- regional aggregation in line with the PLACE model
- fuel and sectoral aggregation according to WEO with some modification such as disaggregation of other fuels in transport

Here, we map fuels and sectoral aggregation to the PLACE model dimension.

Fuels

Using IEA balances (EB and WEO) from the first step described above, projections of demand for the following fuels is available: coal, gas, oil, renewables, biofuels, nuclear, and electricity (including heat). There are slightly different fuels in the GTAP database (see section 1.1):

- coal does not cover coke (it is a part of oil product) in GTAP, while it does inWEO;
- gas might be purchased by users either directly or via a distribution service. In GTAP, direct purchase is assigned to gas, while indirect purchase is assigned to gas distribution product (GDT);
- crude oil (this is mainly demanded by the oil sector for most regions) and refined oil (refining crude oil, coke, nuclear fuels) represent separate products in GTAP, while they are a single product in WEO (i.e., no transformation from crude to refine oil is presented);
- renewables (such as wind or solar energy) are not included in GTAP because they are not products of economic activity and therefore are not valued (while the output from renewables is covered by electricity and heat sector). However, renewables are present in WEO because it is a part of an energy source;
- biofuels and biomass are not directly presented in GTAP, but they can be extracted from agricultural and forestry products using simplifying assumptions; biofuels and biomass are covered by WEO;
- nuclear fuels are a part of refined oil products in GTAP, while they are directly represented in WEO.

Sectors

Using IEA balances (EB and WEO) from the first step described above, projections of energy demand for the following sectors is available: power generation, other energy sector, industry, transport, buildings, and other (which covers non-energy use and agriculture). There are far more sectors in the GTAP database (see section 1.1).