This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

MONROE - Modelling and evaluating the socio-economic impacts of research and innovation with the suite of macro- and regional-economic models

D4.2.2 Technical description of the R&I module of PACE model

March 2019: Public

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

Contents

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 727114

Document Details

Authors	Theodoros Chatzivasileiadis, Sebastian Voigt, Claudio Baccianti
Creation Date	31.01.2019
Date of Last Revision	29.03.2019
Version	V2.0
Description	D4.2.2 Technical description of the R&I module of PACE model

Version History

Version	**Updated By**	**Date**	**Changes / Comments**
V1.0	Theodoros Chatzivasileiadis, Sebastian Voigt	31.01.2019	First draft
V2.0	Theodoros Chatzivasileiadis, Sebastian Voigt	29.03.2019	Second draft

Project Involvement

Project Director	Olga Ivanova <olga.ivanova@pbl.nl>
Project Manager	Iason Diafas <iason.diafas@pbl.nl>
WP Manager	Leonidas Paroussos <paroussos@e3modelling.gr>
Project Leads	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

1. The PACE Model

The quantitative assessment of endogenous R&D is carried out with PACE (Policy Analysis based on Computable Equilibrium), a multi-sector, multi-region computable general equilibrium (CGE) model of global production, consumption, trade and energy use that has been extended to include an endogenous R&D module.

The implementation of PACE is done using MPSGE (Mathematical Programming System for General Equilibrium Analysis; Rutherford, 1999), which is a subsystem of GAMS (General Algebraic Modelling System; Brooke et al. 2010). The solver used in the analysis is PATH (Dirkse and Ferris 1995) for solving the MCP (mixed complementarity problem). PACE can run starting from 2010 until 2050 in five-year time steps and solves for a sequence of market equilibria. The global economy is described by a set of equations (i.e., market clearing, zero profit, and income balance conditions). For each year, the solution algorithm finds the set of prices and quantities that solves these equations.

Zero-profit conditions and market clearing conditions follow directly from the assumptions of profit maximization of firms, perfect competition among them, utility maximization of consumers, constant returns to scale in production, and homothecy of consumer preferences. The latter class of conditions determines the price of each output good as the unit cost to produce this good. This cost equals the marginal and (given constant returns to scale) the average cost of production. Crucially, the zero-profit assumption entails that firms cannot pass on the expenses for emission permits to consumers if those are refunded to them under a free allocation scheme.

In each region of the model there is a representative consumer, and representative producers that are sector specific. Each consumer chooses a bundle of consumption goods that maximizes their utility based on their preferences and budget constraint. This budget is determined by the consumers' income that is received from selling the primary production factors (labour, capital and fossil-fuels) that they own. In

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

addition to that, each region can obtain a certain amount of emission permits in each period. The final demand of the representative consumer is modelled as a constant elasticity of substitution (CES) composite good which combines an energy aggregate with a non-energy aggregate (analogue to the production structure described below). Substitutability between the non-energy aggregate is reflected by a Cobb-Douglas function. The energy aggregate consists of several energy goods combined with a constant elasticity of substitution.

Given the requirements of the MONROE project an additional consumer has been added to PACE, the *Entrepreneur*. The *Entrepreneur* is industry and region specific. The income of the *Entrepreneur* is based on mark-up revenues in each sector. These mark-up revenues are allocated to fixed costs since in equilibrium there are no profits in each sector. Meaning that the mark-up revenues in each sector are converted to demand for fixed costs.

Based on their production possibilities, the producers choose bundles of production goods in order to maximise their profits. The production possibilities are determined by technologies, which efficiently transfer certain amounts of input goods and production factors into certain amounts of unique, sector specific output goods. Production factors entail labour, capital, (both perfectly mobile between sectors within a region) and sector specific resources for agriculture, oil and gas extraction, and coal and other mining. The supply of labour is assumed fixed in each region of PACE, however there is full mobility among sectors and no unemployment. The production functions are nested CES functions with the following nesting structure. At the top level, general sectoral output is combined with total factor productivity (TFP). At the second level, non-energy inputs are employed with an aggregate of energy, capital and labour. At the third level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labour and capital. At the fourth level, capital and labour (and if applicable: sector specific resources) are combined with a constant elasticity of substitution. Moreover, at the fourth level, the energy aggregate consists of electricity and a fossil fuel input. The latter input is further split into coal, gas and oil associated with different elasticities of substitution and with emission permits in fixed proportions (in the presence of a carbon pricing scheme). The CES specification allows producers to substitute fossil fuel inputs by other inputs as a reaction to an increasing carbon price. The extent of substitution, however, is limited by the choice of the cost minimizing input bundle given the elasticities of substitution. Moreover, each good used in intermediate and final demand corresponds to a CES aggregate of a domestically produced variety and a CES import aggregate of the same variety imported from the other regions (Armington, 1969).

The electricity sector is modelled in a bottom-up module (see Figure 1), following a general equilibrium representation based on CES production functions. Nevertheless, energy is disaggregated for different technology types. Hence, technology specific capital is represented in this module. PACE includes different types of technologies, namely coal, refined oil, gas, nuclear and a renewable energy aggregate. The model allows the substitutability between fossil fuel consumption and other inputs in order to mitigate emissions.

The tax system includes production taxes and subsidies, intermediate good taxes, input factor taxes, consumption taxes as well as tariffs. The government collects tax revenues and redistributes them to the representative consumer in a lump-sum way.

The use of fossil energy in production requires producers to pay for the released carbon corresponding to the physical carbon content of each fossil fuel input in the presence of a carbon pricing scheme by means of allowances.

2. The R&I module

The way we choose to introduce Endogenous Technological Change (ETC) in the PACE model is similar to the QUEST III model (Ratto et al., 2009), with the main difference that PACE is a static model instead of a fully intertemporal one. Innovation and increasing returns are modelled using the monopolistic competition framework with fixed costs. The sectoral output already in PACE is now considered as the aggregation of N_j product varieties. The production of one single variety requires the purchase of a patent to start production, which is purchased once as a fixed cost. Patents are produced in a separate R&D sector and are assumed to be sector-specific. This implies that there are as many R&D sectors as production

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

sectors. This is obviously an assumption, which allows us to specify different cost structures for R&D activities in each sector. An example for this reasoning is the pharmaceutical industry where more capital is spent on R&D than in the services sector.

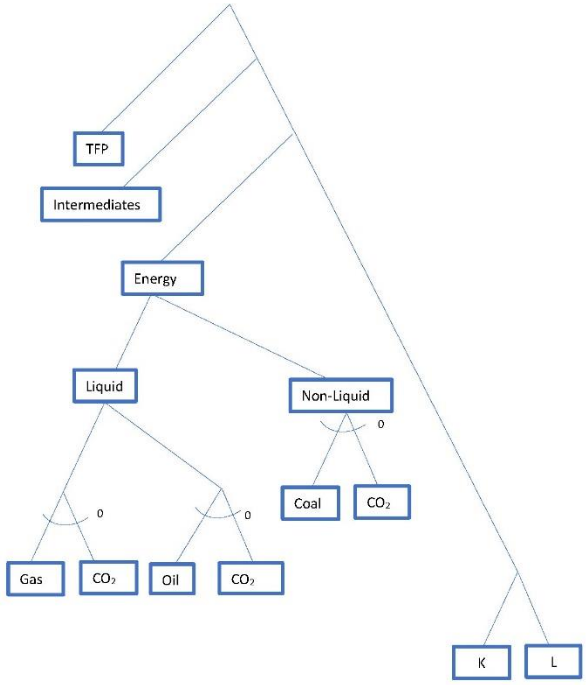

Figure 1 PACE model's nesting structure

Patents, as a good, are produced by the R&D sector. Firms in this sector make positive profits from renting patents out to goods producers. The revenue source for these firms is the price of a patent. Monopolistic competitors instead earn a flow of positive profits. As a result, we have introduced a new production factor into the model, *knowledge*. However, knowledge is assumed to be nonexcludable, therefore nobody owns it.

In each sector, sectoral output is the aggregation of N_j product varieties supplied by monopolistically competitive firms. Each firm acquires monopoly rights in a niche market by purchasing a patented technology from an R&D sub-sector. The firm bears an initial fixed cost to acquire the patent necessary to produce each good.

The R&D sub-sector generates sector-specific patents according to the following knowledge production function:

$$\Delta A_{jt} = A_t^{*\omega} A_{jt}^{\phi} R_{A,jt}^{\lambda}, \qquad (1)$$

Where, $R_{A,jt}$ is the R&D investments, $A_{j,t}$ is the sectoral patent stock, and A_t is the nation-wide patent stock for a level of R&D investment. The opportunity cost of R&D is in units of sectoral output: R&D activities compete with goods production to employ labour. Despite the assumption of sector-specific patents, the knowledge required to produce the single technology might well build on general knowledge. This property is captured by the spillovers from the national (average) knowledge stock A_r.

$$A_r^* = \sum_j \frac{A_{j,r}}{CARD(j)} \qquad (2)$$

The profit maximization problem in the R&D sector is:

$$\Pi_{j,r}^{RD} = \sum_t \beta^t \left(p_{A,j,r} (1 + \mathrm{subs_{j,r}}) \Delta A_{jt} - p_{j,r} R_{j,r} \right) \qquad (3)$$

that gives the one period cost function for a patent:

$$p_{A,j,r}\left(1 + \mathrm{subs_{j,r}}\right) = \frac{\mathrm{p_{jt}}}{\lambda A_r^{*\omega} A_{j,r}^{\phi}} \qquad (4)$$

In MPSGE, this is transformed into a standard cost function by accounting for two subsidies, the actual subsidy $subs_{jr}$ and another endogenous one that is defined by $\lambda A_r^{*\omega} A_{j,r}^{\phi}$.

3. Description of Data and Baseline Calibration

A balanced social accounting matrix (SAM) is necessary for the calibration of a CGE in order to ensure that transactions between sectors and the representative agent and government can inform the production functions of sectors and utility function of agents. The calibration of utility and production functions are done such that cost-minimizing firms and utility maximizing agents make exactly the choices that lead to the transactions represented by the SAM.

Apart from the calibration to a benchmark year of the world economy, there are a set of assumption concerning future growth patterns of regional GDP and sectoral energy use, in order to make multi-period analysis possible in order to compare the effects of endogenous R&D within the model. The GDP growth is introduced by increasing the production factors of each region by their corresponding rates. Assuming production and utility functions as in the base year, the model will endogenously balance trade imbalances caused by asymmetric growth of regions. However, the introduction of changes in energy intensity of economic activities is achieved by changing the production functions themselves, and in turn the model is endogenously rebalanced.

This chapter describes in more detail the data this calibration process was based on for the PACE model.

As mentioned above, starting from 2010, PACE runs in steps of five years till 2050. Using interpolated data for 2011 from the GTAP 9 database (Global Trade Analysis Project; Badri and Walmsley, 2008) we calibrate the model for its starting point. GTAP 9 provides information for the base years 2004, 2007 and 2011. For the MONROE project, the 2011 data has been used for the model calibration.

For European Union we distinguish all EU28 countries, excluding Malta and Cyprus which are aggregated in Italy and Greece respectively.

Regarding the sectoral coverage, the most recent model version distinguishes 15 production sectors that include nine energy intensive sectors (iron and steel; non-ferrous metals; chemicals, rubber and plastics; minerals; pulp and paper; engineering; electricity; refined oil and coke oven products; transport) and five additional sectors (agriculture, food, forestry; textiles, wearing apparel, leather; services; coal; crude oil; gas).

Elasticities of substitution in international trade (so-called Armington elasticities) are based on empirical estimates reported in the GTAP database. Certain CES elasticities of substitution between production factors (capital, labour, energy inputs, and non-energy inputs) are taken from Okagawa and Ban (2008) based on recent sectoral panel data estimates for the period 1995 to 2004. A higher value of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

the Armington elasticity denotes a better possibility to substitute inputs for each other due to price changes. An elasticity value of zero denotes a Leontief relationship without substitution possibilities; this means all inputs are used in fixed proportions.

Data for the future economic development are taken from the International Energy Outlook of the US Department of Energy (IEO 2013) for the non-EU regions. The 2013 IEO provides detailed regional data on total and fuel-specific primary energy consumption and carbon emissions given assumptions on the development of GDP, fossil fuel prices and other factors. The data take population growth and (exogenous) technical progress into account. Moreover, the 2013 IEO offers several additional baselines which will be described further below.

Process emissions were included for all model sectors in all model regions. To this end, we made use of process emissions data from the World Input Output Database (WIOD). The advantage of this database is that the sectors are relatively similar to the PACE sectors and can thus be translated in a relatively straightforward fashion. We calculated the share of process emissions in total emissions. We then included them in the production function using this share. That procedure was chosen since we could use WIOD to obtain process emission for all model sectors. In contrast to fuel-based emissions which are tied to the fossil fuel input into each sectoral production function, process emissions are tied to the output of each sector and hence depend on the production level rather than the fossil fuel input level. In terms of the treatment of emissions trading, each ton of process emissions is connected to one EUA certificate, just as fuel-based emissions.

Finally, the R&D is connected to sectoral data on R&D investments extracted from the STAN (STructural ANalysis Database)[1], and its subset ANBERD (Analytical Business Enterprise Research and Development) database from the OECD[2] for the same base year as used in the model calibration process. R&D is represented as a sum of all patents per sector and region of the PACE model.

---

[1] http://oe.cd/stan

[2] http://www.oecd.org/sti/inno/anberdanalyticalbusinessenterpriseresearchanddevelopmentdatabase.htm

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

4. Algebraic Model Summary of PACE

***Table 1:** Activity variables*

Variable	Description
$y_{i,r}$	Aggregate production in sector i and region r
$y_{tec,r}^{ele}$	Aggregate production in electricity sector of region r and technology tec
$y_{xe,r}$	Aggregate production of exhaustible resource xe in region r
$y_{i,r}^{A}$	Armington aggregate in sector i and region r
$y_{i,r}^{M}$	Import of sector i in region r
y_{r}^{W}	Welfare in region r
$A_{j,r}$	Patent stock of sector j in region r
$R_{A,jr}^{\lambda}$	R&D investments of sector j in region r

***Table 2:** Price variables*

Variable	Description
$p_{i,r}^{Y}$	Price of aggregate output of sector i in region r
$p_{ele,r}^{Y}$	Price of aggregate output in electricity sector of region r and technology tec
$p_{xe,r}^{Y}$	Price of aggregate output of exhaustible resource xe in region r
$p_{j,i,r}^{A}$	Price of Armington good in sector i and region r
$p_{i,r}^{M}$	Price of import good in sector i and region r
p_{i}^{T}	Price of transport good in sector i
p_{r}^{W}	Welfare price in region r
v_{r}	Return to capital in region r
w_{r}	Wage rate in region r
$q_{xe,r}$	Rent to exhaustible resource xe in region r
$p_{r}^{CO_2}$	Price of emission permits in region r
$p_{j,r}^{R\&D}$	Price of R&D investments in sector j and region r
$p_{Aj,r}^{R\&D}$	Price of R&D stock in sector j and region r

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

Table 3: *Additional variables*

Variable	Description
RA_r	Income level of representative agent in region r
μ_r	Subsidy on renewable energy
τ_r	Tax on electricity consumption in region r
ψ_r	Green quota in power production in region r

Table 4: *Cost shares*

Parameter	Description
$\theta_{i,r}^{Mat}$	Benchmark cost share of materials in aggregate output of sector i in region r
$\theta_{i,r}^{E}$	Benchmark cost share of energy in capital-labor-energy composite of sector i in region r
$\theta_{i,r}^{K}$	Benchmark cost share of capital in value added composite of sector i in region r
$\theta_{i,r}^{col}$	Benchmark cost share of the coal-CO_2 permit composite in energy composite of sector i in region r
$\theta_{i,r}^{oil}$	Benchmark cost share of the oil-CO_2 permit composite in oil-gas composite of sector i in region r
θ_{r}^{colem}	Benchmark cost share of coal in coal-CO_2 permit composite in region r
θ_{r}^{oilem}	Benchmark cost share of oil in oil-CO_2 permit composite in region r
θ_{r}^{gasem}	Benchmark cost share of gas in gas-CO_2 permit composite in region r
$\theta_{tec,r}^{K}$	Benchmark cost share of capital in electricity generation for technology tec in region r
$\theta_{ele,r}^{LM}$	Benchmark cost share of material-labor composite in non-technology input of electricity sector in region r
$\theta_{ele,r}^{MatL}$	Benchmark cost share of material-labor composite of electricity sector in region r
$\theta_{xe,r}^{R}$	Benchmark cost share of exhaustible resource xe in region r
$\theta_{s,r}^{Y}$	Benchmark cost share of goods from region s in Armington aggregate of region r
$\theta_{s,r}^{M}$	Benchmark cost share of goods from region s in aggregate import good of region r
$\theta_{j,i,s}^{T}$	Benchmark cost share of transport good from region s from sector j to sector i

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

Table 5: *Endowments*

Parameter	Description
$\overline{K_r}$	Capital endowment in region r
$\overline{k_{i,r}}$	Benchmark capital demand in the value-added nest of sector i in region r
$\overline{tk_{tec,r}}$	Benchmark capital demand in electricity sector of technology tec in region r
$\overline{L_r}$	Labor endowment in region r
$\overline{l_{i,r}}$	Benchmark labor demand in the value-added nest of sector i in region r
$\overline{Q_{xe,r}}$	Endowment of resource xe in region r
$\overline{c_{i,r,s}}$	Benchmark bilateral trade flows
$\overline{CO_{2_r}}$	CO_2 emissions target in region r
$\overline{ren_r}$	Renewable target in region r

Table 6: *Elasticities*

Parameter	Description
σ_{KLEM}	Substitution between materials and the energy-value added composite
σ_{KLE}	Substitution between energy and the value-added composite
σ_{KL}	Substitution between capital and labor
σ_{NEL}	Substitution between coal and the oil-gas composite
σ_{LQD}	Substitution between oil and gas
σ_{tec}	Substitution between technology-specific capital and the non-technology inputs composite in electricity generation
σ_{res}	Substitution between resources and the materials-value added composite in resource extraction
σ^A	Armington elasticity
σ^M	Substitution between imports by origin country

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

Zero-profit conditions

1. Sectoral output (except for electricity in the EU regions and for fossil fuel resources)

$$\left(\theta_{i,r}^{Mat}\left(\sum_{j} p_{j,i,r}^{A}(1+\tau_r)\right)^{1-\sigma_{KLEM}} + \left(1-\theta_{i,r}^{Mat}\right)\left(kle_{i,r}\right)^{1-\sigma_{KLEM}}\right)^{1/(1-\sigma_{KLEM})} \geq p_{i,r}^{Y} \perp y_{i,r}$$

where

$$kle_{i,r} = \left(\theta_{i,r}^{E}\left(en_{i,r}\right)^{1-\sigma_{KLE}} + \left(1-\theta_{i,r}^{E}\right)va_{i,r}{}^{1-\sigma_{KLE}}\right)^{1/(1-\sigma_{KLE})}$$

$$va_{i,r} = \left(\theta_{i,r}^{K} v_r^{1-\sigma_{KL}} + \left(1-\theta_{i,r}^{K}\right)w_r{}^{1-\sigma_{KL}}\right)^{1/(1-\sigma_{KL})}$$

$$en_{i,r} = \left(\theta_{i,r}^{col} col_{i,r}^{1-\sigma_{NEL}} + \left(1-\theta_{i,r}^{col}\right)lqd_{i,r}^{1-\sigma_{NEL}}\right)^{1/(1-\sigma_{NEL})}$$

$$lqd_{i,r} = \left(\theta_{i,r}^{oil} oil_{i,r}^{1-\sigma_{LQD}} + \left(1-\theta_{i,r}^{oil}\right)gas_{i,r}^{1-\sigma_{LQD}}\right)^{1/(1-\sigma_{LQD})}$$

$$col_{i,r} = \max\left\{\theta_r^{colem} p_{col,r}^{Y}; \left(1-\theta_r^{colem}\right)p_r^{CO_2}\right\}$$

$$oil_{i,r} = \max\left\{\theta_r^{oilem} p_{oil,r}^{Y}; \left(1-\theta_r^{oilem}\right)p_r^{CO_2}\right\}$$

and

$$gas_{i,r} = \max\left\{\theta_r^{gasem} p_{gas,r}^{Y}; \left(1-\theta_r^{gasem}\right)p_r^{CO_2}\right\}$$

2. Electricity (only in the EU regions – ψ_r only applies to $tec = ren$)

$$\left(\theta_{tec,r}^{K}\left(\sum_{tec} v_{tec,r}\right)^{1-\sigma_{tec}} + \left(1-\theta_{tec,r}^{K}\right)inp_{ele,r}^{1-\sigma_{tec}}\right)^{1/(1-\sigma_{tec})} \geq p_{ele,r}^{Y}(1+\psi_r)(1+\mu_r) \perp y_{tec,r}^{ele}$$

where

$$inp_{ele,r} = \max\left\{\theta_{ele,r}^{LM} lm_{ele,r}; \left(1-\theta_{ele,r}^{LM}\right)en_{ele,r}\right\}$$

$$lm_{ele,r} = \max\left\{\theta_{ele,r}^{MatL}\sum_{j\backslash fe} p_{j,ele,r}^{A}; \left(1-\theta_{ele,r}^{MatL}\right)w_r\right\}$$

$$en_{ele,r} = \max\left\{\theta_{ele,r}^{col} col_{ele,r}; \theta_{ele,r}^{oil} oil_{ele,r}; \theta_{ele,r}^{gas} gas_{ele,r}\right\}$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

and

$$col_{i,r} = \max\{\theta_r^{colem} p_{col,r}^Y; (1-\theta_r^{colem}) p_r^{CO_2}\}$$

$$oil_{i,r} = \max\{\theta_r^{oilem} p_{oil,r}^Y; (1-\theta_r^{oilem}) p_r^{CO_2}\}$$

$$gas_{i,r} = \max\{\theta_r^{gasem} p_{gas,r}^Y; (1-\theta_r^{gasem}) p_r^{CO_2}\}$$

3. Resource extraction

$$\left(\theta_{xe,r}^R q_{xe,r}^{1-\sigma_{res}} + (1-\theta_{xe,r}^R) klm_{xe,r}^{1-\sigma_{res}}\right)^{1/(1-\sigma_{res})} \geq p_{xe,r}^Y \perp y_{xe,r}$$

where

$$klm_{xe,r} = \max\left\{\theta_{xe,r}^{Mat} \sum_j p_{j,r}^Y ; \theta_{xe,r}^K v_r; \theta_{xe,r}^L w_r\right\}$$

4. Armington aggregate

$$\left(\sum_s \theta_{s,r}^Y p_{i,r}^{Y\ 1-\sigma^A}\right)^{1/(1-\sigma^A)} \geq p_{j,i,r}^A \perp y_{i,r}^A$$

5. Imports

$$\left(\sum_s \theta_{s,r}^M ty_{j,i,s}^{1-\sigma^M}\right)^{1/(1-\sigma^M)} \geq p_{i,r}^M \perp y_{i,r}^M$$

where

$$ty_{j,i,s} = \max\{\theta_{j,i,s}^T p_{i,s}^Y; (1-\theta_{j,i,s}^T) p_j^T\}$$

6. Welfare

$$\sum_j p_{j,r}^Y \geq p_r^W \perp y_r^W$$

Market-clearing conditions

7. Sectoral output

$$y_{i,r} \geq \sum_s \overline{c_{\iota,r,s}}\, y_{i,s}^A \left(\frac{p_{i,s}^A}{p_{i,r}^Y}\right)^{\sigma^A} \perp p_{i,r}^Y$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

8. Capital

$$\overline{K_r} \geq \sum_{tec} \overline{tk_{tec,r}}\, y_{ele,r} \left(\frac{p^Y_{ele,r}}{v_{tec,r}}\right)^{\sigma_{tec}} + \sum_i \overline{k_{i,r}} y_{i,r} \left(\frac{p^Y_{i,r}}{v_r^{\theta^K_{i,r}} w_r^{1-\theta^K_{i,r}}}\right)^{\sigma_{KL}} \frac{v_r^{\theta^K_{i,r}} w_r^{1-\theta^K_{i,r}}}{v_r} \perp v_r$$

9. Labor

$$\overline{L_r} \geq \sum_i \overline{l_{i,r}} y_{i,r} \left(\frac{p^Y_{i,r}}{v_r^{\theta^K_{i,r}} w_r^{1-\theta^K_{i,r}}}\right)^{\sigma_{KL}} \frac{v_r^{\theta^K_{i,r}} w_r^{1-\theta^K_{i,r}}}{w_r} \perp w_r$$

10. Armington

$$\sum_s c_{i,s,r} y^A_{i,r} \geq \sum_s c_{i,s,r} y^W_r \frac{p^W_r}{p^A_{i,r}} \perp p^A_{i,r}$$

11. Welfare

$$y^W_r \sum_{i,s} c_{i,s,r} \geq \frac{RA_r}{p^W_r} \perp p^W_r$$

12. Emissions (only for emissions regulating regions and for both the ETS and NETS market segments)

$$\overline{CO_{2_r}} \geq y_{col,r} + y_{oil,r} + y_{gas,r} \perp p^{CO_2}_r$$

Constraints

13. Green quota in power production

$$y^{ele}_{ren,r} = \overline{ren_r} \sum_{tec} y^{ele}_{tec,r} \perp \psi_r$$

14. Tax on electricity consumption (does not apply to sectors exempted from electricity levy)

$$\tau_r \sum_i p^A_{ele,i,r}\, y_{i,r} = \alpha_r p^Y_{ele,r} \psi_r y^{ele}_{ren,r} \perp \tau_r$$

15. Subsidy on renewable energy (as a recycling option of permit auctioning revenues)

$$\mu_r p^Y_{ele,r} y^{ele}_{ren,r} = \beta_r p^{CO_2}_r \sum_{fe} bC_{fe,r} \perp \mu_r$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727114

16. Knowledge production function of sector-specific patents for each R&D sub-sector

$$\Delta A_{j,r} = A^{*\omega} A_{j,r}^{\phi} R_{A,j,r}^{\lambda} \perp p_{j,r}^{R\&D}$$

17. The spillovers from the national (average) knowledge stock

$$A_r^* = \sum_j \frac{A_{j,r}}{CARD(j)} \perp p_{A,j,r}^{R\&D}$$

18. The one period cost function for a patent

$$p_{A,j,r}(1 + \mathrm{subs_{jt}}) = \frac{\mathrm{p_{j,r}}}{\lambda A_r^{*\omega} A_{j,r}^{\phi}} \perp y_{i,r}$$

Income balance

$$RA_r = \overline{K_r} v_r + \overline{L_r} w_r + \sum_{xe} \overline{Q_{xe,r}}\, q_{xe,r} + \sum_{tec} \overline{tk_{tec,r}}\, v_{tec,r} + \overline{CO_2}_r p_r^{CO_2} - \mu_r p_{ele,r}^{Y} y_{ren,r}^{ele} + \tau_r \sum_i p_{ele,i,r}^{A}\, y_{i,r} - \psi_r p_{ele,r}^{Y} y_{ren,r}^{ele} \perp RA_r$$

Regional coverage of the model

***Table 7:** Regional coverage of the model*

Main aggregates	Countries or groups of countries
EU regions	Austria (AUT)
	Belgium (BEL)
	Bulgaria (BRG)
	Chechia (CZE)
	Croatia (HRV)
	Denmark (DNK)
	Estonia (EST)
	Finland (FIN)
	France (FRA)

	Germany (DEU)
	Greece and Cyprus (GRC)
	Hungary (HUN)
	Ireland (IRL)
	Italy and Malta (ITA)
	Latvia (LVA)
	Lithuania (LTU)
	Luxemburg (LUX)
	Poland (POL)
	Portugal (PRT)
	Rumania (ROU)
	Slovakia (SVK)
	Slovenia (SVN)
	Spain (ESP)
	Sweden (SWE)
	The Netherlands (NLD)
	United Kingdom (GBR)
Non-EU regions	United States of America (USA)
	Norway (NOR)
	Switzerland (CHE)
	Russia (RUS)
	India (IND)
	Brazil (BRA)
	Rest of the word (ROW)

References

Armington, P. (1969). A theory of demand for products distinguished by place of production. IMF Staff Papers 16, 159-178, Washington, DC, USA.

Badri, N. and T. Walmsley, eds. (2008). The GTAP 7 data base. Purdue University, West Lafayette, Indiana, USA. https://www.gtap.agecon.purdue.edu/ (accessed 08/2011).

Brooke, A., D. Kendrick and A. Meeraus (2010). GAMS: A User's Guide. Tutorial by R. Rosenthal. GAMS Development Corporation, Washington, DC, USA, http://www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf (accessed 08/2011).

This project has received funding from the European Union's Horizon 2020 research and innovation programme
under grant agreement No 727114

Dirkse, S. and M. Ferris (1995). The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems. Optimization Methods and Software 5, 123-156.

Edwards, T.H. and J.P. Hutton (2001). Allocation of carbon permits within a country: a general equilibrium analysis of the United Kingdom. Energy Economics 23(4), 371-386.

Eurostat (2011). European economic indicators. Statistical Offices of the European Union, Luxembourg, http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home.

EXIOPOL (2011), A New Environmental Accounting Framework Using Externality Data and Input-Output Tool for Policy Analysis. Project No. 037033 under the Sixth Framework Programme of the European Commission. Database available at: www.exiobase.eu

Horridge, M. (2005) SplitCom: Programs to disaggregate a GTAP sector. Centre of Policy Studies, Monash University, Melbourne, Australia.

IEO (2013). International Energy Outlook. EIA, US Energy Information Administration, Washington, DC, USA. http://www.eia.doe.gov/oiaf/ieo/

Jensen, J. and T.N. Rasmussen (2000). Allocation of CO2 Permits: A General Equilibrium Analysis of Policy Instruments. Journal of Environmental Economics and Management 40(2), 111-136.

Löschel, A., C. Böhringer, V. Alexeeva-Talebi, J. Kremers and S. Voigt (2009). Broadening the scope of the analysis of the possible risk of Carbon leakage induced by the third revision of the Emission Trading Scheme on Energy Intensive Industries. ZEW, Mannheim, Germany (available upon request).

Okagawa, A. and K. Ban (2008). Estimation of Substitution Elasticities for CGE Models. Osaka University, April 2008. http://www2.econ.osaka-u.ac.jp/library/global/dp/0816.pdf

Ratto, M., Werner R., and Veld J (2009). "QUEST III: An estimated open-economy DSGE model of the euro area with fiscal and monetary policy." *economic Modelling* 26.1: 222-233.

Rutherford, T.F. (1999). Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax. Computational Economics 14, 1-46.

UN (2011a). United Nations Industrial Commodity Statistics Database. USA, http://data.un.org/Browse.aspx?d=ICS.

UN (2011b). United Nations Commodity Trade Statistics Database. USA, http://comtrade.un.org/.