2012/63

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DISCUSSION PAPER

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Sensitivity of policy simulation to benchmark scenarios in CGE models: illustration with carbon leakage

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December 2012

Abstract

In a Computable General Equilibrium (CGE) setting, we show how the cost of a carbon policy for an open economy depends on the assumptions made about future exogenous structural changes. For dynamic CGE models, we propose an analytical framework derived from static CGE models and associate structural changes with the construction of a non-stationary dynamic Social Accounting Matrix (SAM). Such matrices are benchmark scenarios that embed the modelers view on how technologies and preferences should evolve. These benchmark scenarios must be replicable and relevant (by matching what the modeler regards as plausible). To combine these two properties and produce alternative benchmark scenarios, we use partial parameter adjustments and general equilibrium computation. We produce three alternative benchmark scenarios that differ in terms of energy efficiency gains and structural shift in GDP. For each benchmark scenario, we then simulate the GDP deviation induced by a shock on carbon price. We show the dependence of the simulated GDP losses and terms of trade response on the benchmark scenario considered.

Keywords: computable general equilibrium model, non-stationary benchmark scenario, carbon leakage.

JEL Classification: C68, F18, H21, Q52

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Olivier Durand-Lasserve has been financially supported by GDF SUEZ. The opinions expressed are not necessarily those of UCL, IFPEN or GDF SUEZ. The authors would like to thank Dr. Andreas Ehrenmann, Prof. Sebastian Rausch and Prof. Raouf Boucekkine for their very useful suggestions and comments.

1. Introduction

Multi-period computable general equilibrium (CGE) models are widely used for policy analysis, in particular to assess the effect of environmental regulation on economic activity. In these models, the price-induced revenue and substitution effects resulting from a counterfactual policy are combined with calibrated exogenous changes of the structure of the economy. Thus multi-period CGE models where energy is represented include a secular trend in energy intensity, called Autonomous Energy Efficiency Improvement (AEEI), that adds up to the effects of a counterfactual carbon price shock. The AEEI can represent assumed future non-price energy conservation policy and shifts in industrial structure toward less energy intensive activities (Manne and Richels, 1992), but also non-price induced technology-driven energy efficiency gains (Babiker et al., 2001). Therefore, the AEEI can significantly limit the long-term cost of reducing emissions (Manne and Richels, 1992; Webster et al., 2008; Babiker et al., 2008b). In CGE models, technologies and preferences are in general represented with nested CES production functions and, typically, for given elasticities, structural changes are represented by changes over time of the scaling factors (Manne et al., 1995) that weight the contributions to production and utility[2]. Therefore, the calibration of the scaling factors is very important in multi-period CGE models.

However, the calibration is very difficult to justify empirically. The existence of time-varying scaling factors corresponds to the notion of biased (or factor-augmenting) technological change (Hicks, 1963; Acemoglu, 2003), and the attempts of empirical measurement can be found in the related literature. There is no consensus about the values of these scaling factors, or about an approach to estimating them (Henningsen and Henningsen, 2011). As soon as one allow factor-augmenting technological change, several identification problems arise, mainly the separation of total factor productivity, factor augmenting technological change, and elasticities (Léon-Ledesma et al., 2010; Klump et al., 2011). Consequently, in multi-period CGE models, the scaling factors are not calibrated on empirical data but they are adjusted so that the trajectories produced by the general equilibrium model are in line with the modeler's view on how the future might look like. In other words, they are set so as to replicate a trajectory regarded as relevant. Nevertheless, this replication is difficult, especially for dynamic forward-looking CGE models. Here the distinction between forward-looking dynamic CGE models and recursive (myopic) dynamic CGE models is important. This paper especially

[2]In Section 2, the scaling factors are defined in line with (Manne et al., 1995).

deals with forward-looking dynamic CGE models[3] like G-C-Cubed (McKibbin et al., 1999), MS-MRT (Bernstein et al., 1999) and the the dynamic version of the EPPA model (Babiker et al., 2008a). It is also relevant for forward-looking energy-environment-economy applied general equilibrium models such as MERGE (Manne et al., 1995), REMIND (Leimbach et al., 2010), WITCH (Bosetti et al., 2006) and DICE (Nordhaus and Boyer, 1999).

The recursive inter-temporal CGE models[4] can be calibrated using the benchmark point replication method, used for static CGE models, initiated by (Mansur and Whalley, 1982) and further developed and explained by (Rutherford, 1998; Bohringer et al., 2003). In this method, the elasticity parameters are set first and, in general by referring to other models in literature. Then scaling factors are computed so that the demand functions implied by profit or utility maximization (i.e. the conditional demand functions) match the benchmark prices and quantities. In static CGE models the benchmark point is typically a Social Accounting Matrix (SAM), in the inter-temporal recursive case it is a sequence of time-indexed SAM. But the calibration that replicates the sequence of SAM is almost equivalent to the one that replicates each SAM separately (Paltsev, 2004). By construction, a SAM has the circular flow property (Sue Wing, 2004), which preserves value and product and makes it replicable by a static general equilibrium model. Therefore, the SAM is an extremely helpful auxiliary for the calibration of static or recursive models.

The calibration of dynamic CGE models, although based on the same idea of benchmark point replication, is far more problematic, because it cannot rely on simple static SAM. To be replicable by a dynamic CGE model, a SAM has to be dynamic. Essentially, it has to represent not only static but also dynamic circular flows: extending value and product preservation, across the time periods, throughout the entire model's horizon. For instance, the value of an investment should correspond to its rental rate and salvage value. The construction of such a SAM is extremely complex. Moreover, any additional features that increase the linkage between the periods of the model, such as putty-clay production functions (Boucekkine et al., 2008) would represent additional construction difficulties. Finally, in practice the

[3]In the remainder of the paper, we use the term dynamic CGE model for "forward-looking dynamic CGE model"

[4]For instance IMACLIM-R (Quirion et al., 2011; Hamdi-Cherif et al., 2010), EPPA (Paltsev et al., 2005), GEMINI-E3 (Bernard and Vielle, 2009) or GEM-E3 (Proost and Van Regemorter, 2003).

calibration of dynamic general equilibrium models is not based on SAM, which makes difficult the explanation of the calibration procedure. This may explain why there is no clear and documented calibration procedure, with calibration often presented as a sort of "backward engineering exercise" devoted to produce an equilibrium that can be used as a benchmark scenario.

In a dynamic CGE setting, we analyze the sensitivity of the policy assessment to the modeler's expectations about the future. We propose an analytical approach to describe the dynamic CGE calibration process by drawing a parallel with the static CGE calibration procedure. We show how the expectations are formulated and embedded in benchmark scenarios that can be non-stationary (Rutherford, 2009). In such scenarios, relative prices and relative quantities are not constant on the long-run[5], which is the expression of change in technology and preference. In addition, we stress that the dependence between expectations and policy analysis can be associated with the formal notion of sensitivity of the policy simulation results to the benchmark scenario. This sensitivity to benchmark scenario is here illustrated with a dynamic CGE model of carbon leakage model of the French economy. We conduct analyzes of the same policy shock by adopting alternative views on energy efficiency gains and on the share of industry in the economy. We insist that this paper does not aim at bringing a new assessment of the carbon leakage problem. It stresses that every the multi-period general equilibrium model is based on some visions of how preferences and technologies will evolve. It emphasizes that this vision, embedded in the calibration of the model, influences the policy analysis.

In the environmental economics literature, the carbon leakage is in general regarded as the incremental global emission induced by a non-global emission policy (Siebert, 1979). In this paper, we define the carbon leakage problem as the emission policy impact on the activity level of the region where it is implemented and we do not consider the effect on the emissions in other regions. This definition, that ignores the final effect of the policy on environment and restricts the impact evaluation to economic activity is not unusual[6]. In addition, we will consider only the specialization leakage:

[5]Note that we deal with calibration on non-stationary benchmark scenarios, while other authors (Wendner, 1999; Paltsev, 2004) focus on non-steady-state calibration, i.e. a calibration where the initial conditions are not at steady state, but where the economy reaches, after a transition period (where, for instance, the capital intensity is adjusted), a stationary growth path.

[6]The definition has for instance been used by the European Parliament and the Council.

the change in comparative advantages that results from environmental policy and leads to a production cost increase and reallocation of energy-intensive activities in regions with no environmental policy[7]. Last, we put aside the emissions-induced and technological spillover externalities[8].

In next section we show that in dynamic CGE models the calibration of scaling factors is associated with the construction of a benchmark scenario that embeds the modeler's view on how technologies and preferences should evolve. In addition we introduce the notion of sensitivity to a benchmark scenario. The subsequent sections provide illustrate a sensitivity analysis to benchmark scenarios with a dynamic CGE model addressing the issue of carbon leakage for the French economy. The model is described in Section 3. In section 4, we explain the construction of alternative benchmark scenarios that differ in terms of energy efficiency gains and sectoral structure of GDP. Finally, in section 5, we compare the responsiveness of sectoral value added and GDP to a change in carbon price for three alternative benchmark scenarios. We emphasis the differences in GDP and terms of trade response. The last section concludes.

2. Calibration of dynamic CGE models on a non-stationary benchmark scenarios

To ease the analytical presentation, we consider the class of dynamic CGE models with Constant Elasticity of Substitution (CES) production functions, logarithmic inter-temporal utility functions and non-zero prices and quantities. However, as already mentioned in the introduction, what is presented in this paper is relevant for several dynamic applied general equilibrium models.

The EU ETS Directives (EU, 2003, 2009) stipulate that the sectors deemed to be exposed to a significant risk of carbon leakage will receive relatively more free allowances than other sectors. The sectors or sub-sectors are regarded as deemed to be exposed to a significant risk of carbon leakage on the basis of sensitiveness of the production cost to the carbon prices and openness to non-EU trade.

[7]Marschinski et al. (2009), defined two other canals of carbon leakage: the free-riding and the supply-side leakage. The free-riding leakage is due to the incentive by a region to lower provision (more emissions) for the public good (the atmospheric CO_2 concentrations) if other regions decide to reduce their emissions. The supply-side leakage relates to the negative effect of mitigation policies on fossil fuel prices that may cause a rebound of fossil fuel consumption in non signatory regions.

[8]The literature about technological spillovers (Di Maria and van der Werf, 2008) puts forward, the contribution of policy-induced technological changes and technology diffusion to limiting the carbon leakage.

2.1. Scaling factors in dynamic CGE models

We use a general representation of CGE models in line with Rutherford (2009), where we define V as the concatenation of variables representing quantities, prices and household revenues.
The general equilibrium conditions can be represented by a system of equations[9] linking a vector V to a policy instrument vector τ (e.g a tax rate):

$$H(V, \tau, a, \Sigma) = 0 \tag{1}$$

This system is parameterized by values that take into account preferences and technologies: a vector Σ of elasticities of substitution and a vector a of time-dependent scaling factors. The scaling factors are multiplicative parameters that: (i) weight the inputs in a production function and (ii) weight the instantaneous utilities in the inter-temporal utility function.

To give a concrete view of what the scaling factors are, we consider a model with T time periods. We note N the set of production sectors (industries) and J the set of commodities and factors used as inputs.
If the technologies are CES, they can be represented as:

$$Z_{i,t} = \left[\sum_k a_{i,k,t} Q_{i,k,t}^{\frac{\sigma_i - 1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i - 1}}, \quad i \in N, \quad k \in J \tag{2}$$

Where $Z_{i,t}$ is sector i output and $Q_{i,k,t}$ is sector i input of type k.
If the inter-temporal utility function is logarithmic, we have:

$$\mathcal{W} = \sum_{t=1}^{T} \beta_t \log C_t \tag{3}$$

Without loss of generality, we add the restriction $\sum \beta_t = 1$. The scaling factors vector a is defined as:

$$a = (a_{i,k,t}, \beta_t)_{i \in N, k \in J, t \leq T} \tag{4}$$

[9]We here consider that the general equilibrium is formulated in the Mixed Complementarity Problem (MCP) form proposed by Mathiesen (1985).

$$0 \leq H(V, \bar{\tau}, a, \Sigma) \perp V \geq 0$$

The Mathiesen MCP formulation allows for idle capacity (zero production) and zero prices. It is therefore fit to deal with problems where constraints are occasionally binding. In our model $V > 0$ at equilibrium, therefore the solutions of the MCP and the SNE (H=0) are equivalent.

The evolution of the scaling factors through time typically takes into account the increase in demographic growth and the increase in labor productivity. But more generally it reflects the evolution of technologies ($a_{i,j,k}$) and preferences (β_t), i.e. changes in consumption and input demand that are not price induced. For instance, in energy-economy models, the autonomous energy efficiency improvements (AEEI), that represent non price-induces changes in energy demand, are modeled through variations of the scaling factors associated with the energy inputs.

Policy analysis in CGE models is based on evaluating the dependence of V to the policy parameter τ. This evaluation is typically assessed by comparing the results of a benchmark policy to counterfactual (alternative) policies. The differences obtained are indeed contingent to the scaling factors chosen. In order to understand this dependence we have to describe how the scaling factors are calibrated.

2.2. CGE model calibration on a benchmark scenario

The possible calibration procedures for CGE models are presented in Figure 1. The empirical estimation of the elasticity parameters and scaling factors, presented in column 1, is difficult, as stressed in the introduction of this paper. Because of these difficulties, CGE models calibration is based on a the benchmark points calibration method presented in columns 2 and 3.

The elasticity parameters are chosen *a priori*, if possible from the literature, but very often by the rule of thumb. A benchmark scenario, noted ($\bar{V}$,$\bar{\tau}$) is set *a priori* and the scaling factors are adjusted so as to match with this scenario. Therefore, they are an implicit function of this benchmark.

$$a = a(\bar{\tau}, \bar{V}, \Sigma) \tag{5}$$

The scaling factors are computed so that the conditional input demands in the various industrial sectors and the Marshallian demand functions of the household replicate the benchmark. From equations (2) and (3), these functions are[10]:

$$Q_{i,k,t} = a_{i,k,t}^{\sigma_i} \left(\frac{\pi_{i,t}}{\pi_{k,t}} \right)^{\sigma_i} Z_{i,t}$$
$$C_t = \beta_t M / \pi_t$$

[10]See Varian (1992).

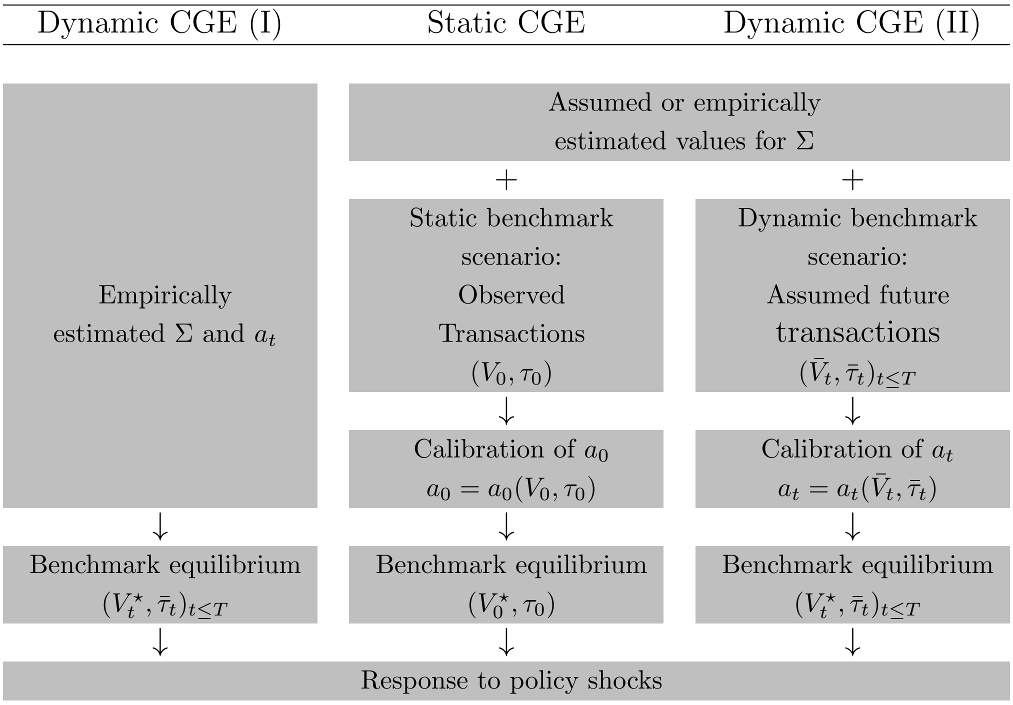

Figure 1: Calibration of CGE models

where π_i is the price of sector i output, π_k is the price of input k, M is the present-value sum of household's incomes and π_c is the present value price of the consumption good price at period t. If assigning to the variables their benchmark values, we can easily identify the scaling factors:

$$a_{i,k,t} = \left(\frac{\bar{\pi}_{k,t} \bar{Q}_{i,k,t}}{\bar{\pi}_{i,t} \bar{Z}_{i,t}} \right) \left(\frac{\bar{Z}_i}{\bar{Q}_{i,k,t}} \right)^{\frac{\sigma_i - 1}{\sigma_i}}, \qquad \beta_t = \frac{\bar{\pi}_{c,t} \bar{C}_t}{\bar{M}}$$

Once the scaling factors are obtained, the general equilibrium is solved and counterfactual policies can be simulated. However, before conducting counterfactual policy analysis, it is natural to wonder whether in the benchmark policy case (i.e. when $\tau = \bar{\tau}$) the equilibrium replicates the benchmark scenario.

In the static case, the benchmark scenario is in general a SAM. By definition, a SAM is a collection of observed transaction data (V_0, τ_0) that meet a circular flow property (Sue Wing, 2004). This property ensures the conservation of value and quantity. More precisely, that the household's revenue is equal to the value of its factor endowments, that firms' activities yield zero profits (the value of output must be equal to the value of inputs) and that demand is equals supply for the various commodities. The circular flow property of the SAM ensures that they are replicated at equilibrium in the benchmark policy case (replication check).

$$H(\bar{V}, \bar{\tau}, a(\bar{V}, \bar{\tau}, \Sigma), \Sigma) = 0 \tag{6}$$

That is the reason why the SAM are very helpful auxiliary for CGE modelers and why we can consider that, once the elasticity parameters are set the calibration of CGE model is almost equivalent to the construction of SAM.

2.3. Benchmark scenarios as replicable and relevant scenarios

Dynamic calibration is based on the same idea of replicating a benchmark scenario set $(\bar{V}_t, \bar{\tau}_t)$ that represents relevant future transactions, i.e, a relevant evolution of the structure of the economy.
The difficulty is that one cannot rely on a SAM as in the static case to ensure replicability, one has to extend the notion of SAM and replicability to a dynamic setting. In addition the transaction information we need is not only observed, but also projected data, and the corresponding view on how the economy will evolve must make sense. We call replicability and relevance these two requirement for the benchmark scenario. If defining SC_{REP} and SC_{REL} as the spaces of replicable and relevant scenarios, a benchmark scenario $(\bar{V}, \bar{\tau})$ must be such that:

$$(\bar{V}, \bar{\tau}) \in SC_{REP} \cap SC_{REL}$$

The properties of SC_{REP} can be defined by purely mathematical conditions. However, the set SC_{REL} is a univocal construction of the modeler.

2.3.1. Replicability

Replicability conditions are basically the extension of the static circular flows property that characterize SAM to transactions involving inter-temporal flows of product and value, such as lending and borrowing behaviors. In other words, a dynamic replicable scenario is an inter-temporal SAM. The more inter-temporal constraints in the model, the most difficult the dynamic SAM construction is. In addition, unlike static SAM an inter-temporal SAM, must contain not only monetary values, but it has also to specify price system to disentangle real and nominal changes through time[11].
Mathematically, the set of replicable scenario S_{REP} is defined as:

$$SC_{REP} \equiv \{(\bar{V}, \bar{\tau}) \text{ such that there exists } a \text{ that solves } \; H(\bar{V}, \bar{\tau}, a, \Sigma) = 0\} \tag{7}$$

[11] In static model, real and nominal values can be regarded as equivalent, by setting arbitrarily the prices to 1.

If the parameter a is free, the problem $H(V, \tau, a, \Sigma) = 0$ has as much equations as the general equilibrium problem (1), but it has as many additional variables as there are of scaling factors. If there are numerous scaling factors, the dimension of SC_{REP} is potentially high. In addition, the set SC_{REP} is typically non convex, because (1) is not convex.

2.3.2. Relevance

The data set must contain a full time path of future, and therefore assumed, transactions between agents. It is very difficult to assess the relevance of such assumptions. In general the relevance is regarded as the similarity with external projections. Very often, the benchmark is made so as to be consistent with projections delivered by the most reliable or informed sources such as, for energy, the IEA World Energy Outlook or the EIA International Energy Outlook.
In multi-models exercises of policy simulation, such as Clarke et al. (2009) or USCCSP (2007), the benchmark is based on a common pool of assumptions. However, if there are no projections available, the modeler has to rely on more personal assumptions.

The set of relevant scenarios can be seen as:

$$SC_{REL} = \{(\bar{V}, \bar{\tau}) \text{ such that } H_{REL}(\bar{V}, \bar{\tau}, B) \leq 0\}$$

Where the mapping H_{REL} and the parameters B are defined by the modeler. In large scale models, it is difficult in practice to translate the relevance conditions from external projections to H_{REL} and B. In addition, the over-specification of the system can lead to non-compatibility with replicability conditions.

2.3.3. Combining replicability and relevance

If using this definition of relevance, the computation of a replicable and relevant scenario (equation 7), is equivalent to searching $(\bar{V}, \bar{\tau})$ such that:

$$(\bar{V}, \bar{\tau}) \in SC_{REP} \tag{8}$$

$$H_{REL}(\bar{V}, \bar{\tau}, B) \leq 0 \tag{9}$$

There is no guarantee that such a $(\bar{V}, \bar{\tau})$ exists. It does not if, for example,(9) is over determined by constraints and bounds. However, if (9) is not sufficiently determined, the only scenarios solving equations (8) and (9) are an economically absurd scenario (e.g. extreme values). One need to have a system (H_{REP}, B) sufficiently large to rule out all the "non-relevant" cases such as extreme values, or erratic variations, without the background of the

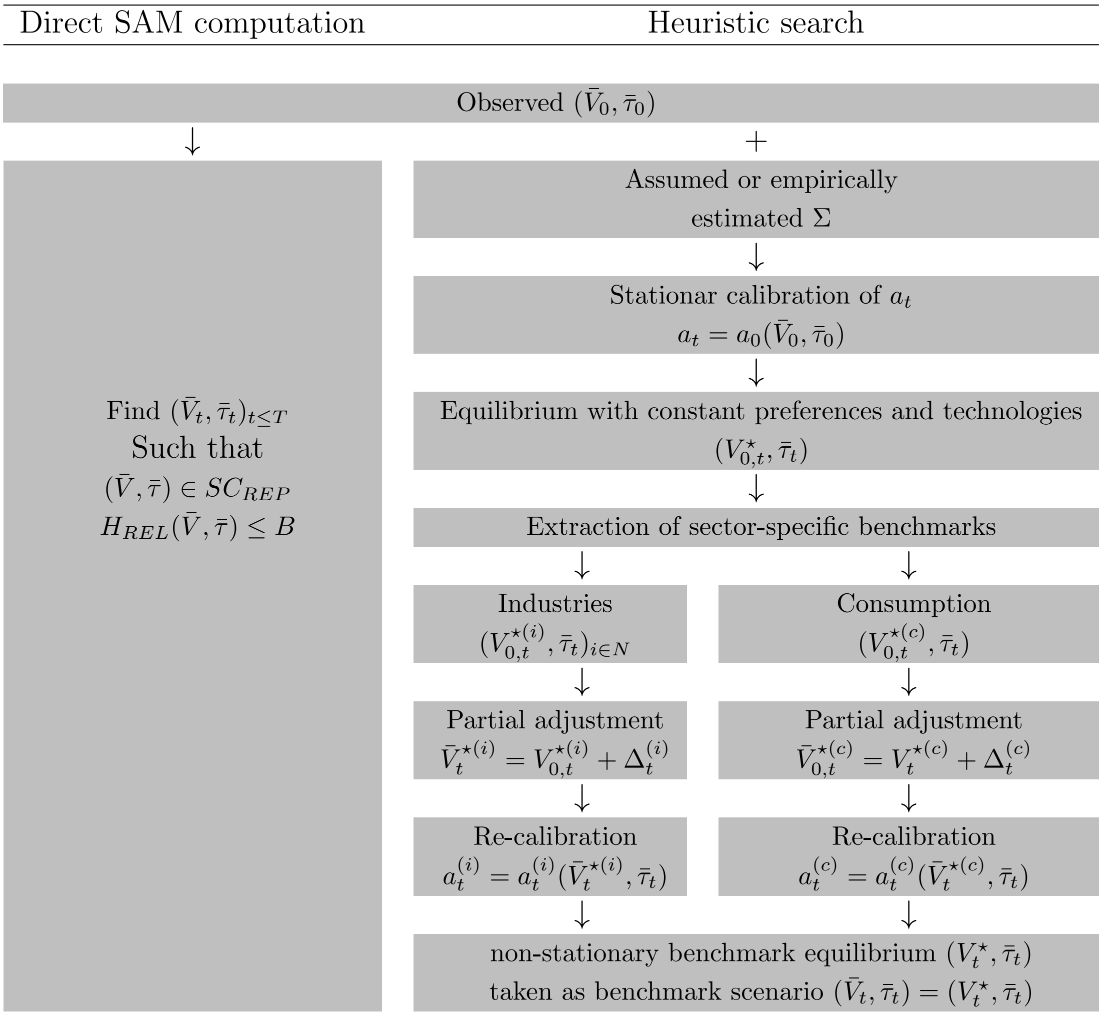

Figure 2: Computation of dynamic SAM

theoretical properties of economic models. Therefore, the specification of (H_{REP}, B) must be exhaustive. The problem $H_{REP} \leq B$ can have more equations than $H = 0$. In addition, the risk of over-specification increases.

2.4. Heuristic search

Another approach avoids the daunting task of specifying mathematical conditions for SC_{REL}. It consists in specifying scaling factors and solving problem 1 to generate replicable scenario and in adjusting these factors so as to attain a relevant replicable scenario. This is the method used in practice by applied general equilibrium modelers. It is presented in Figure 2.

First, a scenario $(V^{\star}_{0,t}, \bar{\tau}_t)$ with constant preferences and technologies is generated by calibrating all the scaling factors on a base-year SAM. The partial benchmark scenarios, one for each industry and one for the representative consumer, are extracted from $(V^{\star}_{0,t}, \bar{\tau}_t)$. They are noted $(V_t^{\star(i)}, \bar{\tau}_t)_{i \in N}$ for industries and $(V_t^{\star(c)}, \bar{\tau}_t)$ for the consumer. The partial benchmark scenarios are independently adjusted by means of user-defined shifts $(\Delta_t^{(i)})_{i \in N}$ and $\Delta_t^{(c)}$. They reflect the modeler's beliefs about the changes in input intensity and consumption profiles that are not price-induced, but that are due to changes in technologies and preferences.
Scaling factors are re-computed, on the basis of the readjusted partial benchmarks, and the CGE model is solved. The general equilibrium outcome takes into account the changes in technologies preference. This equilibrium scenario can be used as a benchmark scenario. By definition, it is replicable. In addition, it conveys the modeler's assumptions expressed into Δ. The re-adjusted sectoral benchmarks are not necessarily replicated. But appropriate choice of Δ allows the modeler to obtain a benchmark scenario that approaches the non-stationary dynamics he desired, at least in terms of the sign of direction of changes in input intensity.

This principle, although rarely documented, is very often used by dynamic applied equilibrium modelers, where playing with sectorial benchmark data is the key for attaining a satisfactory benchmark scenario.

2.5. Dependence of the policy response to the benchmark scenario

To conclude these theoretical considerations we can show how the benchmark scenario influences policy analysis in a dynamic CGE model.

The general equilibrium V with the counterfactual policy τ solves:

$$H(V, \tau, a(\bar{V}, \bar{\tau}, \Sigma), \Sigma) = 0$$

If the user-defined benchmark scenario is $(\bar{V}, \bar{\tau})$, it is replicated in the benchmark policy case $(\tau = \bar{\tau})$:

$$H(\bar{V}, \bar{\tau}, a(\bar{V}, \bar{\tau}, \Sigma), \Sigma) = 0$$

When writing the scaling factors as functions of the benchmark scenario and the elasticities, we obtain a normalized-form model. In this formulation, the variables and policies instruments are expressed in terms of ratio with respect to the benchmark scenario values. Note that this normalized formulation can be more directly implemented, by expressing the various functions of the model in calibrated share form. The calibrated share forms are very useful for formulating CGE models (Rutherford, 1998). More recently, the normalized form have been widely used for deriving the analytical properties of dynamic growth model with CES production functions (Klump and Preissler, 2000; Klump and de La Grandville, 2000; Klump and Saam, 2006).
The normalized form of the model can be written as:

$$H'(\frac{V}{\bar{V}}, \frac{\tau}{\bar{\tau}}, \bar{V}, \bar{\tau}, \Sigma) = 0 \tag{10}$$

By (10), we can see that the deviation form the benchmark $(\frac{V}{\bar{V}})$ is an implicit function of the policy deviation $(\frac{\tau}{\bar{\tau}})$. If we note this implicit function $\mathcal{H}$, and if we define it from the space of the possible deviation to the space of the possible general equilibrium outcome, we have:

$$\mathcal{H}_{\bar{V},\bar{\tau},\Sigma} : \frac{\tau}{\bar{\tau}} \quad \mapsto \quad \frac{V}{\bar{V}} \tag{11}$$

This implicit function is parameterized by the benchmark scenario path and by the elasticities. Therefore the model simulates the deviation from a benchmark scenario responding to a deviation in the value of the policy instrument, for given (i) elasticity parameters Σ and (ii) benchmark scenario $(\bar{V}, \bar{\tau})$.
Note that in the benchmark policy case, there are no deviations from the benchmark scenario, and from equation (10) we have:

$$\mathcal{H}_{\bar{V},\bar{\tau},\Sigma}(1) = 1$$

This is the equivalent in terms of deviation of the replication check.

As the model is dynamic, equation (11) does not describe only intra-period propagation of the policy shock in the economy, but also, how the shock propagates through time. If adding time indexes, (11) becomes:

$$\mathcal{H}_{\bar{V}_0,...,\bar{V}_T,\bar{\tau}_0,...,\bar{\tau}_T,\Sigma} : \quad (1, \frac{\tau_1}{\bar{\tau}_1}, ...\frac{\tau_T}{\bar{\tau}_T}) \quad \mapsto \quad (1, \frac{V_1}{\bar{V}_1}, ..., \frac{V_T}{\bar{V}_T}) \tag{12}$$

The function $\mathcal{H}$ can be interpreted as a response function, giving the dynamics, of the economy's response to a change in the policy instrument trajectory. The magnitude of the deviation caused by a change in policy depends on the present and the assumed future structure of the economy $(\bar{V}_0, ..., \bar{V}_T, \bar{\tau}_0, ..., \bar{\tau}_T)$ chosen as a benchmark scenario. The intuitive explanation is that while, in static CGE models, the response to the policy shock depends on the structure of the economy at a given period used as a benchmark, in dynamic CGE models the response to the policy shock depends on the benchmark scenario that indicates how the structure of the economy is expected to evolve.

3. Model description

We specify a dynamic CGE model (McKibbin et al., 1999; Balistreri and Rutherford, 2001; Bernstein et al., 1999; Babiker et al., 2008a) of an open economy with three production sectors and four commodities. The rest of the world is represented in a generic way, by specifying import supply functions and export demand functions for the various commodities (Boadway and Treddenick, 1978). We model asymmetric climate policy by introducing an exogenous carbon price in the model with no effect on the import supply and export demand functions. This price can be interpreted as a tax or as the market price of carbon resulting from a cap-and-trade system.

We consider an economy with a representative household, four goods (indexed by j) and three industrial sectors (indexed by i). Time is indexed by t. The goods are fossil energy (f), electric energy (e), energy-intensive goods (is) and non energy-intensive goods (ns). The input-output structure of the economy is summarized in Table 1. The rows represent goods, the columns represent industrial sectors. The cells with a zero value are in gray. There is a domestic production sector for electric energy, energy-intensive and non energy-intensive goods but not for fossil energy which is totally imported. In addition, there is international trade of the energy and non energy-intensive goods. Following the Armington paradigm (Armington, 1969), the products are distinguished by their place of production. The production activities in the industrial sectors require intermediate consumption, capital and labor.

<table>
<tr><td colspan="3" rowspan="2">Resources</td><td colspan="3" rowspan="2">Int. Cons.</td><td colspan="5">Final Use</td></tr>
<tr><td colspan="2"></td><td colspan="3">Capital</td></tr>
<tr><td></td><td>Imported</td><td>Domestic</td><td>e</td><td>is</td><td>ns</td><td>Cons.</td><td>Export</td><td>e</td><td>is</td><td>ns</td></tr>
<tr><td>f</td><td></td><td bgcolor="gray"></td><td></td><td></td><td></td><td></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td bgcolor="gray"></td><td bgcolor="gray"></td></tr>
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</table>

Table 1: Table of resource and use in product

The capital is sector specific. It is a mix of energy-intensive and non energy-intensive goods bundled in fixed (exogenous) proportions. The labor mobility between the sectors is limited.

The variables of the model are listed in Appendix A. For the details of the general equilibrium conditions, the reader can refer to Appendix C.

3.1. Production functions and vintages

The adjustment of an economy to changes in energy prices is limited on the short run by the technology choices previously made. In our model, this effect is captured by putty-clay production functions (Boucekkine et al., 2008). We consider that production comes from different vintages of equipment. At each period, the producer chooses the capacity and the input mix on the basis of a production function representing the technologies available. Then the proportion of inputs remains fixed for the following periods. For simplification, we consider that all the equipment decay with the same exogenous exponential rate, i.e. at each period (Manne et al. (1995)), a fraction δ of the equipment is decayed.

For the three industrial sectors the technologies available for each vintage are represented by CES production functions. In each sector i, each vintage can produce an output $z_{i,t}$ using intermediate goods ($x_{i,j,t}$), capital ($k_{i,t}$) and efficient labor ($l_{i,t}$).

The total industry-specific intermediate good, capital, and efficient labor demand are noted $X_{i,j,t}$, $K_{i,t}$ and $L_{i,t}$. The total output is noted $Z_{i,t}$ and J_i is the set of goods used as intermediate consumptions in sector i. The production technology in sector i can be represented as:

$$z_{i,t} = \left[\sum_{j \in J_i} a_{(prod),i,j,t} x_{i,j,t}^{\frac{\sigma_i - 1}{\sigma_i}} + a_{(prod),i,L,t} l_{i,t}^{\frac{\sigma_i - 1}{\sigma_i}} + a_{(prod),i,K,t} k_{i,t}^{\frac{\sigma_i - 1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i - 1}} \qquad i = e, is, ns \tag{13}$$

The dynamics of input and output is:

$$
\begin{aligned}
Z_{i,t+1} = Z_{i,t}(1-\delta) + z_{i,t+1} \quad &, \quad X_{i,j,t+1} = X_{i,j,t}(1-\delta) + x_{i,j,t+1} \\
K_{i,t+1} = K_{i,t}(1-\delta) + k_{i,t+1} \quad &, \quad L_{i,t+1} = L_{i,t}(1-\delta) + l_{i,t+1}
\end{aligned}
$$

The long-term elasticity of substitution is σ_i. Higher σ_i implies more possibilities of substitution between the different inputs, in particular between the energy and non-energy inputs. Therefore, this parameter has an important influence on the ability of the sector to adapt to changes in the energy market with little added-value losses. The parameters $a_{(prod)}$ are scaling factors which represent exogenous increase of the productivity of the different inputs and in particular the AEEI dynamics.

The investment good for each sector is produced from energy-intensive and non-energy intensive goods combined throught a Leontief technology. If IV denotes the quantities of energy-intensive and non energy-intensive goods assigned to the production of the goods I, we have:

$$
I_{i,t} = \min_{IV} \left\{ a_{(capital),i,is,t} IV_{i,is,t}, a_{(capital),i,ns,t} IV_{i,ns,t} \right\} \quad j = e, is, ns \tag{14}
$$

The parameters $a_{(capital)}$ are scaling factors reflecting the productivity of the energy-intensive and non energy-intensive inputs in capital production.

The consumption good, noted U_t, is a composite of the various goods: fossil fuels, electricity, energy-intensive and non energy-intensive goods which are combined through a CES production function. If we note $C_{j,t}$ the quantity of good j included in the composite good at time t, we have:

$$
U_t = \left[\sum_j a_{(cons),j,t} C_{j,t}^{\frac{\sigma_{C,j}-1}{\sigma_{C,j}}} \right]^{\frac{\sigma_{C,j}}{\sigma_{C,j}-1}} \tag{15}
$$

The scaling factors $a_{(cons),j,t}$ represent the relative preferences of the households for the various goods and $\sigma_{C,j}$ is the household's elasticity of substitution between the various goods.

3.2. Foreign trade

The energy and non-energy intensive goods can be supplied by the domestic industry or imported. Following the Armington paradigm, we assume that there is imperfect substitutability between the imported (IM) and the domestic product (Z). The quantity Y of good available to the French economy is given by:

$$Y_{j,t} = \left[a_{(dom),j,t} Z_{j,t}^{\frac{\sigma_{Y,j}-1}{\sigma_{Y,j}}} + a_{(for),j,t} IM_{j,t}^{\frac{\sigma_{Y,j}-1}{\sigma_{Y,j}}} \right]^{\frac{\sigma_{Y,j}}{\sigma_{Y,j}-1}} \quad j = is, is \tag{16}$$

Where $\sigma_{Y,j}$ is the Armington elasticity . If $\sigma_{Y,j}$ is high, small changes in domestic prices can lead to an important switch of consumption towards the foreign goods. $\sigma_{Y,j}$ can be also regarded as a measure of good's homogeneity. The higher the $\sigma_{Y,j}$, the more homogenous domestic and foreign goods are. A high $\sigma_{Y,j}$ implies a higher response of the industry to changes in input prices as less differentiation increases the cost competition. The parameters $a_{(dom)}$ and $a_{(for)}$ are scaling factors reflecting the preferences for the domestic and foreign products.

The various products can be imported or exported. We use a closed-form representation of the rest-of-the world. It intervenes in the model by means of foreign supply functions (supply for import) and foreign demand of domestic goods (demand for exports). Such specifications were introduced by Boadway and Treddenick (1978) and are discussed in Goulder et al. (1983). The supply for imports represents the way the foreign price can be influenced by an increase in the domestic demand. The prices of imported and exported goods $PIWC_{j,t}$ and $PDWC_{j,t}$ are expressed in foreign currencies and in current values considering the following relation:

$$IM_{j,t} = a_{(im),j,t} PIWC_{j,t}^{\sigma_{IM,j}} \quad , \quad j = is, ns \tag{17}$$

The parameter $\sigma_{IM,j}$ is the price elasticity of import supply. As we will consider a small economy (France), the domestic demand weights little in the global demand and won't affect the price of non-domestic products j. In this case, it is reasonable to assume a high $\sigma_{IM,j}$, since $\sigma_{IM,j}$ is related albeit not straightforwardly to the price elasticity of supply for foreign goods. The parameters a_{im} are scaling factors representing the ability of foreign producers to supply the domestic market for a given price. Note that there is no supply for import of fossil fuel as we assumed exogenous fossil fuel prices.
The demand for exports (rest of the world demand for exports) is a decreasing function of the export price.

$$EX_{j,t} = a_{(ex),j,t} PDWC_{j,t}^{-\sigma_{EX,j}} \quad , \quad j = is, is \tag{18}$$

The parameter $\sigma_{EX,j}$ represents the price elasticity of foreign demand to domestic price. A high value of $\sigma_{EX,j}$ means that if the price of the domestic product increases, there will be an important decrease in foreign demand. Therefore, $\sigma_{EX,j}$ can be interpreted as a parameter measuring the degree of differentiation between the French good on the foreign market. The parameters, $a_{(ex)}$ are scaling factors representing the propensity of the foreign economies to consume French products for a given domestic product price.

We assume an exogenous trade balance deficit noted $D\bar{E}F_t$ at each period.

$$D\bar{E}F_t = \sum_{j=f,is,ns} PIWC_{j,t} \cdot IM_{j,t} - \sum_{j=is,ns} PDWC_{j,t} \cdot EX_{j,t} \qquad (19)$$

The trade deficit, denoted $D\bar{E}F_t$, is expressed in current foreign currencies. It corresponds to the foreign savings directed to the French economy. In the rest of the paper we will call it indifferently trade deficit or foreign savings. The exogenous trade balance is respected through the adjustment of an exogenous exchange rate noted EXR_t that represents the terms of trade.

3.3. CO_2 emissions

The CO_2 emissions (EM) in this economy are proportional to the total use of fossil energy (from the households and the industrial sectors). If er is the emission rate of the fossil energy, we have:

$$EM_t = er \left[\sum_i X_{i,f,t} + C_{f,t} \right]$$

The use of non-electric energy causes CO_2 emissions which are submitted to a tax $TAX_{co_2,t}$ whose revenues are lump-sum transfers to the households. Note that the only means to decrease emissions is to decrease fossil/fuel consumption. Emissions are proportional to fossil fuel consumption and imports in the model.

3.4. Utility function

The household's preferences are represented by an inter-temporal time separable utility functions $\mathcal{W}$:

$$\mathcal{W} = \sum_t \beta_t \log U_t, \qquad \sum_t \beta_t = 1 \qquad (20)$$

The parameter β is the social discount factor. The households maximize their utility under inter-temporal budget constraints. The logarithmic inter-temporal utility function corresponds to an elasticity of saving with respect to the interest rate equal to 1. Moreover, with a monotonous transformation (state the expression in exponential), the function becomes Cobb-Douglas, with β_t the value-share of each period's discounted consumption expenses HC_t in total discounted consumption expenses E. Therefore at the household's optimum, we have:

$$HC_t \equiv PU_t U_t = \beta_t E \tag{21}$$

3.5. Limited labor mobility

The household is endowed with an exogenous total labor $L\bar{T}O$ quantity and thus the total labor $l\bar{t}o_{t+1}$ newly available is also exogenous:

$$lto_{t+1} = l\bar{t}o_{t+1} = L\bar{T}O_{t+1} - (1-\delta)L\bar{T}O_t \tag{22}$$

To represent sector-specific marginal productivity of labor at equilibrium (Casas, 1984), we limit the labor mobility between the industrial sectors. We link $l\bar{t}o$ and the labor quantity l_i endogenously allocated to the industrial sectors by using constant elasticity of transformation (CET) functions (Horvath, 2000):

$$l\bar{t}o_t = \left[\sum_i a_{(labor),i,t} l_{i,t}^{\frac{\sigma_L+1}{\sigma_L}} \right]^{\frac{\sigma_L}{\sigma_L+1}} \tag{23}$$

The parameter σ_L represents the elasticity of substitution between labor from the different sectors. In the limit cases, when $\sigma_L = 0$ there is no labor mobility, when $\sigma_L = +\infty$ the labor mobility is perfect. The scaling factors $a_{(labor),i,t}$ represent the weights of the various sectors in the efficient labor supply.

Once the household has chosen to put efficient labor l in a vintage, this labor is bound to the vintage and decreases at the exogenous rate of decay, so that we can write the recursive formula:

$$L_{i,t+1} = (1-\delta)L_{i,t} + l_{i,t+1}, \qquad i = e, is, ns \tag{24}$$

Note that in this representation, when one unit of labor is assigned to a sector, it cannot move to another sector later on. This restriction adds up to the limited labor mobility involved by the CET representation.

The general equilibrium conditions are specified in Appendix C. The problem obtained has 5801 variables and 5801 constraints. The numerical computation is done with GAMS and the CONOPT3 solver (Drud, 1996)[12].

4. Generation of alternative benchmark scenarios

The model contains several macroeconomic functions, therefore several scaling factors that have to be calibrated (see Table D.7). We calibrate the scaling factors on three alternative benchmark scenarios representing alternative evolutions of the French economy. In the first benchmark scenario, we assume no technological changes or preference changes. In the second scenario the technological change improves the energy efficiency. In the last scenario, the share of energy-intensive activities in GDP decreases through time.
These scenarios are generated using the partial adjustment method presented in Section 2. First, we construct a base year SAM and we set the elasticity parameters, then we calibrate the model on a base year. We operate shifts on the sectoral scenario reflecting the expected structural change. Finally, we recalibrate the scaling factors and obtain a benchmark scenario that takes into account our assumptions.

4.1. Base-year data

The base-year data can be summarized in different tables. Table 2 shows the aggregated resource and use in products. It merely represents for each product j the accounting relationship between the value of the product available (rows "resource in products"), and the different uses as intermediate consumptions (in the rows "intermediate consumption"), final household consumption, export and use for capital accumulation (in the rows "final use in products"). This table, contains values in billions euros that were computed from very disaggregated data available on the Eurostat Website[13]. Note that these data are for 2007, but they will be used as a proxy for 2010 that is the base year of our model. By definition, the Gross Domestic Product is equal to the sum of sectoral added-values (output minus intermediate consumptions). In 2007, it is equal to 1641 billion euros $(1657+434-3,5-258-188)$

The energy-intensive sector added value represents 18% of the GDP $(100\times (251+298-258)/1641$, but it weights for more than 50% of the intermediate fossil fuel consumption $(100 \times (25)/(3.5+25+21))$. The share of electricity

[12]As an alternative, one could have tried to write and solve the model using GAMS/MPSGE (Rutherford, 1998) and the PATH solver (Dirkse and Ferris, 1995)
[13]$http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks$

intermediate consumption used in the is sector is 36% $(100 \times (7)/(7+12))$. In addition, Table 2 shows that the energy consumption is more balanced between firms and households for electricity energy than for fossil fuels.

The fossil fuel expenses are very limited in the electricity sector (3.5 billion euros for an electricity output of 37.22 billions euros). This is explained by the extreme predominance of nuclear in the French power production capacity (about 78% of the power production is from nuclear). Therefore, we can expect a very limited effect of CO_2 tax on the power price.

In order to compute base-year quantities corresponding to the base-year expenses, we have to introduce a price system. By convention, we set the base-year price of the *is* and *ns* goods and products to 1. This is equivalent to consider a price index to compute real values from nominal values. The level of the base-year index is not important for *is* and *ns* goods and products, since they are macroeconomic aggregates without specific measurement units. However, for electricity and non-electric energy, which can be regarded as physical variables, it is important to preserve units, in particular as we need to relate the carbon tax to the fossil-fuel energy price. In order to match the energy data of France taken from Eurostat, we have chosen a base-year price of 12 Euros per GJ of fossil fuels and 70 euros per MWh for power price, as shown in Table 3.

Base-year sectoral wage rates and labor breakdown are shown on Table 4. The energy intensive sector represents 11% of the labor. There are significant wage differences between the sectors. Wages are higher in the electric and energy-intensive sectors than in the non energy-intensive sector.
Assuming a 5% rate of decay and a given sectoral growth of capital, the base-year capital stocks in the various sectors can be inferred from the base-year investment in these sectors.
For simplification, we have not taken into account the CO_2 tax for the base year. The values assigned to the various elasticity parameters are presented in Tables 5.

4.2. Three alternative benchmark scenarios

The sensitivity analysis is conducted by comparing the outcomes from 3 benchmark scenarios based on 3 alternative expectations. The scenarios are presented in Table 6. They were build with the partial adjustment method. Therefore, their content has not been fully controlled. However, with this method, it has been possible to build scenarios that represent very different possible evolutions of the structure of the economy in terms of energy prices,

	resource in products		intermediate consumption		
	$PI_j IM_j$	$PD_j ZD_j$	$P_e X_{e,j}$	$P_{is} X_{is,j}$	$P_{is} X_{ns,j}$
f	74.45		3.5	25	21
e		37.22		7	12
is	294	251			155
ns	124	1368		226	
total	492	1657	3.5	258	188

	final use in products				
	$P_j C_j$	$PD_j EX_j$	$PV_e IV_{e,j}$	$PV_{is} IV_{is,j}$	$PV_{ns} IV_{ns,j}$
f	25.26				
e	17.63				
is	148	298	4	34.8	203
ns	1157	136	1.8	15.64	91
total	1348	434	5.8	50.47	295

Notes: the values are in billion current 2007 euros.

Source: Eurostat and authors' computation

Table 2: Resource and use in products for the French economy in 2007

	base-year prices			
	PI_j	PD_j	P_j	PV_j
f	12^a			
e		70^b	70^b	1
is	1	1	1	1
ns	1	1	1	1

Note: ^{a} in Euro per GJ .

^{b} in Euro per MWh.

Table 3: Base-year price system

	labor market	
	W_i^a	L_i^b
e	67.83	0.118
is	45.47	2.81
ns	35.69	22.4

Note: ^{a} in thousands Euro per year .

^{b} in million workers.

Table 4: Base-year labour force and average annual wage

Elasticity	Value
σ_e	0.2
σ_{is}	0.2
σ_{ns}	0.7
$\sigma_{Y,is}$	2
$\sigma_{Y,ns}$	0.8
$\sigma_{IM,is}$	10
$\sigma_{IM,ns}$	10
$\sigma_{EX,is}$	5
$\sigma_{EX,ns}$	2
σ_C	0.8
σ_L	1

Table 5: Elasticity values

sector-specific AEEI, sectoral breakdown between energy-intensive and non energy-intensive activities.

The first benchmark scenario, called "technological stagnation" (TS), represents a situation where preferences and technologies remain the same and where the growth rate of the economy is around 1.5%. The various sectors have quite similar growth rate. The oil price stagnates, and the CO_2 price increases by 5% per year. This benchmark is computed by assuming that the scaling factors are constant through time and equal to their base-year value. The only non-constant parameter is the carbon tax level.
We see on Table 6 that the benchmark scenario reproduces well the desired 1.5% GDP growth rate that remains well balanced among the various industrial sectors. The increasing carbon price involves a slowdown of fossil-fuel consumption (see Figure 4). But the emissions keep on increasing. Except CO_2 price and emissions trajectories, the relative prices and relative quantity remain almost constant.

In the second benchmark scenario, "energy efficiency" (EF), we aimed at creating a situation where AEEI leads to a better fossil fuel efficiency in the various sectors. The CO_2 price is the same as in TS. But unlike TS, the fossil fuel price is not constant and increases through time at an annual 2% rate (see Table 6). As in the TS scenario the economy is assumed to growth at an annual rate of around 1.5%.
This benchmark scenario is obtained by computing the scaling factors on values taken from TS that are then readjusted. In this readjustment the TS

Description	Technological Stagnation (TS)	Energy Efficiency (EF)	De-industrialization (DI)
Fossil fuel price[a]	0	2	
CO_2 tax[a]	5%		
Energy efficiency improvement			
Price induced	yes	yes	yes
AEEI	no	yes	no
Sectoral shift	no	no	yes
Value added [a,b]			
e	1.56	1.31	1.49
is	1.45	1.31	0.52
ns	1.50	1.34	1.76
GDP[a,b]	1.49	1.33	1.59

Notes: [a] percent annual growth rate, [b] real values.

Table 6: Summary description of the benchmark scenarios

fossil fuel intermediate and household final consumptions are downgraded, so as to growth at a lower rate. The fossil fuels imports are also scaled down. Once the scaling factors have been re-calibrated, the general equilibrium model is solved, with a higher exogenous fossil-fuel price.
In the benchmark scenario obtained, the combination of AEEI and increasing fossil-fuel and CO_2 prices leads to a decrease in fossil fuel consumption and in emissions, as shows Figure 4. The GDP growth remains close to 1.5% per year and it is well balanced among the sectors (see Figure 3).

The last benchmark scenario, "deindustrialization" (DI), aims at representing a situation where, as in TS, there is no AEEI, but where the GDP growth is driven to the non energy intensive sector, while the energy-intensive sector stagnates. In addition, as in the EF scenario, fossil-fuel prices and CO_2 prices increase. This benchmark scenario is obtained by computing the scaling factors by readjusting the TS values. This readjustment concerns the demand for energy-intensive goods, the demand for investment and intermediate and final household consumption. On Table 6, we see that in the scenario obtained, the GDP growth is higher than in the other scenario. It is driven by the non-energy intensive sector growth while the growth is very low in the energy-intensive sector. Fossil fuel consumption and CO_2 emissions increase, but at a slow rate, as shows Figure 4.

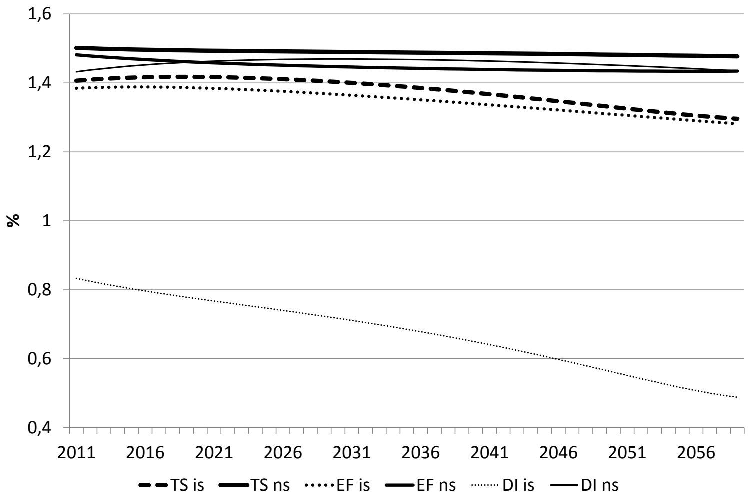

Figure 3: Output growth rate in the is and ns sectors for the various benchmark scenarios

5. Sensitivity to the benchmark scenario

We compare the outcome of a policy shock on the model's results for the various scenarios. We compute response functions (see section 2.5) and present them as percent deviations from the benchmark scenario.

The policy shock takes the form of a long-lasting positive shock on CO_2 prices. In the various benchmark scenarios, the real CO_2 price increases by 2% annually. Starting from 15 euros per ton in 2011, it reaches 100 euros per ton in 2050. The counterfactual policy corresponds to a long-lasting increase in CO_2 price. From 2020 on, the CO_2 price doubles compared with its benchmark value.

The effect of the tax on emissions is shown in Figure 5. The emissions decrease since the very beginning of the model's horizon. Prior to 2020, because of anticipation about an increase in carbon prices, there is less investment in new vintages, and the installed vintages are more capital intensive and less energy intensive. The carbon tax shock in 2020 leads to a sharp drop

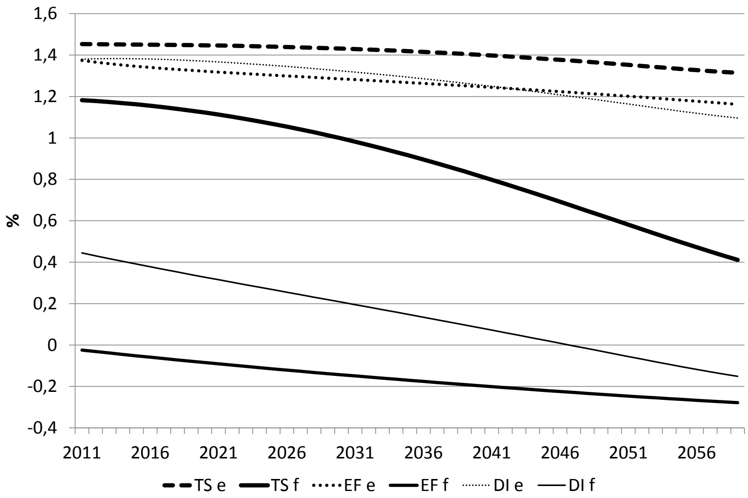

Figure 4: Electric and fossil fuel consumption growth in the various benchmark scenarios

in emissions that is largely driven by the decrease in households fossil fuel consumption, while, in the industrial sectors, the adjustment of demand is slowed-down by the vintage structure of capital. Emissions keep on diverging from the benchmarks. For the same CO_2 price, the emissions reduction realized depends on the benchmark scenario chosen. Emissions reductions are higher with technological stagnation (scenario TS). The main explanation is that unlike the TS benchmark scenario, the Energy Efficiency and Deindustrialization benchmark scenarios assume an increasing fossil fuel price (see figure 6). The price increase limits the share of the carbon price in the end-user fossil fuel price (that includes both fossil-fuel price and the cost of the related CO_2 emissions) and makes it less sensitive to percent deviations in CO_2 prices than with the Energy efficiency benchmark scenario.

The CO_2 tax shock leads first to a production cost increase and therefore to an increase of the prices of the French products with respect to the prices of the foreign products. This loss of price competitiveness can be observed on the upward shifts in terms of trade presented in Figure 5. The shift is particularly important when no technological improvement is assumed (scenario TS). It is less pronounced when autonomous energy efficiency improvements are expected (scenario EF) as the AEEI limits the exposure of the production

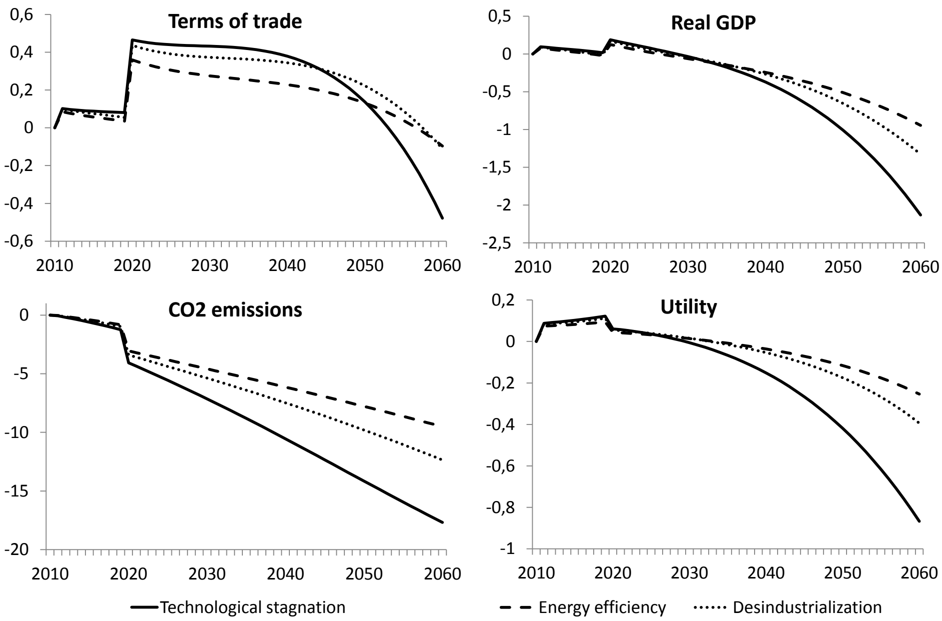

Figure 5: Terms of trade, real GDP, emission and consumption response to the carbon policy shock

cost to the CO_2 price. On the long run, the industries are penalized by losses of competitiveness. This lead to a disinflation process led by the negative effect of the decline of industrial activities on household's revenues (through wages and returns on saving). As the households are "impoverishing", the domestic prices, tend to go down and the competitiveness is partly restored. This explains why the terms of trade worsen on the long run. This disinflation effect is particulary important in the cases whith no AEEI (scenario TS) or no deindustrialization (DI), as the lack of energy efficiency gains lead to very costly adjustment to the carbon price.

The real GDP deviations are presented on Figure 5. Real GDP is computed in terms of purchasing power of foreign goods. Therefore, it is adjusted by the terms of trade. On the short run, the effect on GDP is very limited. The GDP even slightly increases, because the negative effects of the tax are compensated by the improvement of the terms of trade. On the long run, the effect tends to be negative, with an exponential downward deviation from the benchmark scenario. As the economy is less competitive there are less investments in new vintages and less wealth produced in the subsequent periods. The GDP loss is more pronounced when assuming no AEEI (scenario TS). In this case, the deviation observed at the end of the model is around -2.5%. In the scenarios with AEEI (EFF) or deindustrialization (DI), the negative effect on GDP is substantially lower (around -1%). The exponential downward deviation from the baseline remains difficult to explain. In any case, it has to be related to the exponential difference between the counterfactual and the benchmark CO_2 tax.

The carbon tax shock leads to less use of energy input. As the energy and capital inputs were assumed to be complementary ($\sigma < 1$), this has a negative effect on the marginal productivity of capital, and on the interest rate (not presented on these graphs). As the interest rate decreases, there is more incentive to consume and less incentive to save. That is why on the short run, the carbon tax shock leads to an increase in consumption (see Figure 5). On the longer run, however, revenue effects are playing and consumption declines as households resources decrease. The trajectory of the decline depends on the benchmark scenario assumed. In the case where sectoral changes or AEEI limit the energy consumption, the downward shift is substantially delayed. But it is rather brutal when the benchmark scenario assumes a high energy intensity (TS scenario).

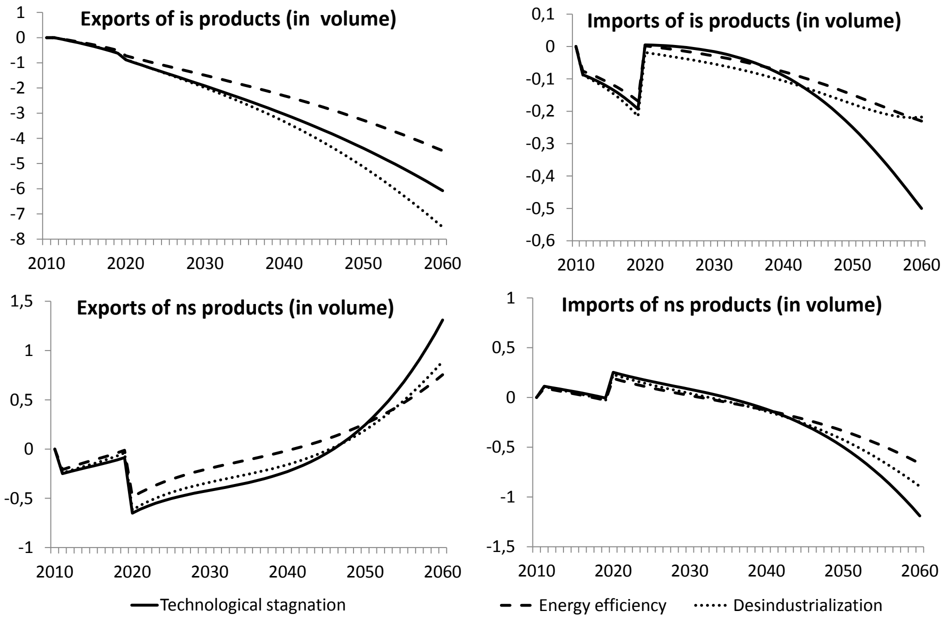

Figure 6: Imports and export of is and ns good response to the policy shock

The effect of the carbon policy shock on external trade is shown on Figure 6. The shock leads to a decrease of exports of energy-intensive products. This decrease begins before the shock, because of the decrease in supply related to the anticipation of the shock (as explained previously). When the shock occurs, the decrease in exports is not dramatic, as it was anticipated by the industry. Then the exports decrease continuously. On the long run, the terms of trade effect is not sufficient to restore the competitiveness of the domestic energy-intensive products and exports are still worsening. The effect on energy-intensive products exports is significantly lower when the assumed AEEI (scenario EF) limits the effect of the carbon tax on prices. The difference observed between the TS and DI scenarios comes from the terms of trade adjustment. The worsening of the terms of trade is less important in the DI scenario, and therefore, the de-inflation and its positive effect on exports is less pronounced, while the negative effect of the carbon tax is more important.

Exports of non energy-intensive products initially decrease because of the carbon tax shock. Nevertheless, on the long run, they increase because they are not too much affected by the increase in carbon prices, and exports of these products benefit from the deterioration of the terms of trade. In other word, for these products, the terms of trade effect dominates the inflationary effect of the energy prices.

Because of the trade balance constraints, the drop in exports is not necessarily compensated by an increase in imports. The carbon tax shock tends to have a negative effect on both imports and exports.

Figure 7 gives the evolution of sectoral output and real gross value added. By definition, the gross value added includes the taxes and therefore the cost of CO_2. The power generation sector is penalized by the carbon tax shock. But we see that it decreases slower than the fossil fuel consumption (see Figure 6). This expresses an increase in the electricity share in energy supply. Power generation is still less penalized when assuming AEEI (scenario EF). However, it is noticeable in this case that the increase in the share of electricity in the energy mix is less pronounced, as the decline of electricity production and fossil fuel use are closer on the long run, respectively -3% (Figure 5) and -7% (Figure 7). The gross value added in the electricity sector increases in the various scenarios, in particular in the EF scenario. It shows that the price effect outweighs the volume effect. In the scenario with energy efficiency, however, the disinflation effect of the carbon tax leads to a decrease of the electric sector value added on the long run.

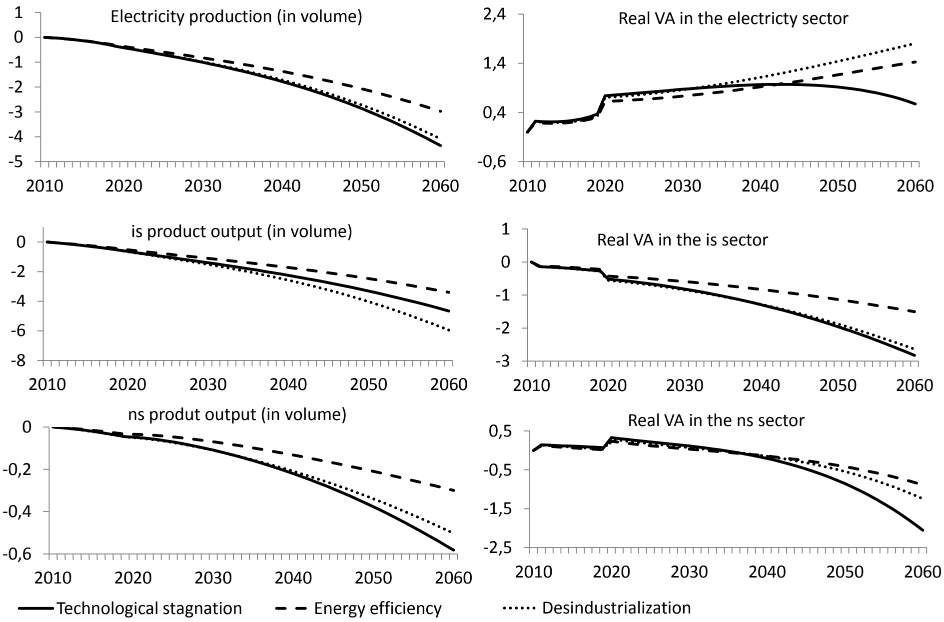

Figure 7: Sectorial value added adjustment to the policy shock

In the TS scenario, output deviations in the electric and energy intensive sector are of quite similar order[14]. The output deviation is less pronounced in the scenarios with energy efficiency as the carbon tax weights less on the domestic and international competitiveness of the energy-intensive sector. The largest effect is observed in the deindustrialization scenario, because the lack of competitiveness on the domestic market is combined with limited terms of trade adjustment. The output is far less affected in the non energy-intensive sector.
When comparing the carbon tax effect in the energy intensive and non energy intensive sectors' gross values added, we see that they are quite similar on the long run. But indeed, the value added net of the carbon tax differs significantly (not on the graph). The non energy-intensive sector gross value added increases on the short run, because of the terms of trade effect, and also because its products are more demanded on the domestic market to compensate for the increase in energy-intensive goods prices. On the longer run, the gross value added loss is due to the effect on domestic demand of the loss of revenue induced by the decline of the energy intensive sector. The non energy-intensive sector is not very open to foreign trade and cannot compensate the decrease in domestic demand by the gains of external competitiveness induced by the degradation of the terms of trade.

6. Conclusion

This paper studies the impact of the choice of a benchmark scenario on counterfactual policy analysis in dynamic forward-looking CGE models. For the sake of illustration, the impact of a carbon-price shock on the French economy is compared for alternative benchmarks that represent different views on the future of the French economy. These benchmarks are contrasted in terms of intra-sectoral energy efficiency gains and shares of energy-intensive activities in the French economy. The results illustrate the dependency of the response on the choice of the benchmark scenario. In particular, the dependence of the GDP contraction on assumptions about energy efficiency gains and reshuffling of industrial activities. In addition, we show some effects of the benchmark scenario on terms-of-trade adjustments.

However, for such a policy analysis, the biggest challenge is the construction of alternative non-stationary benchmark scenarios representing con-

[14]These sectors have comparable initial fossil fuel intensities since the fossil fuel intensity of the French electric sector is limited by the very large share of nuclear.

trasted views of the future. We show that these benchmark scenarios need to satisfy two conditions. The first condition is relevance, i.e. the consistency with the modeler's views on the future. This may require to be consistent with some external (e.g. institutional) projections to which the modeler refers. Alternatively, if projections are not available, the definition of relevance might require the daunting task of specifying a full set of conditions on the prices, quantities and revenues contained in the model.
The second condition is replicability: the benchmark scenario has to be replicable with the general equilibrium model. Equivalently, the scenarios have to satisfy inter-temporal value and product preserving properties. In a static setting, these properties are those on which Social Accounting Matrices are built. In a dynamic model where the value preservation flow property requires not only intra-temporal but also inter-temporal value preservation, this can be very difficult to satisfy. For non-stationary scenarios, the set of replicable scenario is non-convex. This non-convexity adds up to the problems related to the specification of relevant scenarios and makes very complex the direct computation of benchmark scenarios with mathematical programming.

The only solution to obtain relevant and replicable scenarios is backward engineering. This procedure, based on the computation of general equilibrium models, starts with a stationary calibration. Then, from the stationary outcomes, some elements are adjusted so as to obtain a non-stationary path that matches the modeler's view of the future. The control over the computed benchmark scenario however remains loose.

The efforts for a better computation of benchmark scenarios should be continued. The heuristic method proposed in this paper is quite rough and is more a rationalization of what modelers do in practice than a real method generating and controlling non-stationary scenarios. However, the calibration problem might be stated in mathematical programming in a different way. It might be possible to minimize the distance between a benchmark scenario and an external projection under the replicability constraints. As these replicability constraints represent equilibrium conditions one might think about using a formulation of the calibration problem in terms of Mathematical Programming with Equilibrium Constraints (MPEC).

References

Acemoglu, D., 2003. Labor- and capital-augmenting technical change. Journal of the European Economic Association 1 (1), pp. 1–37.

Armington, P. S., 1969. A theory of demand for products distinguished by place of production. Staff Papers - International Monetary Fund 16 (1), 159–178.

Babiker, M., Gurgel, A., Paltsev, S., Reilly, J., Jacoby, H. D., Prinn, R. G., 2008a. A forward looking version of the MIT emissions prediction and policy analysis (eppa) model. Tech. Rep. 161, MIT Joint Program on the Science and Policy of Global Change.

Babiker, M. H., Reilly, J. M., Mayer, M., Eckaus, R. S., Wing, I. S., Hyman, R. C., 2001. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. Tech. Rep. 71, MIT Joint Program on the Science and Policy of Global Climate Change, Cambridge, MA.

Babiker, M. H., Reilly, J. M., Mayer, M., Eckaus, R. S., Wing, I. S., Hyman, R. C., 2008b. The MIT emissions prediction and policy analysis (EPPA) model: Revisions, sensitivities, and comparisons of results. MIT Joint Program Report 165, MIT Joint Program on the Science and Policy of Global Climate Change, Cambridge, MA.

Balistreri, E. J., Rutherford, T. F., 2001. Dynamic General Equilibrium Analysis At the State Level: Assessing the Economic Implications of the Kyoto Protocol. Working paper, University of Colorado, Boulder.

Bernard, A., Vielle, M., 2009. Assessment of European Union transition scenarios with a special focus on the issue of carbon leakage. Energy Economics 31 (Supplement 2), S274 – S284, international, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22.

Bernstein, P. M., Montgomery, D. W., Rutherford, T. F., Yang, G.-F., 1999. Effects on restrictions of international permit trading: The MS-MRT model. The Energy Journal Special Issue, 221–256.

Boadway, R. W., Treddenick, J. M., 1978. A general equilibrium computation of the effect of the canadian tariff structure. Canadian Journal of Economics (Supplement 2), 424 – 446.

Bohringer, C., Rutherford, T. F., Wiegard, W., 2003. Computable general equilibrium analysis: Opening a black box. Tech. Rep. Discussion Paper 03-56, Centre for European Economic Research.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH : A world induced technical change hybrid model. Energy Journal Special Issue.

Boucekkine, R., de la Croix, D., Licandro, O., 2008. Vintage capital. In: Durlauf, S. N., Blume, L. E. (Eds.), The New Palgrave Dictionary of Economics. Palgrave Macmillan, Basingstoke.

Casas, F. R., November 1984. Imperfect factor mobility: A generalization and synthesis of two-sector models of international trade. Canadian Journal of Economics 17 (4), 747–61.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 international scenarios. Energy Economics 31 (Supplement 2), S64 – S81, international, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22.

Di Maria, C., van der Werf, E., February 2008. Carbon leakage revisited: unilateral climate policy with directed technical change. Environmental & Resource Economics 39 (2), 55–74.

Dirkse, S. P., Ferris, M. C., 1995. The path solver: A non-monotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software 5, 123–156.

Drud, A., 1996. CONOPT: A System for Large Scale Nonlinear Optimization, Reference Manual for CONOPT Subroutine Library. Tech. rep., ARKI Consulting and Development A/S, Bagsvaerd, Denmark.

EU, 2003. Directive 2003/87/EC. Tech. rep., European Parliament and the Council.

EU, 2009. Directive 2009/29/EC of the European Parliament and the Council of 23 April 2009 amending Directive 2003/87/EC. Tech. rep., European Parliament and the Council.

Goulder, L. H., Shoven, J. B., Whalley, J., 1983. Behavioral Simulation Methods in Tax Policy Analysis. University of Chicago Press, Ch. Domestic Tax Policy and the Foreign Sector: The Importance of Alternative Foreign Sector Formulations to Results from a General Equilibrium Tax Analysis Model, pp. 333–368.

Hamdi-Cherif, M., Guivarch, C., Quirion, P., 2010. Sectoral targets for developping countries, combining "common but differentiated responsibilities" with "meaningful participation". Nota di Lavoro 37.2010, Fondazione Eni Enrico Mattei.

Henningsen, A., Henningsen, G., 2011. Econometric Estimation of the "Constant Elasticity of Substitution" Function in R: Package micEconCES. Tech. rep., CRAN R-project.

Hicks, J., 1963. The theory of wages. London.

Horvath, M., February 2000. Sectoral shocks and aggregate fluctuations. Journal of Monetary Economics 45 (1), 69–106.
URL http://ideas.repec.org/a/eee/moneco/v45y2000i1p69-106.html

Klump, R., de La Grandville, O., March 2000. Economic growth and the elasticity of substitution: Two theorems and some suggestions. American Economic Review 90 (1), 282–291.

Klump, R., McAdam, P., Willman, A., Feb. 2011. The normalized ces production function - theory and empirics. Working paper series, European Central Bank.

Klump, R., Preissler, H., 2000. CES production functions and economic growth. Scandinavian Journal of Economics 102 (1), 41–56.

Klump, R., Saam, M., 2006. Calibration of normalised CES production functions in dynamic models. ZEW Discussion Papers 06-78, ZEW - Zentrum fr Europische Wirtschaftsforschung / Center for European Economic Research.

Leimbach, M., Bauer, N., Baumstark, L., Edenhofer, O., 2010. Mitigation costs in a globalized world: Climate policy analysis with remind-r. Environmental modeling & assessment 15, 155–173.

Léon-Ledesma, M. A., McAdam, P., Willman, A., September 2010. Identifying the elasticity of substitution with biased technical change. American Economic Review 100 (4), 1330–57.

Manne, A., Mendelsohn, R., Richels, R., January 1995. MERGE : A model for evaluating regional and global effects of GHG reduction policies. Energy Policy 23 (1), 17–34.

Manne, A. S., Richels, R. G., 1992. Buying Greenhouse Insurance, The Economic Costs of CO2 Emission Limits. The MIT Press.

Mansur, A., Whalley, J., November 1982. A decomposition algorithm for general equilibrium computation with application to international trade models. Econometrica 50 (6), 1547–57.
URL http://ideas.repec.org/a/ecm/emetrp/v50y1982i6p1547-57.html

Marschinski, R., Jakob, M., Endhofer, O., 2009. Analysis of carbon leakage in an extended Ricardo-Viner model. Tech. rep., Presented at the Conference on the International Dimensions of Climate Policies.

Mathiesen, L., 1985. Computational experience in solving equilibrium models by a sequence of linear complementarity problems. Operation Research 33 (6), 1225–1250.

McKibbin, W. J., Ross, M. T., Shackleton, R., Wilcoxen, P. J., 1999. Emissions trading, capital flows and the Kyoto protocol. The Energy Journal Special Issue, 287–333.

Nordhaus, W., Boyer, J., 1999. Roll the DICE Again: Economic Models of Global Warming. MIT Press, Cambridge, USA.

Paltsev, S., June 2004. Moving From Static to Dynamic General Equilibrium Models (Notes for a beginner in MPSGE). Technical Note 4, MIT Joint Program on the Science and Policy of Global Change.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFraland, J., Sarofim, M., Asadoorian, M., Babiker, M., 2005. The MIT emissions prediction and policy analysis (EPPA) model version 4. Tech. Rep. 125, MIT Joint Program on the Science and Policy of Global Change.

Proost, S., Van Regemorter, D., 2003. Climate change policy in European countries and its effect on industry. Energy, Transport and Environment Working Papers Series ete0305, Katholieke Universiteit Leuven, Centrum voor Economische Studin, Energy, Transport and Environment.

Quirion, P., Rozenberg, J., Sassi, O., Adrien, V.-S., 2011. How CO2 capture and storage can mitigate carbon leakage. Nota di Lavoro 15.2011, Fondazione Eni Enrico Mattei.

Rutherford, T. F., 1998. Economic equilibrium modelling with gams, an introduction to gams/mcp and gams/mpsge.

Rutherford, T. F., July 2009. Strategies for calibrating ramsey models with non-stationary growth. Lecture notes for short course in dynamic general equilibrium analysis, Centre for Energy Policy and Economics ETH Zrich.

Siebert, H., 1979. Environmental policy in the two-country-case. Journal of Economics 39 (3-4), 259–274.

Sue Wing, I., September 2004. Computable general equilibrium models and their use in economy-wide policy analysis. Technical Note 6, MIT Joint Program on the Science and Policy of Global Change.

USCCSP, 2007. (U.S. Climate Change Science Program), Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, Synthesis and Assessment Product 2.1a.

Varian, H. R., 1992. Microeconomic Analysis, 3rd Edition. New-York, N.Y.

Webster, M., Paltsev, S., Reilly, J., 2008. Autonomous efficiency improvement or income elasticity of energy demand: Does it matter? Energy Economics 30 (6), 2785 – 2798.

Wendner, R., June 1999. A Calibration Procedure of Dynamic CGE Models for Non-steady State Situations Using GEMPACK. Computational Economics 13 (3), 265–87.
URL http://ideas.repec.org/a/kap/compec/v13y1999i3p265-87.html

Appendix A. Notations of the model's variable

$C_{j,t}$ Quantity of goods j consumed by the household at time t
DEF_t Trade deficit / foreign savings at period t, expressed in current foreign currency.
E is the sum of discounted household's consumption expenditures
EM_t Total regional CO_2 emissions
$EX_{j,t}$ Quantity of goods j exported at time t
EXR_t Exchange rate in the economy (value of the foreign currency in Euros)
$I_{i,t}$ Investment in industry i at time t
$IM_{j,t}$ Quantity of goods j imported at time t
$IV_{i,j,t}$ Quantity of good j used to create capital at period t
$K_{i,t}$ Stock of capital is sector i at time t
$k_{i,t}$ Stock of capital required by vintage t sector i at time t
$L_{i,t}$ Quantity of labour used in sector i at time t
$l_{i,t}$ Quantity of labour used by the new vintage in sector i at period t
LTO_t Overall quantity of labour at time t
lto_t Overall quantity of labour used in new vintages period t
$P_{j,t}$ Price of good j at time t
$PD_{j,t}$ Price of the domestic good j at time t
$PDW_{j,t}$ Present value of the international price of the domestic product j at time t
$PDWC_{j,t}$ Current value of the international price of the domestic product j at time t
$PI_{j,t}$ Import price of good j at time t
$PIW_{j,t}$ Present value of the international price of foreign product j at time t in foreign currency
$PIWC_{j,t}$ Current value of the international price of foreign product j at time t in foreign currency
PR_t Aggregated profits in the domestic economy at time t
PU_t Marginal utility of revenue at time t
$PV_{i,t}$ Purchase price of one unit of capital from sector i at time t
R_t Interest rate of the economy at period t
$RK_{i,t}$ Gross rental rate of capital in sector i on period t
S_t Domestic households' saving on period t
$TAX_{m,t}$ Present-value tax on commodity m at period t
U_t Instantaneous household's utility quantity at time t
$W_{i,t}$ Wage in sector i at time t
WT_t Index value of wage at time t
$X_{i,j,t}$ Intermediary consumption of good j by industry i at time t
$x_{i,j,t}$ Intermediary consumption of good j by vintage t in industry i at time t

$Y_{j,t}$ Quantity of goods j supplied at time t
$Z_{i,t}$ Domestic production in sector i at time t
$z_{i,t}$ Capacity of equipment period t vintage in sector i at time t
$ZD_{j,t}$ Domestic demand for good j at time t

Appendix B. Technologies and labor supply with putty-clay functions and exponential decay

Appendix B.1. Production with vintage: zero-profit condition and conditional factor demand

We consider that the total production is the sum of the output of different vintages with exponential decay. The inputs and outputs corresponding to each vintage are noted in small letters. The cost-minimization problem of the firm with the putty-clay production function:

$$\begin{aligned}
\min_{X_i,K_i,L_i} \sum_t \left[\sum_{j\in J_i} P_{j,t}X_{i,j,t} + RK_{i,t}K_{i,t} + W_{i,t}L_{i,t}\right] \\
Z_{i,t+1} = z_{i,t+1} + (1-\delta)Z_{i,t} \\
X_{i,j,t+1} = x_{i,j,t+1} + (1-\delta)X_{i,j,t} \\
K_{i,t+1} = k_{i,t+1} + (1-\delta)K_{i,t} \\
L_{i,t+1} = l_{i,t+1} + (1-\delta)L_{i,t} \\
F_t(x_{i,1,t},\dots,x_{i,J,t},k_{i,t},l_{i,t}) = z_{i,t} \quad (\lambda_{(z),t})
\end{aligned} \tag{B.1}$$

At equilibrium, the dual variable λ_t is equal to the output market price $PD_{i,t}$. The problem (B.1) can be re-written as:

$$\begin{aligned}
\min_{X_i,K_i,L_i} \sum_t m_t \Bigg[\sum_j \sum_{n\geq 0} P_{j,t}x_{i,j,t-n}(1-\delta)^n + \sum_{n\geq 0} RK_{i,t}k_{i,t-n}(1-\delta)^n \\
+ \sum_{n\geq 0} W_{i,t}L_{i,t-n}(1-\delta)^n\Bigg] \\
F_t(x_{i,1,t},\dots,x_{i,J,t},k_{i,t},l_{i,t}) = z_{i,t} \quad (PD_{i,t})
\end{aligned} \tag{B.2}$$

If rearranging the terms in the sum, the problem can be transformed in:

$$\begin{aligned}
\min_{x_i,k_i,l_i} \sum_t \left[\sum_{j\in J_i} P'_{j,t}x_{i,j,t} + RK'_{i,t}k_{i,t} + W'_{i,t}l_{i,t}\right] \\
F_t(x_{i,1,t},\dots,x_{i,J,t},k_{i,t},l_{i,t}) = z_{i,t} \quad (PD'_{i,t})
\end{aligned} \tag{B.3}$$

This problem is equivalent to solving separately T independent problem of the form:

$$\min_{x_i,k_i,l_i} \left[\sum_{j\in J_i} P'_{j,t} x_{i,j,t} + RK'_{i,t} k_{i,t} + W'_{i,t} l_{i,t} \right] \tag{B.4}$$
$$F_t(x_{i,1,t}, \ldots, x_{i,J,t}, k_{i,t}, l_{i,t}) = z_{i,t} \quad (PD'_{i,t})$$

The prices noted with $'$ are indexes of future prices defined as:

$$\begin{aligned}
P'_{j,t} &= \sum_{m=0,\ldots,T-t-1} (1-\delta)^m P_{j,t+m} + P_{j,T} P_{j,T-1} / (P_{j,T-1} - P_{j,T}(1-\delta)) \\
PD'_{i,t} &= \sum_{m=0,\ldots,T-t-1} (1-\delta)^m PD_{i,t+m} + PD_{i,T} PD_{i,T-1} / (PD_{i,T-1} - PD_{i,T}(1-\delta)) \\
RK'_{i,t} &= \sum_{m=0,\ldots,T-t-1} (1-\delta)^m RK_{i,t+m} + RK_{i,T} RK_{i,T-1} / (RK_{i,T-1} - RK_{i,T}(1-\delta)) \\
W'_{i,t} &= \sum_{m=0,\ldots,T-t-1} (1-\delta)^m W_{i,t+m} + W_{i,T} W_{i,T-1} / (W_{i,T-1} - W_{i,T}(1-\delta))
\end{aligned} \tag{B.5}$$

These indexes take into account not only the current price, but also the sum of discounted prices weighted by the decay of the vintage at the corresponding period (first right-hand terms). The sum of future prices in post-terminal periods is approximated. This proxy (the second right-hand term) is made assuming that the discount factor is stable after T and that the (non-discounted) prices growth rate between $T-1$ and T is infinitely repeated after T.

There are no inter-temporal constraints in the problems (B.4). The cost-minimization behaviour of the producer with vintages and exogenous scrapping time can be solved as a set of independent static cost-minimization problems by considering in each subproblem prices derived from the current and expected market prices using formula (B.5).

Finally, the decision of the final good producer with the putty-clay production function can be seen as a set of independent static production decisions with the CES technology corresponding and indexes of future prices. This allows us to cast the vintage problem in the textbook formulation of producer behavior with flexible technologies. If the production function is CES, the analytical computation of conditional factor demands can be directly derived from the many existing textbook examples that deal with flexible technologies. In particular, in the case of the production function defined in (13), at each period, the conditional factor demand can be derived from Varian (1992):

$$\begin{aligned} X_{i,j,t+1} &= X_{i,j,t}(1-\delta) + a_{i,j,t+1}\left(\frac{PD'_{i,t+1}}{P'_{j,t+1}}\right)^{\sigma_i} z_{i,t+1}, \quad j \in J_i \\ K_{i,t+1} &= K_{i,t}(1-\delta) + a_{i,K,t+1}\left(\frac{PD'_{i,t+1}}{R'_{t+1}}\right)^{\sigma_i} z_{i,t+1} \\ L_{i,j,t+1} &= L_{i,j,t}(1-\delta) + a_{i,L,t+1}\left(\frac{PD'_{i,t+1}}{W'_{i,t+1}}\right)^{\sigma_i} z_{i,t+1} \end{aligned} \tag{B.6}$$

And the zero profit condition is:

$$PD'^{1-\sigma_i}_{i,t} = \sum_{j \in J_i} a^{\sigma_i}_{(prod),i,j,t} P'^{1-\sigma i}_{j,t} + a^{\sigma_i}_{(prod),i,K,t} RK'^{1-\sigma_i}_{i,t} + a^{\sigma_i}_{(prod),i,L,t} W'^{1-\sigma_i}_{i,t}, t \geq 1$$

Appendix B.2. Household Labor supply

In order to maximize their consumption, the households allocate their labor among the different sectors so as to maximize the sum of discounted wages. They solve the problem:

$$\begin{aligned} &\max \sum_{t \geq 1} W_{i,t} L_{i,t} \\ L\bar{T}O_{t+1} &= L\bar{T}O_t(1-\delta) + l\bar{t}o_{t+1}, \quad t < T \\ L_{i,t+1} &= L_{i,t}(1-\delta) + l_{i,t+1} \\ l\bar{t}o_t &= \left[\sum_i a_{(labor),i,t} l_{i,t}^{\frac{\sigma_L+1}{\sigma_L}}\right]^{\frac{\sigma_L}{\sigma_L+1}} \qquad (\lambda_{(lto),t}) \end{aligned}$$

At equilibrium, the dual variable $\lambda_{(lto),t}$ is equal respectively to the value of the wage aggregate WT_t.
Similarly to the cost-minimizing problem of the producer with vintages (equation B.1), this problem of labor supply can solved as t independent problems of the form:

$$\begin{aligned} &\max_{t \geq 1} W'_{i,t} l_{i,t} \\ l\bar{t}o_t &= \left[\sum_i a_{(labor),i,t} l_{i,t}^{\frac{\sigma_L+1}{\sigma_L}}\right]^{\frac{\sigma_L}{\sigma_L+1}} \qquad (WT'_t) \end{aligned}$$

By parallelism with equation B.1, we can derive the conditional labor supply function of the households:

$$L_{i,t+1} = (1-\delta)L_{i,t} + a^{\sigma_i}_{(prod),i,L,t} W'^{-\sigma_i}_{i,t} PD'^{\sigma_i}_{i,t} z_{i,t+1} \quad i = e, is, ns$$

And the zero profit condition for labor supply:

$$WT_t'^{1+\sigma_L} = \sum_i a_{(labor),i,t}^{-\sigma_L} W_{i,t}'^{1+\sigma_L}, \qquad t \geq 1$$

With WT_t' the index of total wage, defined as:

$$WT'_{i,t} = \sum_{m=0,\dots,T-t-1} (1-\delta)^m WT_{i,t+m} + WT_{i,T} WT_{i,T-1} / (WT_{i,T-1} - WT_{i,T}(1-\delta)) \tag{B.7}$$

Appendix C. The model's equations

Appendix C.1. Household' budget balance

Households' consumptions expenditures HC_t and the savings S_t are equal to household's revenue. The households' revenue is made of wages, rents from capital net profits (PR_t), the lump-sum transfers of the carbon tax revenues, and the deficit of the trade balance (often labeled foreign savings). We assume that $D\bar{E}F_t$, the present-value of the trade balance deficit (or foreign savings) at period t is exogenous. It is expressed in terms of foreign currencies and therefore must be converted to Euros using the endogenous exchange rate ER_t. The budget constraint of the representative household is:

$$HC_t + S_t =$$
$$\sum_i RK_{i,t} K_{i,t} + \sum_i W_{i,t} L_{i,t} + D\bar{E}F_t EXR_t + er \cdot IM_{f,t} \cdot PU_t \cdot TAX_{co_2,t} + PR_t$$

Profits less carbon tax are:

$$PR_t = \sum_{i,t} \left[PD_{i,t} Z_{i,t} - L_{i,t} W_{i,t} - RK_{i,t} K_{i,t} - \sum_{j \in J_i} P_{j,t} X_{i,j,t} \right]$$

Note that the vintage structure of capital does not rule out non-zero profits at some periods, despite the constant return to scale in for the specification of each generation of technologies.

Appendix C.2. Zero profit conditions

On the composition of the consumption basket:

$$PU_t^{1-\sigma_C} = \sum_j a_{(cons),j,t}^{\sigma_C} P_{j,t}^{1-\sigma_C} \qquad t \geq 1$$

On the production from a new vintage, for $i = e, is, ns$:

$$PD'^{1-\sigma_i}_{i,t} = \sum_{j \in J_i} a^{\sigma_i}_{(prod),i,j,t} P'^{1-\sigma i}_{j,t} + a^{\sigma_i}_{(prod),i,K,t} RK'^{1-\sigma_i}_{i,t} + a^{\sigma_i}_{(prod),i,L,t} W'^{1-\sigma_i}_{i,t}, t \geq 1$$

On the labor composite:

$$W'^{1-\sigma_L}_t = \sum_i a^{-\sigma_L}_{(labor),i,t} W'^{1+\sigma_L}_{i,t}, \quad t \geq 1$$

The end-user price of fossil fuel is equal to the price of imported fossil fuels plus the carbon tax cost; the end-use cost of electricity is equal to the price of the electricity produced:

$$P_{f,t} = ER_t \cdot PIW_{f,t} + er \cdot PU_t \cdot TAX_{co_2,t}, \quad t \geq 1$$
$$P_{e,t} = PD_{e,t}$$

On the production of capital goods:

$$PV_{i,t} = a_{(capital),i,is,t} P_{is,t} + a_{(capital),i,ns,t} P_{ns,t} \quad i = e, is, ns, \quad t \geq 1$$

On the composition of the Armington good:

$$P^{1-\sigma Y,i}_{i,t} = a^{\sigma Y,i}_{(dom),i,t} PD^{1-\sigma Y,i}_{i,t} + a^{\sigma Y,i}_{(for),i,t} PI^{1-\sigma Y,i}_{i,t} \quad i = is, ns, \quad t \geq 1$$

On the inter-temporal transfer of investment goods;

$$PV_{i,t} = RK_{i,t} + PV_{i,t+1}(1-\delta) \quad i = e, is, ns, \quad t \geq 1$$

On the inter temporal transfer of consumption:

$$PU_{t+1}(1+R_t) = PU_t, \quad t \geq 1$$

Since there are no transaction costs and no tariffs, the present-value international commodity price adjusted by the exchange rate is equal to the present-value of the commodity price in the domestic market:

$$PI_{j,t} = EXR_t \cdot PIW_{j,t} \quad j = f, is, ns$$
$$PD_{j,t} = EXR_t \cdot PDW_{j,t} \quad j = is, ns$$

The present value international commodity prices of export are deduced from their current value using PU_t as a discount factor.

$$PIW_{j,t} = PU_t \cdot PIWC_{j,t} \quad j = f, is, ns$$
$$PDW_{j,t} = PU_t \cdot PDWC_{j,t} \quad j = is, ns$$

Appendix C.3. Conditional demand conditions

As written in Equation (21), the period t present-value consumption expenditure of a household represents a fraction β_t of its total present value expenditures.

$$\beta_t E = HC_t, \quad t \geq 1$$

At a period t, the household's Marshallian demand of good j is:

$$C_{j,t} = a_{(cons),j,t}^{\sigma_C} P_{j,t}^{-\sigma_C} PU_t^{\sigma_C - 1} HC_t, \quad t \geq 1$$

The conditional labor supply by the households derived is computed in Appendix B.2 as:

$$L_{i,t} = (1-\delta)L_{i,t} + a_{(labor),i,t+1}^{-\sigma_L} W_{i,t+1}^{\prime \sigma_L} WT_{t+1}^{\prime -\sigma_L} \bar{l}t_{t+1}$$

The conditional demand for intermediate consumption is computed in Appendix B.1 as:

$$L_{i,t+1} = (1-\delta)L_{i,t} + a_{(prod),i,L,t}^{\sigma_i} W_{i,t}^{\prime -\sigma_i} PD_{i,tm}^{\prime \sigma_i} z_{i,t+1} \quad i = e, is, ns$$
$$K_{i,t+1} = (1-\delta)K_{i,t} + a_{(prod),i,K,t}^{\sigma_i} RK_{i,t}^{\prime -\sigma_i} PD_{i,tm}^{\prime \sigma_i} z_{i,t+1} \quad i = e, is, ns$$
$$X_{i,j,t+1} = (1-\delta)X_{i,j,t} + a_{(prod),i,j,t}^{\sigma_i} P_{j,t}^{\prime -\sigma_i} PD_{i,tm}^{\prime \sigma_i} z_{i,t+1} \quad i = e, is, ns$$

The conditional demand of inputs to produce capital goods is proportional to the production of capital goods (as the capital goods are produced by a Leontieff technologies)

$$IV_{i,j,} = a_{(capital),i,j,t} I_{i,t} \quad i = e, is, ns. \; j = is, ns, \quad t \geq 1$$

The conditional demand for domestic and foreign goods are:

$$ZD_{j,t} = a_{(dom),j,t}^{\sigma_{Y,j}} P_{j,t}^{\sigma_{Y,j}} PD_{j,t}^{-\sigma_{Y,j}} Y_{j,t} \quad j = is, ns, \quad t \geq 1$$
$$IM_{j,t} = a_{(for),j,t}^{\sigma_{Y,j}} P_{j,t}^{\sigma_{Y,j}} PI_{j,t}^{-\sigma_{Y,j}} Y_{j,t} \quad j = is, ns, \quad t \geq 1$$

The total supply of products i is equal to the production from the new vintage and the remaining part of the old vintages.

$$Z_{i,t+1} = Z_{i,t}(1-\delta) + z_{i,t+1}$$

The capital sock in $t+1$ is equal to the remaining part of the capital plus investments

$$K_{i,t+1} = K_{i,t}(1-\delta) + I_{i,t}$$

Foreign supply function (supply for import) and foreign demand of domestic goods (demand for exports) were given by equations (17 and 18).

Appendix C.4. Market clearing conditions

The import of fossil fuels is equal to fossil fuel use (household's and intermediate consumption).

$$IM_{f,t} = C_{f,t} + \sum_{i=e,is,ns} X_{i,f,t}, \quad t \geq 1$$

Electricity production is equal to electricity use (household's and intermediate consumption).

$$Z_{e,t} = C_{e,t} + \sum_{i=is,ns} X_{i,e,t}, \quad t \geq 1$$

The supply of is and ns goods is equal to the use (household's and intermediate consumption plus investment).

$$Y_{is,t} = C_{is,t} + X_{is,ns,t} + \sum_{i=e,is,ns} IV_{i,is,t}, \quad t \geq 1$$
$$Y_{ns,t} = C_{ns,t} + X_{ns,is,t} + \sum_{i=e,is,ns} IV_{i,ns,t}, \quad t \geq 1$$

The market must clear for is and ns domestic products (supply equal domestic demand plus exports).

$$Z_{i,t} = ZD_{i,t} + EX_{i,t} \quad i = is, ns, \quad t \geq 1$$

Appendix C.5. Initial conditions

The base-year prices ($P_{j,0}$, $PD_{j,0}$, $PI_{j,0}$, $PV_{i,0}$, $W_{i,0}$, W_0, $RK_{i,0}$) and the base-year quantities (CC_0, $C_{j,0}$, $Y_{j,0}$, $Z_{j,0}$, $ZD_{j,0}$, $IM_{j,0}$, $X_{i,j,0}$, $K_{i,0}$, $L_{i,0}$, L_0, $I_{i,0}$, $IV_{i,j,0}$) are given.
The fossil international fossil-fuel price is exogenous, i.e. $PIWC_{f,t)}$ is given. In addition, for the scaling of the model, we set the PU_1 equal to 1. It is possible to check for the homogeneity of the model w.r.t. to PU_1.

Appendix C.6. Model closure and the Walras law

The model is closed by equating domestic and foreign saving (trade deficit) to investment:

$$S_t + PU_t \cdot EXR_t \cdot D\bar{E}F_t = \sum_i PV_{i,t} I_{i,t}$$

If all the market-clearing conditions of section hold and if the other general equilibrium conditions are met, the last market, which is the market for foreign capital clears. The trade deficit is financed by the flow of foreign capital, i.e. equation (19) is satisfied.

Appendix D. Computation of the scaling factors from a benchmark scenario

Scaling factors (a)	Scaling factor formula
$a_{(prod),i,j,t}$	$= \frac{\bar{P}'_{j,t}\bar{x}_{i,j,t}}{\bar{PD}'_{i,t}\bar{z}_{i,t}}\left(\frac{\bar{z}_{i,t}}{\bar{x}_{i,j,t}}\right)^{\frac{\sigma_i-1}{\sigma_i}}$
$a_{(prod),i,K,t}$	$= \frac{\bar{RK}'_{i,t}\bar{k}_{i,t}}{\bar{PD}'_{i,t}\bar{z}_{i,t}}\left(\frac{\bar{z}_{i,t}}{\bar{k}_{i,t}}\right)^{\frac{\sigma_i-1}{\sigma_i}}$
$a_{(prod),i,L,t}$	$= \frac{\bar{W}'_{i,t}l_{i,t}}{\bar{PD}'_{i,t}\bar{z}_{i,t}}\left(\frac{\bar{z}_{i,t}}{\bar{l}_{i,t}}\right)^{\frac{\sigma_i-1}{\sigma_i}}$
$a_{(cap),i,is,t}$	$= \frac{\bar{I}_{i,is,t}}{\bar{IV}_{i,t}}$
$a_{(cap),i,ns,t}$	$= \frac{\bar{I}_{i,ns,t}}{\bar{IV}_{i,t}}$
$a_{(dom),j,t}$	$= \frac{\bar{PD}_{i,t}\bar{ZD}_{i,t}}{\bar{P}_{i,t}\bar{Y}_{i,t}}\left(\frac{\bar{Y}_{i,t}}{\bar{ZD}_{i,t}}\right)^{\frac{\sigma Y,i-1}{\sigma Y,i}}$
$a_{(for),j,t}$	$= \frac{\bar{PI}_{i,t}\bar{IM}_{i,t}}{\bar{P}_{i,t}\bar{Y}_{i,t}}\left(\frac{\bar{Y}_{i,t}}{\bar{IM}_{i,t}}\right)^{\frac{\sigma Y,i-1}{\sigma Y,i}}$
$a_{(im),j,t}$	$= \frac{\bar{IM}_{j,t}}{\bar{PIWC}_{j,t}}^{\sigma_{IM,j}}$
$a_{(ex),j,t}$	$= \frac{\bar{EX}_{j,t}}{\bar{PDWC}_{j,t}}^{-\sigma_{EX,j}}$
β_t	$= \frac{\bar{HC}_t}{\bar{E}}$
$a_{(cons),j,t}$	$= \left(\frac{\bar{C}_{j,t}}{\bar{HC}_{j,t}}\right)^{1/\sigma_{C,j}} \bar{PU}_t^{\frac{1-\sigma_{C,j}}{\sigma_{C,j}}} \bar{P}_{j,t}$
$a_{(labor),i,t}$	$= \frac{\bar{W}'_{i,t}l_{i,t}}{\bar{WT}'_t\bar{ltot}_t}\left(\frac{\bar{WT}_t}{\bar{W}_{i,t}}\right)^{-\sigma_L-1}$

Table D.7: Formula to compute the scaling factors from a benchmark scenario

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