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▶ To cite this version:

Céline Guivarch, Renaud Crassous, Olivier Sassi, Stéphane Hallegatte. The costs of climate policies in a second best world with labour market imperfections. Climate Policy, 2011, 11 (1), pp.768-788. 10.3763/cpol.2009.0012 . halshs-00724487

HAL Id: halshs-00724487

https://shs.hal.science/halshs-00724487

Submitted on 21 Aug 2012

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# The costs of climate policies in a second best world with labour market imperfections

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Cite this article as: Guivarch, C., Crassous, R., Sassi, O. and Hallegatte, S. 2010. *The costs of climate policies in a second best world with labour market imperfections*. Climate Policy 11, 1 : 768–788.

## Abstract

The critical role of labour market imperfections is explored in climate stabilisation costs formation, using a dynamic recursive energy-economy model that represents a second best world with market imperfections and short-run adjustments constraints along a long-term growth path. The degree of rigidity of the labour markets is a central parameter and a systematic sensitivity analysis of the model results confirms this. When labour markets are represented as highly flexible, the model results are in the usual range of existing literature, i.e. less than 2% GDP losses in 2030 for a stabilisation target at 550ppm $CO_2$ equivalent. However, when labour markets rigidities are accounted for, mitigation costs increase dramatically. Accompanying measures are identified, namely labour subsidies, which guarantees against the risk of large stabilisation costs in the case of high rigidities of the labour markets. This complements the usual view that mitigation is a long-term matter that depends on technology, innovation, investment and behavioural change. The results support the view that mitigation is also a shorter-term issue and a matter of transition on the labour market.

**Keywords:** *labour market rigidities, climate policies costs, second best world, sensitivity analysis.*

## Coût des politiques climatiques dans un monde de second rang avec des marchés du travail imparfaits

**Résumé** Le rôle déterminant des imperfections du marché du travail dans la formation des coûts de l'atténuation du changement climatique est exploré, avec un modèle de l'interface énergie-économie, récursif et dynamique, qui représente un monde de second rang avec des imperfections du marché du travail et des contraintes d'ajustement de court terme le long d'une trajectoire de croissance à long terme. Le degré de rigidité des marchés du travail est un paramètre central, ceci étant confirmé par une analyse de sensibilité systématique des résultats. Lorsque les marchés du travail sont représentés comme très flexibles, les résultats se situent dans la fourchette habituelle de la littérature existante (c'est-à-dire moins de 2% de pertes de PIB mondial en 2030 pour une cible de stabilisation à 550 ppm équivalent $CO_2$). Cependant, lorsque les rigidités du marché du travail sont prises en compte, le coût de l'atténuation augmente très significativement. Des mesures d'accompagnement, à savoir des subventions sur le travail, garantissent contre le risque de coûts de la stabilisation élevés dans le cas de fortes rigidités sur le marché du travail. Cette vision complète la conception habituelle selon laquelle l'atténuation est une question de long terme qui dépend de la technologie, de l'innovation, de l'investissement et des changements de comportements. L'article signale que l'atténuation est aussi un problème de plus court terme et une question de transition sur les marchés du travail.

**Mots clés**: rigidités des marchés du travail, coût des politiques climatiques, monde de second rang, analyse de sensibilité

## Introduction

There is now a global scientific consensus that halving current world GHG emissions before 2050 is necessary to limit the high risks associated with anthropogenic climate change. Such a mitigation target will necessarily require deep structural and technological change in the economic production system and in the use of energy, materials and lands around the world. According to the last IPCC report, one can be confident about the feasibility of this challenge thanks to existing or future technologies: the global macroeconomic mitigation cost is estimated to be below five percent of GDP in 2050, even for the most stringent emission constraints (IPCC 2007). However these IPCC results are subject to a critical caveat that is specified in Box SPM-3: “Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century”. One may wonder whether the imperfections of the real world are likely to weaken the robustness of the range of GDP variations due to ambitious mitigation policies.

A significant body of literature is devoted to the analysis of existing market imperfections that are known to place barriers to the adoption of optimal behaviours and the diffusion of efficient technologies. Notably, the topic has been at the heart of the debate about ‘no-regret potentials’, which opposed top-down and bottom-up modellers in the 1990s. While it remains hard to identify and assess market imperfections, comparison of the results of optimal planning models, on one side, and market simulation models[1] on the other, can convey rough ideas about the magnitude of the existing barriers to changes in technology and behaviour.

Beyond this, there may be other imperfections outside of the technological sphere but nevertheless critical: for example, on labour, capital and other non energy markets. Disappointingly, those imperfections are insufficiently analysed in the economic literature about climate policies, even though they are likely to condition the efficiency and the net cost of climate policies. The ‘visible part’ of the iceberg includes carbon leakages (that hangs on both trade and capital flows) and investment crowding-out. Labour market imperfections were considered in the past but have been neglected for the past decade.

Indeed, one has to hark back to the double dividend controversy that occurred during the nineties to find several articles that explored the links between mitigation policies and labour market dynamics (Bovenberg and van der Ploeg 1994); (Welsch 1996); (Carraro et al 1996); (Bovenberg and van der Ploeg 1996) (Bovenberg 1999). The general issue then was to determine to what extent the replacement of a fraction of payroll taxes by a $CO_2$ tax could generate extra economic benefit that could eventually offset the costs of mitigation. The answer has not really been resolved, as the

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[1] However it should be noticed that the status of most simulation models is unclear, since they represent perfect markets with no imperfection, but calibrated on real imperfect markets. Their output is then unclear, somehow hybrid between the economic potential –what is profitable- and the market potential -what is achievable with the current conditions.

assessment of the magnitude of the double dividend critically depends on the intricate representation of the labour market in models.

Since then, there have been only a few contributions quantitatively examining the importance of labour market imperfections on the costs of climate policies. To our knowledge, the study of Babiker and Eckaus (2007) is the most developed, in the sense that the authors (i) recognized the importance of the issue, (ii) modified the EPPA model to assess the impact of sector-specific labour and wage rigidities, (iii) demonstrated that such imperfections may increase mitigation costs, (iv) eventually showed that additional appropriate labour policies, namely outplacement assistance and wage subsidies, could offset the cost increase. It may appear surprising that after the innovative demonstration that labour market dynamics are critical in the assessment of climate policies[2], the EPPA team never used again the modified version of the model in the dozens that followed.

By shelving the issue, one runs the risk of missing both the appropriate parallel policies that could reconcile employment and climate, and a safe stabilization of our climate. This article explores the critical role of labour market imperfections in climate policy costs. Our approach differs from previous ones since labour and capital market imperfections are intrinsically represented in our model, IMACLIM-R. This model is a dynamic recursive energy-economy model, designed to handle three well-known methodological problems: (i) consistently hybridizing disaggregated technical potentials with general equilibrium constraints (Hourcade and al. 2006), (ii) representing short-run adjustments constraints along a long term growth path (Solow 2000), and (iii) allowing for market imperfections, suboptimalities and adaptive expectations[3]. This new modelling paradigm has been recognized earlier as producing an important transitional slowdown of economic growth during two decades after the start of stringent climate policies (Edenhofer and al. 2006); (Hourcade and Crassous 2008). This study was originally motivated by the need to identify the very sources of these costs and to understand which policies could smooth the transition while achieving the same environmental results, and led us to understand the critical role of labour market. Technically, in each region of the model, the labour market is modelled through an aggregate regional *wage curve* that links real wages to the unemployment rate (Blanchflower and Oswald 1995).

Assuming this representation can encapsulate most of labour markets' imperfections, we found that the calibration of the wage curve is a critical parameter that can shift the model from our initial high-cost simulations to scenarios in which policy costs are within the usual range. The conclusion would be of limited interest if we had to interpret the sensitivity of the model results, to such a hidden and

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[2] In another modelling report, the same team recognized that 'a third limitation is that, like capital, labour is treated as being in inelastic supply. This, combined with the full employment assumption that is standard in many CGE models, implies that the reduction in labour demand associated with the decline in fossil fuel and energy-using sectors cannot generate unemployment. Instead, the wage falls, allowing the labour market to clear and surplus labour to move to the rest of the economy, where it is re-absorbed.' (Wing 2004)

[3] IPCC, 2007

uncertain parameter as a harmful weakness. On the contrary, this sensitivity reveals the importance of labour market dynamics on climate policy costs. This is ignored in all models based on a full utilization of the labour force. While we do not pretend to represent the labour market accurately enough to derive precise policy recommendations, our conclusion is that achieving ambitious reductions at a reasonable macro cost (within the range of costs assessments gathered by the IPCC) will certainly require specific parallel policies on the labour market. As an example, in the last part of the article, a recycling policy is tested that re-allocates the tax revenue to labour subsidies. It was found that such a policy succeeds in lowering mitigation costs, whatever the calibration of the wage curve.

The first section considers the literature on the links between climate policy assessments and the representations of the labour market. The second section describes the Imaclim-R model used in this article, while the third section presents and considers the simulation results. The final section discusses the results and concludes.

# 1. Modelling interactions between labour market imperfections and climate policies

## 1.1 Existing models

Almost all numerical models used in climate policy studies assume a perfect labour market and neglect unemployment issues, even those complex computable general equilibrium models whose comparative advantage is intended to represent subtle macro feedbacks. In general, labour supply is equal to active population multiplied by an exogenously increasing productivity and is fully flexible across all sectors, so that it always remains fully utilized with its price equalizing its marginal productivity in all (CES) production functions.

This representation contrasts with the imperfections of real world labour markets. Indeed, friction arises in the labour markets due to e.g. geographic immobility, the time-consuming job search process, and the specific skills required for a specific job sector. Moreover wages are not fully flexible: wage rigidities are linked to work contracts, the power of unions, and laws on minimum wage etc. Since J.M. Keynes, the study of labour market rigidities and their macroeconomic implications is one of the central preoccupations of macroeconomists[4]. The attention devoted to this issue in the macroeconomic field, and the refinement of theories and representations of labour market rigidities proposed in the

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[4] The seminal contributions in this field are too numerous to single out in this text. The interested reader may refer to the recent article by Blanchard and Galí (2007) who analyse the implications of the introduction of real wage rigidities in the New Keynesian Model and also give an overview of recent developments in the theories and representations of labour market rigidities.

literature, stands out against the very poor representation of labour markets in most energy-economy-environment (E3) models.

Notable exceptions are E3MG (Köhler et al. 2006), SGM (Fawcett and Sands, 2005) and the version of EPPA mentioned in the introduction (Babiker and Eckaus, 2007). Technically, in E3MG, employment is output-driven and real wages are linked to the unemployment rate through an econometric equation. In SGM, labour supply stems from a leisure-labour trade-off while labour demand remains elastic, so that there is no involuntary unemployment. The most refined representation of labour markets is probably in the version of EPPA by Babiker and Eckaus (2007), which includes the inertia of inter-sector reallocation (e.g. a share of the labour force is sector specific in the short-run) and wage rigidities (e.g. the model takes into account a constraint of minimum nominal wage equal to the calibration year wage). However this representation of labour markets' rigidities is not included in the standard version of EPPA, which assumes perfect labour markets.

Our approach differs from the previous one since labour markets imperfections are represented in the basic version of our model and are critical, as will be seen, to explain the magnitude of the climate mitigation costs it estimates.

The next section details Imaclim-R's architecture, in which the labour market is output-driven while real wages are linked to unemployment through regional wage curves.

## 1.2 The Imaclim-R model: partial factor utilisation and short-run adjustments

### a. Model architecture and major features

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy that is split into 12 regions and 12 sectors (Crassous and al. 2006), (Sassi and al. 2009). It is hybrid in two senses: (1) It is a classical hybrid model in that its structure is designed to combine Bottom-Up information in a Top-Down consistent macroeconomic framework. Energy is explicitly represented in both money metric values and physical quantities so as to capture the specific role of energy sectors and their interaction with the rest of the economy. Indeed the existence of explicit physical variables allows a rigorous incorporation of sector based information about how final demand and technical systems are transformed by economic incentives. (2) It is hybrid in the sense of Solow (2000)[5], i.e. it tries to bridge the gap between long-run and short-run macroeconomics. In designing IMACLIM-R, we attempt not only to model long-term mechanisms but also to focus on transition and suboptimal pathways through

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[5] Solow (2000) : 'I can easily imagine that there is a 'true' macrodynamics, valid at every time scale. But it is fearfully complicated [...] At the five-to-ten-year time scale, we have to piece things together as best we can, and look for a hybrid model that will do the job.'

the possible underutilization of production factors. The intention is to capture the transition costs with a modeling architecture that allows for endogenous disequilibrium generated by the inertia in adapting to new economic conditions due to both imperfect foresight and non-flexible characteristics of equipment vintages available at each period (putty-clay technologies[6]). In the short run, the main available flexibility lies in the rate of utilization of capacities, which may induce excess, or shortage, of production factors, unemployment and unequal profitability of capital across sectors. This framework therefore represents a second-best world.

Technically, the model can be labelled as 'recursive dynamic', since it generates an energy-economy trajectory by solving successive yearly static equilibria of the economy, interlinked by dynamic modules. Within the static equilibrium, domestic and international markets for all *goods* – except *factors* such as capital and labour – are fully cleared by a unique set of relative prices that depend on the behaviours of representative agents on the demand and supply sides. The calculation of this equilibrium determines the following variables: relative prices, wages, labour, quantities of goods and services, value flows.

Within each yearly static equilibrium, the behaviour of producers is not represented by a flexible production function allowing for substitution between factors. These substitutions are treated between two equilibria in sector-specific dynamic modules. Producers are therefore assumed to operate under short-run constraints of (i) a fixed maximal production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with the equipment built and accumulated previously, and (ii) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of a good $i$ in region $k$ requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods $j$ and $l_{k,i}$ of labour. In this context, the only margin of freedom of producers is to adjust the utilisation rate $Q_{k,i}/Cap_{k,i}$ according to the relative market prices of inputs and output, taking into account increasing costs when the production capacities utilization rate approaches one[7]. This represents a different paradigm from usual production specifications, since the 'capital' factor is not always fully utilized.

Between two static equilibria, technical choices are flexible but they modify, only at the margin, the input-output coefficients and labour productivity embodied in existing equipment vintages that result from past technical choices. This general putty-clay assumption is critical to represent the inertia in technical systems.

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[6] The representation of « putty-clay » technologies, originally introduced by Johansen (1959), corresponds to production factors assumed to be substitutable ex ante, but once the capital installed, no substitution is possible and technology is represented by fix coefficients (Leontieff coefficients). This representation allows distinguishing short term rigidities and long term flexibilities.

[7] Following (Corrado and Mattey, 1997), we assume that this is generally caused by higher labour costs due to extra hours with lower productivity, costly night work and more maintenance works.

Our model is calibrated on 2001 data from GTAP 6 database (Dimaranan and McDougall 2002) that provides, for the year 2001, a set of balanced input-output tables of the world economy, detailed in 87 regions and 57 sectors. We modified the original GTAP-6 dataset (i) to aggregate regions and sectors according to the IMACLIM-R mapping (ii) to make it fully compatible with the 2001 IEA energy balances[8].

Our model growth engine is composed of exogenous demographic trends (UN World Population Prospects, medium scenario, United Nations, 2005) and exogenous trends of labour productivity, as in Solow's neoclassical model of economic growth (Solow 1956). To build these trends we draw on stylized facts from the literature, in particular the convergence assumption (Barro and Sala-i-Martin 1992) and two empirical analyses on economic convergence, one investigating the past trends by Maddison (1995), and the other one looking at future trends, by Martins and al. (2005). We retained a "leader", the US, whose labor productivity growth trend lies between 2% today and 1.65% in the long run. The other regions labor productivity trends catch up with the leader's, i.e. their labour productivity growth is higher all the more as their absolute labour productivity is far from the leader's level.

The two sets of assumptions on demography and technical change, although exogenous, only prescribe potential growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labor and capital). The next section details this last point.

### b. Labour market representation

As already mentioned in the previous section, producers operate in static equilibria with a fixed input of labour per unit of output. This labour input, corresponding to labour productivity, evolves between two yearly equilibria following exogenous trends of labour productivity.

Three of the model features explain the possibility of under-utilisation of labour as a production factor, and thus of unemployment. First, rigidity of real wages, represented by a wage curve (as shown below) can prevent the wages falling to their market-clearing level. Put another way, the wages are adjusted instantaneously to the economic context in the static equilibrium, but not in an optimal manner. Second, in the static equilibrium, the fixed technologies (Leontief coefficients even for labour input) prevent substitution among factors on the short run. And third, the installed productive capital is

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[8] This process of building hybrid input-output matrices is very precisely discussed in (Sands et al., 2005).

not mobile across sectors, which creates rigidities in the reallocations of productions between sectors when relative prices change.

In each region $k$, each sector employs the labour force $l_{k,i} Q_{k,i}$, where $l_{k,i}$ is the unitary labour input (in hours worked) and $Q_{k,i}$ the production. The underutilization of the labour force, equivalently referred to as the 'unemployment rate'[9] in the following, $z_k$ is therefore equal to one minus the ratio of employed labour force in all sectors over $L_k$, the total labour if all active population was fully employed:

$$z_k = 1 - \frac{\sum_i l_{k,i} \cdot Q_{k,i}}{L_k} .$$

No endogenous mobility of workers between regions is allowed in the model. Thus twelve separate labour markets are represented.

We chose to model labour markets imperfections through an aggregate regional *wage curve* that links real wage levels to the unemployment rate. This representation is based on theories developed in the 1980s and early 1990s in which an aggregate wage curve, or *wage setting curve*, is the primary distinguishing feature (an overview can be found in Layard et al., 2005; Lindbeck, 1993; or Phelps, 1992). The novel approach of these models, when introduced, was to replace the conventional labour supply curve with a negatively-sloped curve linking the level of wages to the level of unemployment. The interpretation of this wage curve is given either by the bargaining approach (Layard and Nickell, 1986) or the wage-efficiency approach (Shapiro and Stiglitz, 1984). Both interpretations rely on the fact that unemployment represents an outside threat that leads workers to accept lower wages when the threat is important. The bargaining approach emphasizes the role of workers' (or unions') power in the wage setting negotiations, power that is weakened when unemployment is high. The wage-efficiency approach takes the firms' point of view and assumes that firms set wage levels so as to discourage shirking; this level is lower when the threat of not finding a job after being caught shirking gets higher. The wage curve specification allows the theories to be consistent with both involuntary unemployment and the fact that real wages fluctuate less than the paradigm of the conventional flexible labour supply curve predicts. Microeconometric evidence for such formulation was given in a seminal contribution by (Blanchflower and Oswald 1995).

In practice, the wage curve for each region k in our model is implemented through the relation:

$$\frac{w_k}{pind_k} = aw \cdot \frac{wref_k}{pindref_k} \cdot f\left(\frac{z_k}{zref_k}\right),$$

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[9] Contrary to the definition by the U.S. Bureau of Labour Statistics, the unemployment is here expressed in terms of worked hours and not in terms of persons.

where *w* is the hourly nominal wage level, *pind* the consumption price index, *z* the unemployment rate, *ref* indexes represent the value at the calibration date, *pindref* is derived from the final consumption prices and volumes at the calibration date, *wref* is calibrated from the total salaries per sector in GTAP 6 database and the shares of labour force per sectors in the International Labour Organisation statistics. By default, *aw* is calibrated to 1 and evolves in parallel to the labour productivity so that unitary real wages are indexed on labour productivity. *zref* represents the underutilization of the labour force at the calibration date. *f* is a function equal to one when the unemployment rate is equal to its calibration level, and negatively sloped, representing a negative elasticity of wages level to unemployment[10].

There remain important uncertainties about the values to assign to the elasticity of wages level to unemployment and to the underutilization of the labour force at the calibration date. By default, we assume all regions' labour markets are identical and set the underutilization of the labour force at 10%[11] and the wage curve elasticity at -0.1 for all regions (This is a value emerging from many econometric studies, e.g. see (Blanchflower and Oswald 1995), (Blanchflower and Oswald 2005)). But, it is uncertain enough to justify a systematic sensitivity analysis of our model's results, which is the topic of the following section.

## 2. Numerical experiments and results

### 2.1 Experimental protocol

The model is used to consider two sets of scenarios: a set of 'reference' scenarios, i.e. without climate policies, and a set of '550ppm' scenarios with climate policies, starting in 2010, represented by carbon pricing so as to fit a given global emissions profile corresponding to stabilisation target at a concentration of 550ppm for all gases.[12] This provides a "cost-efficiency" context.

For each set of scenarios, the model is run with alternative values for the elasticity of the wage curve exploring a wide interval from zero to high values. For each scenario, the wage setting function is thus recalibrated so that it has the chosen elasticity at the calibration point. Low values represent very rigid labour markets whereas high values get closer to perfect labour markets. An infinite elasticity would be equivalent to the full employment assumption, but it is not compatible with the Leontief

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[10] Choosing a functional form and calibrating the function is particularly tricky, notably due to the lack of reliable data to fully inform the functioning of the labour markets worldwide. We chose a function of the form $a \cdot \left(1 - \tanh\left(c \cdot z\right)\right)$, and calibrate the parameters *a* and *c* so as to have the desired value and elasticity at the calibration point.

11 Obviously, this is a limitation of the current calibration of the model. Future developments will look into the possibility to differentiate labour markets per regions. However, one important difficulty lies in the lack of reliable data on the underutilization of the labour forces in all regions, in particular due to informal economy, very diverse accounting rules for unemployment rates and variations in hours worked per person across countries.

[12] By default, the carbon tax revenues are rebated to households in a lump-sum manner.

specification for the production function. Therefore, we limit the interval and we stop our exploration at the upper value of seven.

### 2.2 Results

There are several different concepts of climate mitigation costs: technical cost, macroeconomic cost and welfare cost (see for instance Hourcade and Ghersi, 2009). This article focuses on the macroeconomic cost of mitigation, which will be measured through the global GDP variations, as it is common practice in the IPCC. This allows comparison of our model results to the range of existing costs evaluations reported in the last IPCC report. Thus, the results of the numerical experiments are shown in terms of discounted real GDP losses[13] over the period 2010-2050 between each 550ppm scenario and the corresponding reference scenario[14].

Figure 1 presents the global discounted GDP variations over the period 2010-2050 between each of the ‘550ppm’ scenarios, and the corresponding ‘reference’ scenario with the same wage curve elasticity, plotted against the wage curve elasticity. As it is beyond the scope of this article to discuss what suitable discount rate should be taken, Figure 1 gives the curves for two contrasted discount rates that correspond to the values used by the US Office of Management and Budget to analyze policy decisions (OMB, 2003; see Appendix D, OMB Circular A-4). The discount rate chosen shifts a little the curve up for higher discount rates, but does not change its shape. It clearly appears that the lower the wage curve elasticity, the higher the global GDP losses. This result is not surprising considering that the elasticity of the wage curve determines the balance between the adjustment of the economy in prices (high elasticity) or in quantities (low elasticity). The wage curve could be interpreted as playing the role of a spring anchoring the aggregated production quantities through labour intensity to the value $L_k.(1\text{-}zref_k)$, with a constant spring inversely related to the elasticity of the wage curve (the more the wage curve is elastic, the less the spring is stiff). For a fully flexible wage curve, the aggregate of production quantities is anchored to the $L_k.(1\text{-}zref_k)$ value. The rigidity of the wage curve gives the possibility to move away from the anchor, thus adding to the impact of the reallocation of production across sectors on real GDP, an impact on the general level of activity.

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[13] We measure the real GDP with the Laspeyres index of quantities.

[14] Note that we do not have a single reference scenario but one per value of the elasticity of the wage curve tested. Indeed the elasticity influences the results, GDP growth in particular, in the scenario without climate policy as well. Therefore each 550ppm scenario has to be compared with the scenario without climate policy but with the same representation of the labour market, provided that the climate policies do not modify the functioning of the labour market.

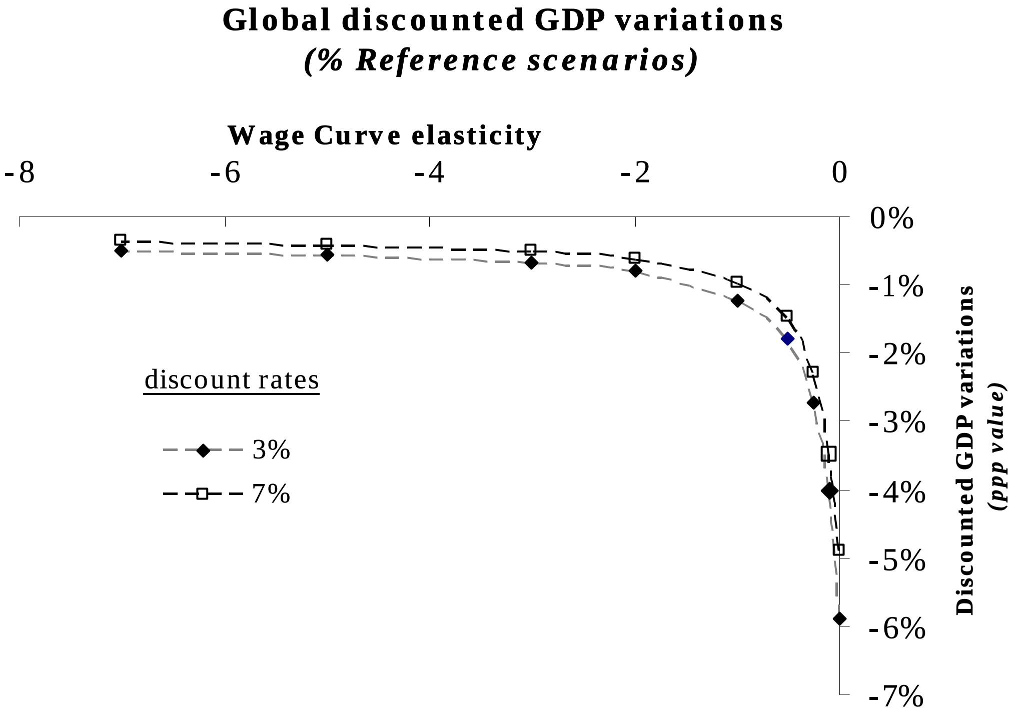

**Figure 1 :** Global GDP variations discounted over the period 2010-2050 between stabilisation scenarios and corresponding reference scenarios, depending on the wage curve elasticity, and for two discount rates (3% and 7%).

When we get close to fully flexible labour markets (high elasticity, in absolute value), costs are limited, which connects our model's results to existing literature. Using the IPCC AR4 measures, our model results are ranging from 0.5% to 1.5% global GDP losses in 2030 for the wage curve elasticity going from -7 to -1, and from 0.9% to 1.6% in 2050 for the same wage curve elasticity range. This makes our results compatible with the intervals given in the IPCC AR4: 2030 GDP losses ranging from 0.2% to 2.5% in 2030, and from slightly negative (actual gains) to 4% loss in 2050, with median values of 0.6% in 2030 and 1.3% in 2050.[15] It remains true, however, that the high values of the wage curve elasticity necessary to replicate IPCC results are not compatible with econometrically estimated values, all the more since what matters here is the downwards flexibility of wages, which was evaluated to even lower values than upwards flexibility of wages (Akerlof et al. 1996), (Kahn 1997), (Altonji and Devereux 1999) and (Dickens et al. 2007).

When moving to lower values, in absolute value, of the wage curve elasticity (e.g. below 1), the slope of the curve is steep and mitigation costs increase dramatically. This interval of wage curve elasticities explored is more compatible with econometrically estimated elasticities. We acknowledge that wage

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[15] Note that the carbon price emerging in our simulations is around 50$/tCO$_2$ in 2030 and around 100$/tCO$_2$ in 2050, with slight variations depending on the value of the wage curve elasticity. This order of magnitude is within the range given by the IPCC AR4: 30-150$/tCO2 in 2050 for stabilisation levels between 535 and 590ppm CO$_2$-eq.

curves are only one of several alternative representations of labour market rigidities. Moreover, the value of the wage curve elasticity valid for each country is still debated: the value of -0.1 found by (Blanchflower and Oswald, 1995) for twelve countries has been confirmed by many studies (For example, Blanchflower and Oswald, 2005 give an impressive list of such studies). However, it has been challenged by others, for instance Nijkamp et al. (2005), who show that reported elasticities do vary, even excluding outliers, between -0.5 and +0.1. However, without taking a stand on what the “right” representation of labour market rigidities is or on what the “exact” elasticity of the wage curve is, we show that taking into account labour market imperfections leads to higher macroeconomic costs of climate mitigation than in the case of perfect labour markets.

Our results are not fully comparable to those of Babiker and Eckaus (2006) because we consider different climate policies (Kyoto Protocol emissions caps throughout the 2010-2100 horizon in Babiker and Eckaus, 2006 *v.* a 550ppm stabilisation target here) and different ways of representing labour market rigidities (shares of sector specific labour and minimum nominal wages *v.* wage curves). Nevertheless, we may note that both studies show that labour market imperfections induce larger macroeconomic costs of climate mitigation than perfect labour markets. The magnitude of the impact is, however, different. Babiker and Eckaus (2006) find relatively small impacts: US GDP variations between the climate policy scenario and the reference scenario in 2100 equal -3.5% of the reference GDP without labour market imperfections and -5% with labour market imperfections. For Japan, the same indicator changes from -10% to -12% when labour market imperfections are taken into account, whereas it has almost no impact in Europe. Our results suggest more significant impacts of labour markets rigidities on mitigation costs: the discounted world GDP loss varies from 0.35% with the wage curve elasticity equal to -7 (close to perfect labour market) to almost 3.5% with an elasticity equal to -0.1.

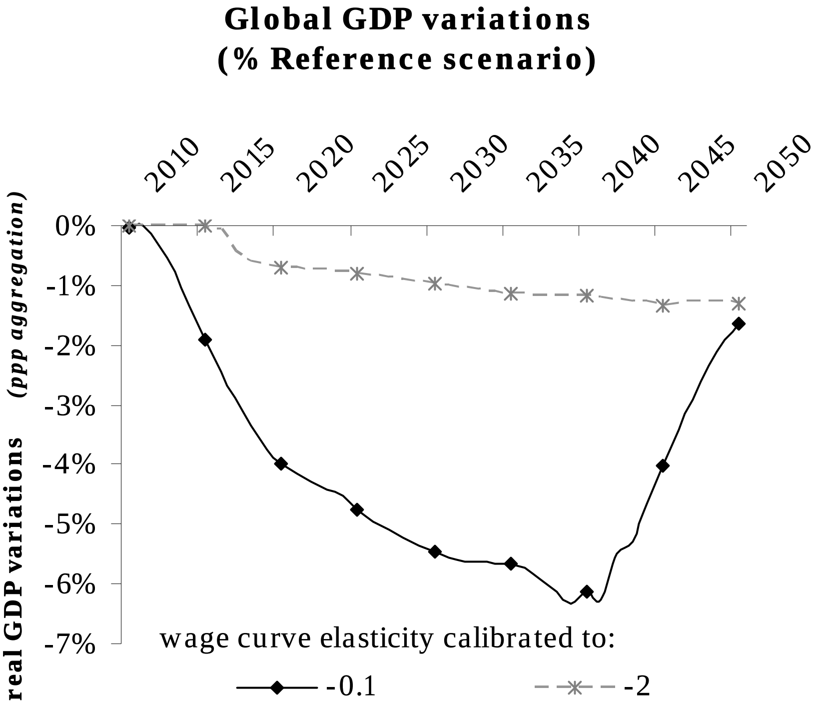

**Figure 2 :** Global GDP relative variation in ppp values between a stabilisation scenario corresponding to a 550ppm concentration target and the corresponding reference scenario, for two alternative elasticities of the wage curve calibrated to -0.1 (black diamonds) and -2 (grey crosses) respectively.

Figure 2 shows the temporal profile of global GDP relative variation, between a stabilisation scenario and the corresponding reference scenario, for two alternative elasticities of the wage curve calibrated to -0.1 and -2 respectively. It illustrates another peculiarity in our model's results: it exhibits transition costs whereas a majority of models give costs increasing over time. In the last decade of the time horizon, global GDP partially catches up with its baseline level. This partial catch-up is explained by (i) induced technological change which lowers costs of low carbon techniques (Crassous et al., 2006) and (ii) lower vulnerability to peak oil in the stabilisation scenario than in the baseline[16]. The economic vulnerability to peak oil is linked to the imperfect expectation of a steep increase in oil price[17] and the subsequent investment decisions that eventually reveal inadequate to high oil prices. In stabilisation scenarios, this imperfect expectation is partially corrected by carbon pricing: technical change and consumption structure change induced by climate policies reduce the economic dependence on oil and lower tensions on oil markets. Exploring further the issue of the time profile of GDP losses is beyond the scope of this paper, but Figure 2 calls into question the common attitude of most economists who claim to be

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[16] Investigating the respective influence of both mechanisms is beyond the scope of this paper.

[17] For instance, in the baseline scenario with a wage curve elasticity calibrated to -0.1, the endogenous international oil prices rise from 85$/bbl in 2040 to 184$/bbl in 2050.

‘neoclassical on the long run’[18]. When transposed to the field of climate change this attitude leads to the use of models based on a full utilization of production factors along stabilized growth pathways because climate stabilization is interpreted mostly as a long run challenge while rigidities in the labour market and unemployment are considered as a short to medium term issue. We argue that this position is restrictive because it makes it impossible to analyze the transitional pathways that lead to a low carbon economy. The *goal* of climate policies – avoiding a dangerous climate change – is obviously relevant in the long term only, but climate policies themselves are likely to impact the short and medium term before delivering their final outcome. We demonstrate here that a mechanism considered as purely short-term has impacts over the long-term: stronger rigidities in the labour markets lead to a larger reduction in growth rates over three decades in climate stabilisation scenarios when compared to baseline scenarios.

The previous results indicate that stabilisation costs may race out of control in case of high rigidities on the labour markets. These results do not mean that ambitious mitigation actions should not be undertaken because of high mitigation costs, but that we should concentrate on how to reduce these costs if they eventually turn out to be higher than what classical literature gives. More precisely, as there is uncertainty on the functioning of the labour markets today, *a fortiori* on how they will change over time, accompanying measures are needed to reduce the risk of the steep increase of mitigation costs. To do so, we focus here on measures that tend to offset the rise in production costs due to carbon pricing and are directed towards labour. Below, we assess how using carbon tax revenues to lower payroll taxes, or subsidise labour[19], changes mitigation costs. Figure 3 shows that this policy largely offsets GDP losses. The curve of discounted GDP losses, as a function of the wage curve elasticity, is now almost flat. The steep increase of stabilisation costs when wages are rigid does not occur with the tax-recycling policy tested here. These results are consistent with the literature on the double dividend and labour market imperfections, which have tended to show that the more flexible the labour market, the lower the magnitude of the double dividend (Welsch 1996). Figure 3 shows that for very low absolute values of the wage curve elasticity, global discounted GDP variations between the stabilisation scenario and the corresponding reference scenario may even become positive, in the case of a 3% discount rate. This result is due to the facts that in the long run, (i) the stabilisation scenario exhibits actual GDP gains compared to the reference and (ii) the lower discount rate gives more importance to these gains. These GDP gains confirm the fact that our model represents a second best world, or more precisely that our baselines are not optimal in terms of GDP growth. These results

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[18] Solow (2000): ‘ I can easily imagine that there is a "true" macrodynamics, valid at every time scale. But it is fearfully complicated, and nobody has a very good grip on it. At short time scales, I think, something sort of "Keynesian" is a good approximation, and surely better than anything straight "neoclassical." At very long time scales, the interesting questions are best studied in a neoclassical framework, and attention to the Keynesian side of things would be a minor distraction.’

[19] By default, the revenues of the carbon tax are rebates to households in a lump-sum manner.

corroborate those of Babiker and Eckaus (2006), who conclude that “...if the one type of interference with the markets is imposed, in this case the imposition of emissions restrictions, and there are labour market imperfections, an offsetting policy, e.g. wage subsidies, as an example, can ameliorate, and possibly eliminate the negative effects...”.

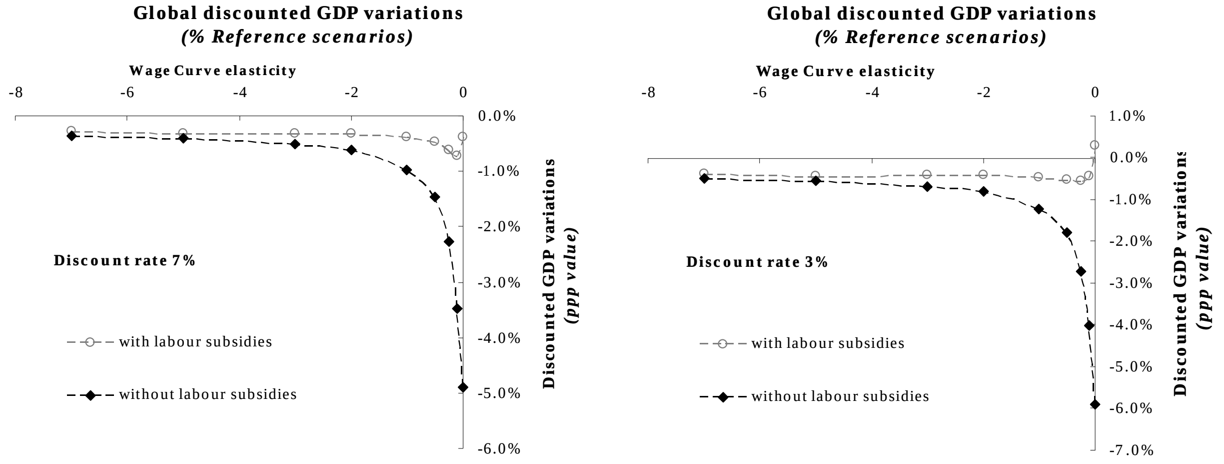

**Figure 3 :** Discounted global GDP variations between stabilisation scenarios and corresponding reference scenarios, depending on the wage curve elasticity, with (grey rounds) or without (black diamonds) labour subsidies in the stabilisation scenarios, for two discount rates 7% (left panel) and 3% (right panel).

## 3. Conclusions

The aim of the study was to understand why our model’s results were at the higher end of existing mitigation costs estimations. This led us to show that the representation of rigidities in labour markets is critical to the assessment of mitigation costs. When labour markets are highly flexible, the mitigation costs are very limited in the model (less than 2% real GDP losses in 2050). This positions our results into the usual range of costs assessments. But these results are based on unrealistic values of the elasticity of the wage curve (especially for downward flexibility). Using more realistic values for this elasticity leads to a dramatic increase of mitigation costs. The use of wage curves is admittedly only a very stylised representation of labour markets imperfections; there are many alternative representations of rigidities in wage adjustment (e.g. nominal wage stickiness, minimum wage etc.) or in labour mobility (e.g. the costs of labour reallocation across sectors). Nonetheless, in the absence of certainty on the functioning of labour markets, our results constitute a warning that there is a risk that costs might be higher than current assessments indicate and call for a cautious assessment of the role of rigidities in the labour markets in the modelling architectures used to evaluate the costs of climate policies.

Our results also demonstrate that, mechanisms considered as purely short-term such as maladjustment of the labour markets can have impacts over the long-term (as already argued in (Guivarch et al, 2009)). It contradicts the common attitude of most climate change economists who neglect short-term mechanisms and use models based on a full utilization of production factors along stabilized growth pathways on the grounds that climate stabilization is a long-term challenge. We do not claim that the representation of labour markets rigidities adopted in this study is perfect, and more subtle representations exist in the macroeconomic literature. However, labour markets rigidities have important implications for the analysis of climate policies. From a methodological point of view, it is therefore a priority to integrate in energy-economy-environment models second-best representations from macro models.

The model in its current form cannot be used to analyse the trade-offs posed by labour market rigidity because it does not take into account all consequences of more or less flexible labour markets. In particular, it does not include the possibility of insufficient demand (in a Keynesian sense), which can make a high flexibility lead to instability and cyclical behaviours. An illustration of this effect is provided by Hallegatte and Ghil (2008), who show how investment flexibility enhances economic resilience to supply-side shocks up to a certain level, beyond which flexibility leads to instability and high vulnerability phases. Moreover, the model does not account for all consequences of high labour flexibility, especially on income distribution between capital and labour revenues and between skilled and unskilled labour revenues. This distribution, however, has important consequences on inequalities and on the saving ratio (e.g., Pasinetti, 1962; Venieris and Gupta, 1986; Barro, 2000), with potentially significant macroeconomic impacts.

This article focused on the macroeconomic mitigation costs in presence of labour markets imperfections, but did not investigate the employment content of the sectoral structural change and technological change triggered by climate policies. Our model has a too high level of aggregation to answer this issue in a satisfactory manner. However, employment is one of the main concerns for policy makers, as shown by the current emphasis on “green jobs”. Studies analysing in detail the employment content of climate change mitigation policies are therefore a necessary complement to this article. For instance, Jochem and Homeyer (1992), Laitner et al. (1998) and Walz (1999) propose quantifications of mitigation driven jobs creation. More recent publications (OECD, 2004; Moreno and Lopez, 2008; Fankhauser et al., 2008; ETUC et al., 2009) illustrate the renewed interest in this topic.

From a climate policy design point of view, the article identifies accompanying measures, namely labour subsidies, which guarantee against the risk that stabilisation costs race out of control in the case of high rigidities of the labour markets. Again, the policy of recycling the carbon tax revenues (in reducing payroll taxes or in labour subsidies) was tested in only a very crude representation of more sophisticated policies that could be implemented to accompany the transition toward low carbon economies. The policy package will probably encompass measures such as continuing education to facilitate professional reconversions, new training offers to meet new demands on the labour market (e.g. specialists in buildings energy efficiency) etc. That vision complements the usual view that mitigation is only a matter of technology, innovation, investment and behavioural change. It has already been emphasized that climate policy costs will depend on subtle mechanisms such as induced technical change and innovation (Arthur, 1989), international trade feedbacks (McKibbin et al. 2000) or the formation of expectations (Paltsev et al. 2009). Here we add the warning that mitigation is also a matter of labour market transition. This transition can be made easier by specific collateral policies that need to be assessed. Ignoring them could result in much larger costs that what most models suggest.

## Acknowledgements

The authors wish to thank Camille Thubin, Frédéric Ghersi, Louis-Gaëtan Giraudet and Philippe Quirion for their useful comments and suggestions. We are also grateful to three anonymous reviewers who helped us improve our article.

This research was supported by the European Commission’s project FP7-SSH-2009-A ‘AUGUR’ and the Chair ‘Modeling for sustainable development’, led by MINES ParisTech, Ecole des Ponts ParisTech, AgroParisTech and ParisTech, and financed by ADEME, EDF, RENAULT, SCHNEIDER ELECTRIC and TOTAL. The views expressed in this article are the authors’ and do not necessarily reflect the views of the aforementioned institutions.

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# Appendix : Equations of the static equilibrium

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy that is split into 12 regions and 12 sectors. Technically, the model can be labelled as 'recursive dynamic', since it generates an energy-economy trajectory by solving successive yearly static equilibria of the economy, interlinked by dynamic modules (Figure 4).

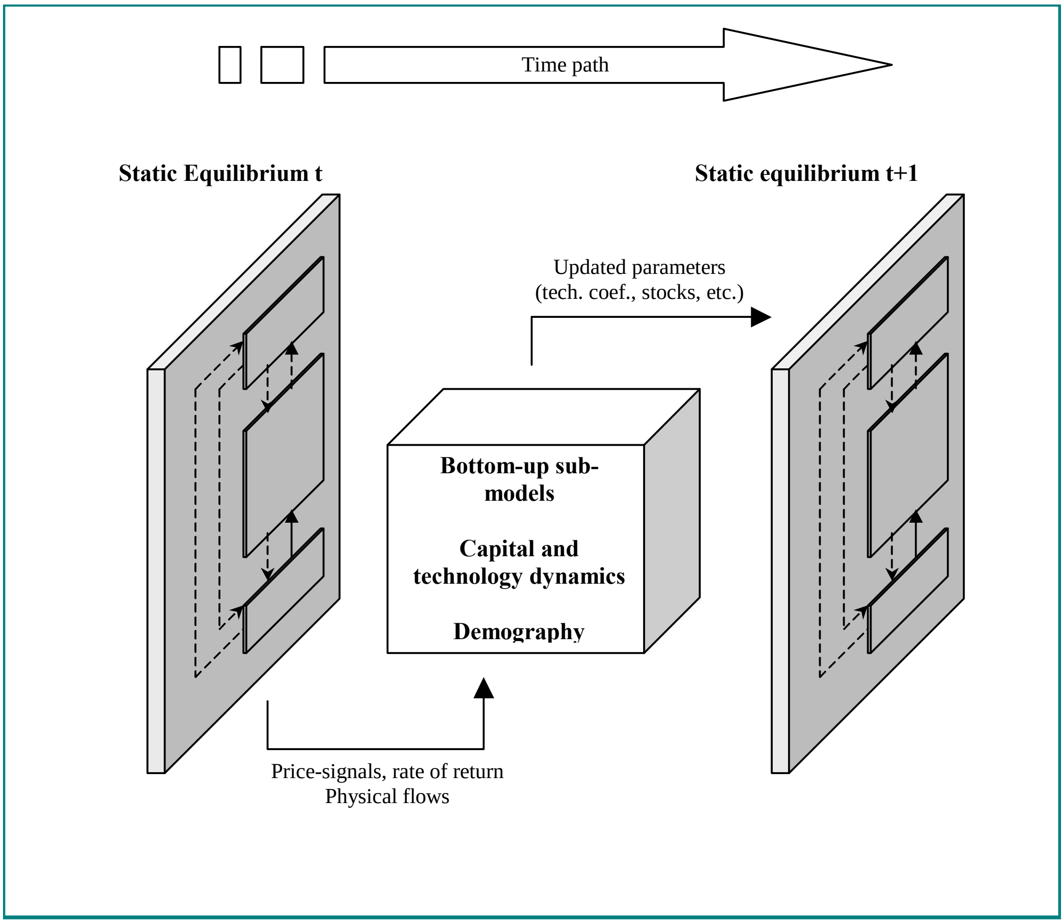

**Figure 4 : The recursive dynamic framework of IMACLIM-R. Source: Sassi et al. (2010).**

The calculation of the equilibria determines the following variables at each date *t*: relative prices, wages, labour, quantities of goods and services, value flows. Dynamic modules represent the evolutions of the static equilibria parameters.

This appendix details the equations of the static equilibria. The equations from the dynamic modules are not specified here as it is not the focus of the article.

**Equations of the static equilibrium**

Bold=variable

k index represents regions, *i* and *j* indexes represents sectors.

*t* refers to the date of the equilibrium, (*t*-1) to the previous equilibrium.

## Core equations

Income formation

$$\mathbf{Income_k} = \sum_{sectors\ i} \mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}} \cdot l_{k,i} \cdot \mathbf{Q_{k,i}} + \sum_{sectors\ i} div_{k,i} \cdot \pi_{k,i} \cdot \mathbf{p_{k,i}} \cdot \mathbf{Q_{k,i}} + \mathbf{transfers_k}$$

Governments' budget

$$\sum \mathbf{taxes} = \sum_{sectors\ i} G_{k,i} \cdot \mathbf{pG_{k,i}} + \mathbf{transfers_k} + InvInfra_k$$

The sum of taxes corresponds to the total of tax revenues, i.e. the tax rates (parameters) applied to the taxable amounts (often endogenous to the equilibrium): for instance the tax rate on labour $tax^{w}_{k,i}$ applied to total salaries $\sum_{sectors\ i} \mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}} \cdot l_{k,i} \cdot tax^{w}_{k,i} \cdot \mathbf{Q_{k,i}}$.

Utility maximisation

$$\mathbf{U_k}\left(\vec{\mathbf{C}}_\mathbf{k}, \vec{\mathbf{S}}_\mathbf{k}\right) = \prod_{\substack{\text{goods } i \\ \text{services } j}} \left(\mathbf{C_{k,i}} - bn_{k,i}\right)^{\xi^{C}_{k,i}} \left(\mathbf{S_{k,j}} - bn_{k,j}\right)^{\xi^{S}_{k,j}}$$

$$\mathbf{S_{k,mobility}} = \left(\left(\frac{\mathbf{pkm_{k,air}}}{b_{k,air}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,public}}}{b_{k,public}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,cars}}}{b_{k,cars}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,nonmotorized}}}{b_{k,nonmotorized}}\right)^{\eta_k}\right)^{\frac{1}{\eta_k}}$$

Income constraint

$$ptc_k \cdot \mathbf{Income}_k = \sum_{sectors\ i} \mathbf{pC_{k,i}} \cdot \mathbf{C_{k,i}} + \sum_{Energies\ Ei} \mathbf{pC_{k,Ei}} \cdot \left(\mathbf{pkm^{cars}_k} \cdot \alpha^{cars}_{k,Ei} + S^{m^2}_k \cdot \alpha^{m^2}_{k,Ei}\right)$$

Travel time budget constraint

$$Tdisp_k = \sum_{\text{means of transport j}} \int_0^{\mathbf{pkm_{k,j}}} \tau_{k,j}\left(\frac{u}{Captransport_{k,j}}\right) du\ ,$$

where $\tau_j$ represents the marginal efficiency in transport time (the time necessary to travel an additional passenger.kilometer with mode j) and is an increasing function of the form $\tau_{k,j}(x) = atrans_{k,j} \cdot x^{ktrans_{k,j}} + btrans_{k,j}$.

The first order conditions give N+S equations, with N the number of consumption goods and S the number of services, and add two unknowns, the Lagrange multipliers for both constraints.

Sector budget (supply curve)

$$\mathbf{p_{k,i}} = \sum_{sectors\ j} \mathbf{pIC_{j,i,k}} \cdot IC_{j,i,k} + \left(\mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}}\right) \cdot l_{k,i} \cdot (1 + tax^{w}_{k,i}) + \pi_{k,i} \cdot \mathbf{p_{k,i}}$$

$\mathbf{\Omega_{k,i}} = \Omega\left(\frac{\mathbf{Q_{k,i}}}{Cap_{k,i}}\right)$ represents an increasing cost (or decreasing returns) function of the productive capacities utilisation rate. The functional form for $\Omega$ is: $a - b \cdot \tanh\left(c \cdot \left(1 - \frac{Q}{Cap}\right)\right)$.

Labor market (wage curve)

$$\mathbf{z_k} = 1 - \frac{\sum_{sectors\ i} l_{k,i} \cdot \mathbf{Q_{k,i}}}{L_k}$$

$$\frac{\mathbf{w_{k,i}}}{\mathbf{pind_k}} = aw_{k,i} \cdot \frac{wref_{k,i}}{pindref_k} \cdot f\left(\frac{\mathbf{z_k}}{zref_k}\right)$$

Equilibrium constraints on physical flows

$$\mathbf{M_{k,i}} = \mathbf{shareC^{imp}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{imp}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{imp}_{k,i}} \cdot \mathbf{I_{k,i}} + [\sum_{sectors\ j} \mathbf{Q_{k,j}} \cdot IC^{imp}_{i,j,k} \cdot \mathbf{shareIC^{imp}_{i,j,k}}]$$

$$\mathbf{Q_{k,i}} = \mathbf{shareC^{dom}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{dom}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{dom}_{k,i}} \cdot \mathbf{I_{k,i}} + [\sum_{sectors\ j} \mathbf{Q_{k,j}} \cdot IC_{i,j,k} \cdot \mathbf{shareIC^{dom}_{i,j,k}}] + \mathbf{X_{k,i}}$$

Investment formation

$$\mathbf{NRB_k} = \mathbf{GRB_k} \cdot (1 - shareExpK_k) + \left(\sum_{countries\ k'} \mathbf{GRB_{k'}} \cdot shareExpK_{k'}\right) \cdot shareImpK_k$$

$$\mathbf{GRB_k} = \mathbf{Income_k} \cdot (1 - ptc_k) + \sum_{sectors\ j} \pi_{k,j} \cdot \mathbf{p_{k,j}} \cdot \mathbf{Q_{k,j}} \cdot (1 - div_{k,j})$$

$$\mathbf{InvFin_{k,i}} = \mathbf{NRB_k} \cdot shareInvFin_{k,i}$$

$$\mathbf{pCap_{k,i}} = \sum_{sectors\ j} \left(\beta_{j,i,k} \cdot \mathbf{pI_{j,i,k}}\right)$$

$$\mathbf{\Delta Cap_{k,i}} = \frac{\mathbf{InvFin_{k,i}}}{\mathbf{pCap_{k,i}}}$$

$$\mathbf{I_{k,j}} = \sum_{\text{sectors } i} \beta_{j,i,k} \cdot \mathbf{\Delta Cap_{k,i}}$$

**<u>Intermediate variables</u>**

Armington goods

$$\mathbf{C_{k,i}} = \left(b^{dom}_{k,i} \cdot \left(\mathbf{C^{dom}_{k,i}}\right)^{-\rho_{k,i}} + b^{imp}_{k,i} \cdot \left(\mathbf{C^{imp}_{k,i}}\right)^{-\rho_{k,i}}\right)^{-\frac{1}{\rho_{k,i}}}$$

$$\mathbf{pC_{k,i}} = \left(\left(b^{dom}_{k,i}\right)^{\sigma_{k,i}} \left(\mathbf{p_{k,i}} \cdot (1 + tax^{domC}_{k,i})\right)^{1-\sigma_{k,i}} + \left(1 - b^{dom}_{k,i}\right)^{\sigma_{k,i}} \left(\mathbf{p^{imp}_{k,i}} \cdot (1 + tax^{impC}_{k,i})\right)^{1-\sigma_{k,i}}\right)^{\frac{1}{1-\sigma_{k,i}}}$$

$$\mathbf{shareC^{dom}_{k,i}} = \left(b^{dom}_{k,i} \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p_{k,i}} \cdot (1 + tax^{domC}_{k,i})}\right)^{\sigma_{k,i}}$$

$$\mathbf{shareC^{imp}_{k,i}} = \left(\left(1 - b^{dom}_{k,i}\right) \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p^{imp}_{k,i}} \cdot (1 + tax^{impC}_{k,i})}\right)^{\sigma_{k,i}}$$

Similar equations to the four previous are valid for the States final consumptions, the investments and the intermediate consumptions.

$$\mathbf{p^{imp}_{k,i}} = \mathbf{wp_i} \cdot \left(1 + taxe^{M}_{k,i}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}} \cdot nit^{it}_{k,i}$$

$$\sum_{countries\ k} \left( \mathbf{shareC^{imp}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{imp}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{imp}_{k,i}} \cdot \mathbf{I_{k,i}} + \sum_{sectors\ j} \mathbf{shareIC^{imp}_{i,j,k}} \cdot IC_{i,j,k} \cdot \mathbf{Q_{k,j}} \right) = \mathbf{X_i} = \left[ \sum_{countries\ k} \psi_{k,i} \cdot \mathbf{X}_{\mathbf{k,i}}^{-\theta_i} \right]^{-\frac{1}{\theta_i}}$$

$$\mathbf{X_{k,i}} = \left[ \psi_{k,i} \cdot \frac{\mathbf{wp_i}}{\mathbf{p_{k,i}} \cdot (1 + tax^{X}_{k,i})} \right]^{\lambda_i} \cdot \mathbf{X_i}$$

$$\mathbf{wp_i} = \left( \sum_{countries\ k} \left(\psi_{k,i}\right)^{\lambda_i} \left(\mathbf{p_{k,i}} \cdot (1 + tax^{X}_{k,i})\right)^{1-\lambda_i} \right)^{\frac{1}{1-\lambda_i}}$$

Energy goods

$$\mathbf{C_{k,i}} = \mathbf{C^{dom}_{k,i}} + \mathbf{C^{imp}_{k,i}}$$

$$\mathbf{pC_{k,i}} = \mathbf{shareC^{dom}_{k,i}} \cdot \mathbf{p_{k,i}} \cdot (1 + tax^{domC}_{k,i}) + \mathbf{shareC^{imp}_{k,i}} \cdot \mathbf{p^{imp}_{k,i}} \cdot (1 + tax^{impC}_{k,i})$$

$$\mathbf{shareC^{imp}_{k,i}}\left(\mathbf{t}\right) = \frac{shareC^{imp}_{k,i}\left(t-1\right) \cdot \left( \dfrac{\mathbf{p^{imp}_{k,i}}\left(t\right) \cdot (1 + tax^{impC}_{k,i}(t))}{p^{imp}_{k,i}\left(t-1\right) \cdot (1 + tax^{impC}_{k,i}(t-1))} \right)^{\eta^{imp}_{k,i}}}{shareC^{imp}_{k,i}\left(t-1\right) \cdot \left( \dfrac{\mathbf{p^{imp}_{k,i}}\left(t\right) \cdot (1 + tax^{impC}_{k,i}(t))}{p^{imp}_{k,i}\left(t-1\right) \cdot (1 + tax^{impC}_{k,i}(t-1))} \right)^{\eta^{imp}_{k,i}} + \left(1 - shareC^{imp}_{k,i}\left(t-1\right)\right) \cdot \left( \dfrac{\mathbf{p_{k,i}}(t) \cdot (1 + tax^{domC}_{k,i}(t))}{p_{k,i}(t-1) \cdot (1 + tax^{domC}_{k,i}(t-1))} \right)^{\eta^{imp}_{k,i}}}$$

$$\mathbf{shareC^{dom}_{k,i}}\left(\mathbf{t}\right) = 1 - \mathbf{shareC^{imp}_{k,i}}\left(\mathbf{t}\right)$$

Similar equations to the four previous are valid for the States final consumptions, the investments and the intermediate consumptions.

$$\mathbf{p^{imp}_{k,i}} = \mathbf{wp_i} \cdot \left(1 + taxe^{M}_{k,i}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}} \cdot nit^{it}_{k,i}$$

$$\sum_{countries\ k} \left( \mathbf{shareC^{imp}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{imp}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{imp}_{k,i}} \cdot \mathbf{I_{k,i}} + \sum_{sectors\ j} \mathbf{shareIC^{imp}_{i,j,k}} \cdot IC_{i,j,k} \cdot \mathbf{Q_{k,j}} \right) = \mathbf{X_i}$$

$$\mathbf{MS^{X}_{k,i}}\left(\mathbf{t}\right) = \frac{MS^{X}_{k,i}\left(t-1\right) \cdot \left( \dfrac{\mathbf{p_{k,i}}\left(t\right) \cdot \left(1 + tax^{X}_{k,i}\left(t\right)\right)}{p_{k,i}\left(t-1\right) \cdot \left(1 + tax^{X}_{k,i}\left(t-1\right)\right)} \right)^{\eta^{X}_{k,i}}}{\sum_{countries\ k'} MS^{X}_{k',i}\left(t-1\right) \cdot \left( \dfrac{\mathbf{p_{k',i}}\left(t\right) \cdot \left(1 + tax^{X}_{k',i}\left(t\right)\right)}{p_{k',i}\left(t-1\right) \cdot \left(1 + tax^{X}_{k',i}\left(t-1\right)\right)} \right)^{\eta^{X}_{k',i}}}$$

$$\mathbf{X_{k,i}} = \mathbf{MS^{X}_{k,i}}\left(t\right) \cdot \mathbf{X_i}$$

$$\mathbf{wp_i} = \frac{\sum_{countries\ k} \mathbf{p_{k,i}} \cdot \left(1 + tax^{X}_{k,i}\right) \cdot \mathbf{X_{k,i}}}{\sum_{countries\ k} \mathbf{X_{k,i}}}$$

## Table of variables and parameters

| Variables of the static equilibria | |
|---|---|
| $Income_k$ | Households total revenues in region k |
| $transfers_k$ | Transfers from States to households in region k |
| $p_{k,i}$ | Production price of good i in region k |
| $pC_{k,i}$ | Final consumption price for households for good i in region k |
| $pG_{k,i}$ | Final consumption price for States for good i in region k |
| $pI_{k,i}$ | Price for investments for good i in region k |
| $pIC_{j,i,k}$ | Intermediate consumption price for sector i for good j in region k |
| $pind_k$ | Households final consumption price index in region k |
| $wp_i$ | International price of good i |
| $p_{k,i}^{imp}$ | Import price of good i in region k |
| $w_{k,i}$ | Unitary salary in sector i in region k |
| $\Omega_{k,i}$ | Increasing cost factor in sector i in region k |
| $Q_{k,i}$ | Volume of production of good i in region k |
| $C_{k,i}$ | Households final consumption volume of good i in region k |
| $pkm_{k,mode}$ | Passengers.kilometers travelled per mode (air transport, public transport, private vehicle, non motorized mode) in region k |
| $I_{k,i}$ | Volume of good i purchased for Gross Fixed Capital Formation (Investment) in region k |
| $z_k$ | Unemployment level in region k |
| $M_{k,i}$ | Volume of imports of good i in region k |
| $X_{k,i}$ | Volume of exports of good i from region k |
| $X_i$ | Volume of the international market of good i |
| $MS_{k,i}^X$ | Market share of exports from region k in the international market of good i |
| $shareC_{k,i}^{imp/dom}$ | Imports (/Domestic production) share in households final consumption of good i in region k |
| $shareG_{k,i}^{imp/dom}$ | Imports (/Domestic production) share in States final consumption of good i in region k |
| $shareI_{k,i}^{imp/dom}$ | Imports (/Domestic production) share in investments of good i in region k |
| $shareIC_{k,i}^{imp/dom}$ | Imports (/Domestic production) share in sector i intermediate consumption of good j in region k |
| $NRB_k$ | Net regional savings of region k |
| $GRB_k$ | Gross regional savings of region k |
| $InvFin_{k,i}$ | Investment allocated to sector i in region k |
| $pCap_{k,i}$ | Price of one unit of productive capital in sector i and region k |
| $\Delta Cap_{k,i}$ | New productive capital in sector i and region k |
| Parameters modified in the recursive framework by dynamic modules between each static equilibrium | |
| $G_{k,i}$ | States final consumption of good i in region k |
| $IC_{j,i,k}$ | Sector i intermediate consumption of good i in region k |
| $L_k$ | Total active population in region k |
| $l_{k,i}$ | Quantity of labour per unit of output in sector i in region k |
| $aw_{k,i}$ | Wage curve parameter for sector i in region k |
| $\pi_{k,i}$ | Markup rate in sector i in region k |
| $ptc_k$ | Households propensity to spend (one minus saving rate) in region k |
| $div_{k,i}$ | Share of profits in sector i in region k given as revenues to households |
| $bn_{k,i}$ | Basic need of consumption of good i in region k |

| | |
|---|---|
| $\alpha_{k,Ei}^{cars}$ | Mean consumption of energy Ei per passenger.kilometer by car in region k |
| $\alpha_{k,Ei}^{m2}$ | Mean consumption of energy Ei per square meter of residential buildings in region k |
| $Tdisp_k$ | Total households travel time in region k |
| $Cap_{k,i}$ | Productive capacity of sector i in region k |
| $Captransport_{k,j}$ | Total capacity of transport mode j in region k |
| $tax_{k,i}^{w}$ | Labour tax rate in sector i in region k |
| $tax_{k,i}^{M}$ | Tax rate on imports of good i in region k |
| $tax_{k,i}^{X}$ | Tax rate on exports of good i from region k |
| $tax_{k,i}^{domC}$ | Tax rate on households final consumption of domestic production of good i in region k |
| $tax_{k,i}^{impC}$ | Tax rate on households final consumption of imports of good i in region k |
| $shareExpK_k$ | Share of gross regional savings of region k exported to the international 'pool' of capital |
| $shareImpK_k$ | Share of the international 'pool' of capital imported in region k |
| $shareInvFin_{k,i}$ | Share of net regional savings of region k allocated to sector i |
| $\beta_{j,i,k}$ | Quantity of good j necessary to build one unit of productive capacity of sector i in region k |
| $nit_{k,i}^{it}$ | Transport need in mode it for imports of good i in region k |
| Fixed parameters | |
| $\xi_{k,i}^{C}$ , $\xi_{k,i}^{S}$ | Parameters of the utility function |
| $b_{k,mode}$ | Calibration parameters for the constant elasticity of substitution function giving the transport service in function of passengers.kilometers per mode in region k |
| $\eta_k$ | $\eta = \frac{s-1}{s}$, with s the elasticity of substitution of the function giving the transport service in function of passengers.kilometers per mode in region k |
| $wref_{k,i}$ | Salaries at calibration date in sector i in region k |
| $pindref_k$ | Households final consumption price index in region k at calibration date |
| $zref_k$ | Underutilization of the labour force at the calibration date for region k |
| $\rho_{k,i}$ | $\rho = \frac{1-\sigma}{\sigma}$ |
| $\sigma_{k,i}$ | Armington elasticity for good i in region k |
| $b^{dom}$, $b^{imp}$ | Calibration parameters for Armington expression for good i in region k |
| $\theta_i$ | $\theta = \frac{1-\lambda}{\lambda}$ |
| $\lambda_i$ | Armington elasticity in the international market for good i |
| $\psi_{k,i}$ | Calibration parameter for Armington expression for exports of good i from region k in the international market 'pool' |
| $\eta_{k,i}^{imp}$ | Parameter for the expression of the imports (/Domestic production) share in households final consumption of good i in region k |

| | |
|---|---|
| $\eta_{k,i}^{X}$ | Parameter for the expression of the market share of exports from region k in the international market of good i |