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# Technological change facing an environmental constraint : the case of France

Alexandra Niez Lempp

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**Le Progrès Technique Face à une Contrainte  
Environnementale : Le Cas de la France**

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# Table des matières

<b>Introduction Générale</b>	<b>7</b>
<b>Bibliographie</b>	<b>25</b>
<b>1 Modeling Technological Change in Energy Economy Models : State of Art</b>	<b>27</b>
1.1 Introduction . . . . .	28
1.2 Environmental Policies and the Effect of Technological Change : An Uncertain Outcome . . . . .	30
1.2.1 Diffusion Barriers . . . . .	31
1.2.2 Cost Assessment . . . . .	33
1.3 Exogenous Technological Change . . . . .	35
1.3.1 The Autonomous Energy Efficiency Improvement Parameter . . . . .	35
1.3.2 Backstop Technologies . . . . .	37
1.4 Endogenous Technological Change . . . . .	41
1.4.1 Learning by Doing . . . . .	43
1.4.2 The Stock of Knowledge Approach or Investments in R&D . . . . .	48
1.5 Conclusion . . . . .	57
<b>Bibliographie</b>	<b>61</b>
<b>2 A CGE Model for France with Exogenous Technological Change : Conclusions on the French National Allocation Plan</b>	<b>69</b>
2.1 Introduction . . . . .	70
2.2 Description of the Static Model . . . . .	75
2.2.1 Database and Calibration . . . . .	75
2.2.2 Labor Market Differentiation and Unemployment . . . . .	80
2.2.3 The Government . . . . .	84
2.3 Policy Descriptions . . . . .	84
2.3.1 Business as Usual General Forecast . . . . .	85
2.3.2 The French National Allocation Plan . . . . .	90
2.4 Conclusion . . . . .	120
<b>Bibliographie</b>	<b>129</b>

<b>3</b>	<b>The Effect of an Energy Constraint on the Direction of Technological Change : The Study of a Partial Theoretical Model</b>	<b>135</b>
3.1	Introduction . . . . .	136
3.2	Le Cas d'une Technologie CES à Trois Facteurs Sans Contrainte Energétique : Confirmation du Résultat de Nordhaus . . . . .	138
3.2.1	Présentation de la Fonction de Production . . . . .	138
3.2.2	La Technologie de Production et d'Innovation . . . . .	139
3.2.3	La Dynamique du Modèle . . . . .	141
3.2.4	Le Programme du Planificateur : Détermination du Hamiltonien	142
3.2.5	Détermination du Sentier de Croissance de Long Terme . . . . .	143
3.2.6	Détermination du Taux de Progrès Technique sur le Sentier de Croissance de Long Terme . . . . .	145
3.2.7	Caractérisation Complète de l'Etat Stationnaire . . . . .	147
3.2.8	Les Conditions Necessaires de l'Optimum sont Suffisantes si $\sigma < 1$	148
3.3	Cas d'une Politique de Limitation des Emissions : Quelques Conjectures sur les Formes du Progrès Technique . . . . .	156
3.3.1	Les Conditions d'Optimalité . . . . .	157
3.3.2	Caractérisation de l'Etat Stable et du Progrès Technique Associé	158
3.4	Conclusion . . . . .	165
	<b>Bibliographie</b>	<b>167</b>
<b>4</b>	<b>A Forward Looking CGE Model for the French Economy with Endogenous Technological Change</b>	<b>169</b>
4.1	Introduction . . . . .	170
4.2	Technological Change in Energy-Economy Models . . . . .	172
4.3	Induced Technological Change and the Stock of Knowledge Approach .	174
4.3.1	The Inducement Process : a Description of the Dynamics of the Stock of Knowledge Approach in our Framework . . . . .	174
4.3.2	A Dynamic CGE Model for the French Economy . . . . .	176
4.4	A Social Accounting Matrix . . . . .	184
4.5	Extracting Human Capital Services and R&D from the SAM . . . . .	186
4.5.1	The Extraction . . . . .	186
4.5.2	Data and Sources for Extraction . . . . .	190
4.6	Induced Technological Change and the NAP . . . . .	197
4.6.1	Business as Usual . . . . .	197
4.6.2	The National Allocation Plan : A Very Small Energy Constraint	200
4.7	Conclusion . . . . .	229
	<b>Bibliographie</b>	<b>291</b>
	<b>Conclusion Générale</b>	<b>297</b>
	<b>Résumé de Thèse</b>	<b>301</b>

# Table des figures

1.1	Relative prices of backstop and conventional technologies relatively to $t$	38
2.1	Benchmark tax shares in the government budget . . . . .	79
2.2	Tax burden per sector as a percentage of production . . . . .	79
2.3	Wage curve specification . . . . .	82
2.4	Classical unemployment . . . . .	83
2.5	Concentration of workers per category of sector and per qualification .	84
2.6	Business as Usual growth of GDP . . . . .	85
2.7	Skilled workers unemployment rate general trend . . . . .	86
2.8	Unskilled workers unemployment rate general trend . . . . .	87
2.9	Business as Usual emissions for France . . . . .	87
2.10	Benchmark sectoral emissions . . . . .	88
2.11	Estimated business as usual relative emissions for covered sectors in 2005	89
2.12	Covered and non covered sectors benchmark emissions . . . . .	89
2.13	Percentage production difference relative to the BAU. . . . .	93
2.14	France's total emissions . . . . .	95
2.15	Percentage total emissions reductions for France relative to the BAU .	95
2.16	Carbon price in dollars per metric tons of carbon . . . . .	96
2.17	Emission reductions for covered and non covered sectors relative to the BAU . . . . .	97
2.18	Sectoral emissions reductions due to the introduction of the NAP. . . .	99
2.19	Unemployment rates for skilled and unskilled workers relative to the BAU	100
2.20	Sectoral production change relative to the BAU. . . . .	103
2.21	Effect of the Kyoto constraint on the production of covered sectors . . .	104
2.22	France's total emissions with NAP and Kyoto constraints . . . . .	105
2.23	Covered and non covered sectors emissions with the NAP and Kyoto .	106
2.24	Covered sectors permit price after the introduction of the Kyoto protocol	107
2.25	Covered and non covered sectors emission reductions . . . . .	107
2.26	Covered sectors' sectoral emissions changes with the Kyoto and the NAP	108
2.27	Sectoral effects of the Kyoto constraints on the buyers and sellers of pollution permits . . . . .	109
2.28	Percentage difference in unemployment rates relative to the BAU . . .	111



2.29	Unemployment rates percentage difference between the NAP without the Kyoto constraints and the NAP with the Kyoto constraints starting 2008 . . . . .	111
2.30	Covered and non covered sectors production variations relative to the BAU . . . . .	114
2.31	The effect on the emissions of covered and non covered sectors in the case where the NAP is made more stringent in 2008 . . . . .	115
2.32	Pollution permit price comparaison with Kyoto : NAP forever and NAP constrained after 2008 . . . . .	115
2.33	Sectoral effects of the NAP constraint on the buyers and sellers of pollution permits . . . . .	116
2.34	Sectoral emission reductions in the case where the Kyoto protocol is implemented and the NAP is constrained . . . . .	117
2.35	Unemployment rate percentage difference relative to the BAU . . . . .	118
2.36	The impact on unemployment rates of the introduction of the tax on non covered sectors . . . . .	119
3.1	Frontière des possibilités d'innovation . . . . .	140
3.2	Taux de croissance du progrès technique sur le sentier de croissance de long terme en fonction de la part du capital dans l'agrégat capital-energie.164	
4.1	Business as Usual emissions for France in the case of ITC and NO ITC	198
4.2	Business as usual emissions for covered and non covered sectors with ITC and with NO ITC . . . . .	199
4.3	Business as usual human capital services . . . . .	199
4.4	Business as usual physical capital services . . . . .	200
4.5	Emission difference relative to the BAU in the case of ITC and NO ITC	202
4.6	Covered sectors emission difference relative to the BAU . . . . .	203
4.7	Non covered sectors emission difference relative to the BAU . . . . .	203
4.8	Production difference relative to the BAU in the case of ITC and NO ITC	205
4.9	Covered sectors' production difference relative to the BAU . . . . .	206
4.10	Non covered sectors production difference relative to the BAU . . . . .	206
4.11	Non covered sectors production difference relative to the BAU in the case of ITC and NO ITC . . . . .	208
4.12	Covered sectors production difference relative to the BAU with ITC and NO ITC . . . . .	209
4.13	Difference in total human capital services relative to the BAU . . . . .	213
4.14	Price difference for human capital services and physical capital services relative to the BAU . . . . .	216
4.15	Covered sectors demand for human capital services relative to the BAU	221
4.16	Non covered sectors demand for human capital services relative to the BAU . . . . .	222

4.17	Difference in demand for physical capital services relative to the BAU in the case of ITC and NO ITC . . . . .	225
4.18	Covered sectors demand for physical capital services relative to the BAU with ITC . . . . .	226
4.19	Non covered sectors demand for physical capital services relative to the BAU with ITC . . . . .	227
4.20	CO <sub>2</sub> emissions for France . . . . .	233
4.21	Elasticities of substitution in the model . . . . .	234



# Introduction Générale

While some controversies still remain as to whether global warming is the consequence of past human choices or the simple evidence of entirely natural and recurrent temperature changes, there is however no doubt that peoples' and firms' economic and environmental choices today, will influence their economic and environmental well-being tomorrow. The European Union's ratification of the Kyoto protocol in May 2002, not only reflected this position, but also led the debate on environmental protection to be even further acknowledged on the national and international political arena. By ratifying the Kyoto protocol in 2002, the European Union recognized the urgency in taking action to limit its emissions today, and therefore contain the environmental damage of increasing emissions tomorrow. Therefore the European Union, now with others, has accepted to be subject to new constraints that may jeopardize its economic growth.

Indeed, the existence of a dichotomy between the protection of the environment and unbounded economic growth can be a major stumbling block for many countries whose environmental concerns may often, and understandably so, become overridden by the "political and social pressure" of the pursuit of economic growth. Indeed, the financial and economic well-being, as well as the demand of electing citizens for a constantly increasing purchasing power, is the fundamental focus of all democratic countries, often to the detriment of ideological principles. For this reason, governments may choose to release themselves from environmental constraints that may seem to them in contradiction with their initial points of focus. Indeed, it is often supposed that the introduction of an environmental policy<sup>1</sup>, the goal of which is the protection of the environment, will necessarily lead to negative impacts on the overall economy. In fact, this argument was the fundamental one used by the United States, to support the Bush Administration's rejection of the Kyoto Protocol. In an interview to the Danish

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<sup>1</sup>The goals of an environmental policy can be many. It can range from seeking, on the earth, to protect biodiversity by preventing the extinguishing of different animal species, to working towards protecting, in the skies, the ozone layer. But while the objectives of environmental policies may be multitude, the instruments that can be used to serve such goals are few, and well known. Policy makers for instance may use norms and quotas, taxes, emission permits, subventions or public awareness to serve their purposes.

television in June 2005, the United States' President George W. Bush explained his refusal to sign the Kyoto Protocol by suggesting that adhering to the Kyoto treaty on climate change would have "wrecked" the U.S. economy. But, he adds :

"And so my hope is [...] to move beyond the Kyoto debate and to collaborate on new technologies that will enable the United States and other countries to diversify away from fossil fuels so that the air will be cleaner [...]" .

In the context of the apparent dichotomy between this need for environmental protection and the pursuit of unconstrained economic growth, the International Energy Agency (IEA (1999)), undertook an international consultation to identify the expected technologies that could help reduce greenhouse gas emissions. A surprisingly long list was published. Taking note of this work, Maurice Claverie (former president of the scientific council of the ADEME), among others, reconciles these apparently opposite trajectories, with the solution of technological change.

"As it is morally unacceptable, and in any case completely unrealistic, to curb economic development, and specifically in the Third World, the ways that we may have to control greenhouse gas emissions are those of technological progress, lifestyle choices, and better organisation of the society."  
(see Maurice Claverie (2000))

We place this thesis at the heart of the debate linking emission constraints or generally environmental policies, economic growth and technological change. The object of this thesis is to study technological change in the context of an emission constraint, and to develop a method to incorporate induced technological change in energy-economy models, in order to improve modeling projections, and to determine how technological change may alter the impact of the constraint on the economy.

In the first chapter of the thesis we develop the state of art of the different main

methods for modeling technological change in energy-economy models. We first specifically note the uncertainties that are linked to the diffusion or the use of new technologies, due to "lock in" or "crowding out" effects, which may limit the introduction of technological progress. We then note that technological change can be portrayed either as an exogenous or as an endogenous process, according to whether the technology choices are previously exogenously determined or included in the model. We mathematically describe how both the autonomous energy efficiency improvement parameter (AEEI) and backstop technologies can be incorporated in energy-economy models as a method to model technological change as an exogenous process, and we list the models that use such formulations. We address the advantages and disadvantages of using such methods. We then mathematically describe how both the process of learning by doing, and the stock of knowledge approach can be introduced in energy-economy models as a method to model endogenous technological change, and we list the models that rely on such formulations.

In the second chapter, we build a recursive dynamic general equilibrium model for the French economy, in which we implement the French National Allocation Plan (NAP), as well as the Kyoto targets. We calibrate our model on data from 1995 for the French economy, and use the elasticities of substitution of the MIT-EPPA model (Paltsev et al. (2005)). We model technological change as an exogenous process through the autonomous energy efficiency parameter, and we suppose that, each year, the efficiency of energy is increased by 0.75 %. We differentiate between two types of labor qualification (skilled and unskilled labor), and model skilled unemployment through the wage curve specification, and unskilled unemployment through the minimum wage specification. We therefore take into account these two labor market unbalances, namely unemployment for both skilled and unskilled workers. In the context of exogenous technological change, we assess the stringency of the NAP and of the Kyoto targets by deriving the expected prices of emission permits, and detail the effects of these emis-

sion constraints on the economy. We give insights as to which sectors will buy emission permits and which ones will sell them. We conclude on the stringency of the NAP for France.

Capturing the process of endogenous or induced technological change in energy-economy models is a complex task<sup>2</sup>. It is however today quite widely accepted that an energy-economy model where technological change is not portrayed as inducible or endogenous, may not manage to replicate some of the major economic interactions one can expect to see in the reality. We therefore take note of the shortcomings of using the autonomous energy efficiency parameter to model technological change in our CGE model for France, and seek in the following two chapters to focus our attention on the process of technological change. Our approach is twofold : through a partial equilibrium model we seek to determine how an emission constraint can influence technological change, and then through a general equilibrium model we seek to assess the effects on the rest of the economy of technological change induced by an emission constraint. In chapter 3, we therefore give conclusions on the direction of technological change in the case of an emission constraint, and show that in a theoretical partial equilibrium model such a constraint does in fact influence its direction. In chapter 4, we then propose a method to model induced technological change through the stock of knowledge approach in a computable general equilibrium model. We implement this method in the forward looking version of the model we built in chapter 2. Our goal is to assess how an emission constraint may influence technological change, but also, how induced technological change may influence the rest of the economy.

Therefore, in the third chapter, we study how the direction of technological change may be affected by an emission or energy constraint. Indeed, the exogeneity of techno-

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<sup>2</sup>"If the choice of technologies is included within the models and affects energy demand and/or economic growth, then the model includes endogenous technical change (ETC). With ETC, further changes can generally be induced by economic policies, hence the term induced technical change (ITC); therefore ITC implies ETC (...)". See Barker et al. (2005)



logical change constrains a model in its reactivity, while, in the reality, technological change can be expected to increase the efficiency of various inputs to production differently, according to the policies that are introduced in an economy. To address this issue, and to determine how technological change can increase the efficiency of inputs to production in the case of an emission constraint, we place ourselves in Nordhaus' (1968) frame of work. We work with a small theoretical model representing an economy on a balanced growth path. We modify Nordhaus' production function, and add energy as an additional input to production. In this new production function, physical capital and energy are bound together through a Cobb Douglas (CD) function. This bundle is then linked to labor through a Constant Elasticity of Substitution (CES) function. Capital can be accumulated, and labor is a non reproducible input, while energy is produced each year (just like electricity is).

The goal of our work in this framework is to shed light on the direction of technological change in the case where the use of energy as an input to production, is constrained (case of an environmental policy or an emission constraint). We show that, when emissions are not constrained in the economy, technological change will mainly increase the efficiency of the non reproducible factor, in our case labor. Technological change will therefore be Harrod-neutral. We then show, that, in the case of an emission constraint<sup>3</sup>, the optimal direction of technological change will depend on the share of capital in the capital-energy bundle. Indeed, we show that the smaller the share of capital in the capital-energy bundle, the more technological change will tend towards Hicks-neutrality, and similarly, the greater the share of capital in the capital-energy bundle the more technological change will tend towards Harrod-neutrality. However, contrary to the case where energy is an unconstrained input, we show that technological change may never be Harrod-neutral in the case of an emission constraint if the share

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<sup>3</sup>In our model we constrain the amount of energy per capita  $e$  used as a input in the production function to not be greater than a total fixed amount  $\bar{e}$ .

of capital  $\alpha$  belongs to  $]0; 1[$ <sup>4</sup>. These results lead us to conclude that technological change will tend to increase the efficiency of the inputs constrained by the limitations, whether these limitations are non reproducibility (such as the inherent limitations in labor) or simply environmental constraints. Finally, we note that the direction of technological change is entirely independent of the intensity of the emission constraint. This chapter allows us to support the thesis whereby, modeling technological change as an exogenous and therefore independent process, is a suboptimal method to model technological change, as the direction of technological change will not stay unaffected by various economic constraints.

In the last chapter of this thesis, we take note of the conclusions of our first chapter listing the different modeling methods to account for technological change in energy-economy models, and of the inherent limitations of modeling technological change as an exogenous process, as it was modeled in the second chapter. We moreover take note of the conclusions of our theoretical model in the third chapter whereby technological change will tend to increase the efficiency of constrained inputs, and is affected in its direction by energy constraints. We then develop a method to introduce induced technological change in computable general equilibrium models, so as to increase the accuracy of the assessment of the impacts of economic constraints on the economy.

To do so, we build our work on Sue Wing (2001), and propose a method for implementing induced technological change through the stock of knowledge approach in energy-economy models. We suppose that there is a stock of human capital that exists and is available for the whole economy, from which flow human capital services, which are intangible inputs that may be used as inputs to production. This human capital

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<sup>4</sup>For technological change to be Harrod-neutral it is necessary for the share of capital  $\alpha$  in the capital-energy bundle to be equal to 1 (this would mean that there is no energy in the production function). But in this case, the existence of an emission constraint on energy would have no sense if it is not an input to production. Similarly, technological change will be Hicks-neutral if  $\alpha = 0$  meaning that there is no capital in the capital-energy bundle. Therefore, technological change will increase the productivity of both non reproducible labor and constrained energy in the same way.

stock is increased through investments in human capital (in the same way that the physical capital stock is increased through investments in physical capital). Induced technological change kicks in following an emission constraint, as firms will demand more of the intangible input, and less of the tangible constrained good.

To implement endogenous technological change in our computable general equilibrium model for France, we create an inter-industry technology matrix using data for the French economy on patent flows, from the Johnson and Evenson Patent data set (see Evenson and Johnson (1997)), and values of investment in R&D for France. We extract this matrix, proxy for the industries knowledge flows, from the social accounting matrix (SAM) on which our model for France was initially calibrated. After extracting knowledge also from the labor row, we modify the SAM for France, and create an extra column representing investment in research and development and a new row representing knowledge services. We rebalance the SAM such that human capital and physical capital may grow on the balanced growth path at the rate of growth of the economy.

We then calibrate a forward looking version of the model replicating the French economy, on this new SAM. The object of this work is to give conclusions on the effects of an environmental constraint such as policy similar to the French National Allocation Plan on the French economy, in the case where technological change is modeled as an endogenous process.

We show, similarly to Nordhaus' (2002) findings, that in the case of the introduction of as policy similar to the French National Allocation Plan the process of induced technological change (ITC) is not as important as the substitution effects that take place between the tangible inputs in the years following the introduction of the constraint.

We show, that in the case where ITC is modeled, sectors that are not subject to the constraint increase their demand for human capital services more than sectors that are constrained by the energy policy, because of the substitution effect leading to

an increased demand for the production of unconstrained sectors, which mechanically increases their demand for input.

We show that there is an eviction effect or crowding out effect that relates the demand for human capital services and the demand for physical capital services, because of the aggregate income accounting equation. When investment in research and development increases this leads to a necessary decrease in the investment in physical capital.

Finally, we show, similarly to Popp (2002) that there are peaks in the demand for human capital services, the first years of the introduction of the NAP, for both types of sectors, which disappear the following years during which the constraint is still active.

We conclude, that technological change is therefore a shortly lived process that can be induced solely through the constant increase in a policy's stringency.

The purpose of this thesis is to address how technological change can be affected by an emission constraint such as the French National Allocation Plan, and how this constraint impacts the rest of the economy. To seek to answer these questions, we study the consequences on the French economy of the introduction of such an environmental policy. We build our own CGE model to carry out our simulations on France. We study the model's results both in the case where technological change is modeled as an exogenous process and where it is modeled as an endogenous process. Finally, we propose a new method for modeling technological change in forward looking computable general equilibrium models, and implement it in our model for France.

Même si des doutes persistent encore sur la cause du réchauffement de la planète, à savoir si elle est la conséquence de comportements humains passés, ou simplement le témoignage de changements climatiques entièrement naturels et récurrents, il n'y a pourtant aujourd'hui aucun doute sur le fait que les choix économiques et environnementaux des entreprises ou des hommes aujourd'hui, influenceront demain leur bien-être économique et environnemental. La ratification du protocole de Kyoto par l'Union Européenne en Mai 2002, a non seulement reflété cette position, mais a aussi contribué à relancer le débat sur la protection de l'environnement sur les scènes nationales et internationales. En ratifiant le protocole de Kyoto en 2002, l'Union Européenne a reconnu l'urgence d'agir pour réduire les émissions des gaz à effet de serre aujourd'hui, afin de limiter demain les conséquences sur l'environnement des dommages liés à la croissance de ces émissions. Ainsi, avec d'autres, l'Union Européenne a accepté d'être sujet à de nouvelles contraintes qui peuvent mettre sa croissance économique en péril.

En effet, l'existence d'une dichotomie entre la protection de l'environnement et une croissance économique illimitée peut devenir une pierre d'achoppement majeure pour nombre de pays dont les préoccupations d'ordre environnementales peuvent être, et ceci se comprend aisément, outrepassées par les pressions politiques et sociales de la poursuite de la croissance économique. En effet, la recherche du bien-être économique et financier est l'objectif premier de tout pays démocratique, et ce parfois au détriment de principes idéologiques. C'est pour cette raison, que les gouvernements parfois choisissent de ne pas se soumettre à des contraintes d'ordre environnementales qui peuvent leur sembler à première vue en contradiction avec leurs objectifs premiers. En effet, il est souvent présupposé que l'introduction d'une politique environnementale<sup>5</sup>, dont l'objectif est la protection de l'environnement, aura nécessairement des impacts

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<sup>5</sup>Les objectifs d'une politique environnementale peuvent être multiples. Ils peuvent aller de la volonté de protéger sur terre la biodiversité, en prévenant l'extinction de différentes races animales, à la protection dans le ciel de la couche d'ozone. Mais, alors que les objectifs des politiques environnementales sont nombreux, les instruments qui peuvent être utilisés sont eux peu bien moins nombreux et bien connus. Par exemple, les normes, les quotas, les permis d'émissions négociables, les subventions ou la publicité peuvent servir ces propos.

négatifs sur le reste de l'économie. C'était d'ailleurs l'argument fondamental du Président Américain George Bush, pour expliquer pourquoi son Administration a refusé de signer le Protocole de Kyoto. Dans un interview donné à la télévision Danoise en juin 2005, le Président Américain George Bush, expliqua son refus de signer le Protocole de Kyoto en suggérant que le traité sur le changement climatique détruirait l'économie Américaine. Mais il rajouta :

"And so my hope is [...] to move beyond the Kyoto debate and to collaborate on new technologies that will enable the United States and other countries to diversify away from fossil fuels so that the air will be cleaner [...]" .

Au vu de l'apparente dichotomie entre la nécessité d'instaurer des politiques environnementales, et la poursuite d'une croissance illimitée, l'Agence Internationale de l'Energie (IEA (1999)) a entrepris une consultation internationale pour identifier les technologies qui pourraient dans le futur contribuer à réduire les émissions de gaz à effet de serre. Une liste, surprenante par sa longueur, fut publiée. Prenant acte de cette publication, Maurice Claverie (ancien président du conseil scientifique de l'ADEME), avec d'autres, réconcilie ces deux trajectoires apparemment opposées, avec la solution du changement technologique.

"As it is morally unacceptable, and in any case completely unrealistic, to curb economic development, and specifically in the Third World, the ways that we may have to control greenhouse gas emissions are those of technological progress, lifestyle choices, and better organisation of the society."  
(see Maurice Claverie (2000))

Nous plaçons cette thèse au coeur de ce débat liant les contraintes d'émissions, ou plus généralement les politiques environnementales, la croissance économique et le changement technologique. L'objet de cette thèse est d'étudier, la question du changement technologique dans un contexte de contrainte des émissions et de développer

une méthode pour modéliser le progrès technique induit dans les modèles économie-énergie. Le but est d'améliorer les projections de ces modèles et de déterminer comment le changement technologique peut modifier l'effet d'une contrainte énergétique sur une économie.

Dans le premier chapitre de cette thèse, nous présentons les différentes méthodes pour modéliser le progrès technique dans les modèles économie-énergie. Nous notons premièrement tout particulièrement les incertitudes liées à la diffusion ou à l'utilisation de nouvelles technologies, en raison de phénomènes de "lock-in" ou de "crowding-out". Nous notons ensuite que le changement technologique peut être représenté comme un processus exogène ou endogène, en fonction de si le modélisateur suppose que son taux ou sa direction peuvent être influencés ou non par une politique. Nous définissons mathématiquement, comment le paramètre Autonomous Energy Efficiency Improvement (AEEI) ainsi que les backstop technologies peuvent être incorporés dans les modèles économie-énergie comme méthode pour modéliser le changement technologique exogène. Nous élaborons une liste des modèles qui utilisent de telles formulations pour le progrès technique. Nous adressons de plus, les avantages et les inconvénients liés à l'utilisation de telles formules. Nous définissons ensuite mathématiquement, comment le processus de "Learning by Doing" (LBD) ainsi que l'"Approche du Stock de Connaissance" peut être introduit dans les modèles économie-énergie, comme méthode pour modéliser le progrès technique endogène, et nous élaborons une liste de modèles qui utilisent de telles formulations.

Dans le deuxième chapitre, nous construisons un modèle d'équilibre général dynamique pour l'économie Française, dans lequel nous modélisons le Plan National d'Allocation des Quotas (PNAQ), ainsi que les objectifs dictés par le Protocole de Kyoto. Nous calibrons ce modèle sur des données de 1995, pour l'économie française, et nous utilisons les élasticités de substitution du modèle MIT-EPPA (Paltsev et al. (2005)). Nous modélisons le changement technologique comme un processus exogène

grâce à l' AEEI et nous supposons que, chaque année, l'efficacité énergétique croît de 0.75 %. De plus, nous différencions entre deux types de qualifications du travail (qualifié et non qualifié), et nous modélisons le chômage des travailleurs qualifiés grâce à une courbe de salaire, et le chômage des travailleurs non qualifiés grâce au salaire minimum. Nous prenons ainsi en compte ces deux déséquilibres sur les marchés du travail. Dans ce contexte de changement technologique exogène, nous étudions le Plan National d'Allocation des Quotas, et les objectifs de Kyoto en dérivant les prix des permis d'émissions négociables, et en détaillant les effets de ces contraintes d'émissions sur l'économie. Nous explicitons quels secteurs se porteront acheteurs de permis sur le marché des permis d'émissions et quels secteurs se porteront vendeurs. Nous concluons sur la rigueur du PNAQ.

Réussir à capturer dans les modèles économie-énergie, le processus de changement technologique endogène ou induit reste une tâche complexe. Il est pourtant aujourd'hui largement accepté qu'un modèle dans lequel le changement technologique n'est pas représenté comme induit ou endogène, risque de ne pas pouvoir mettre en évidence les interactions économiques majeures que l'on peut s'attendre à observer dans la réalité. Nous prenons donc note des limites quant à l'utilisation de l'AEEI pour modéliser le changement technologique dans notre CGE pour la France, et cherchons à déterminer comment une contrainte d'émissions peut influencer le changement technologique. Ensuite, à travers la construction d'un modèle d'équilibre général nous cherchons à déterminer les effets sur le reste de l'économie du changement technologique induit par une contrainte d'émissions.

Dans le chapitre 3 de cette thèse, nous donnons donc des conclusions sur la direction du progrès technique dans le cas d'une contrainte d'émissions, et nous montrons que dans un modèle d'équilibre partiel, une telle contrainte influence en effet sa direction. Dans le chapitre 4, nous proposons ensuite une méthode pour modéliser le changement technologique induit dans un CGE en reprenant l' Approche du Stock de



Connaissances. Nous appliquons cette méthode dans une version "forward-looking" du modèle décrit dans le chapitre 2. Notre objectif est de déterminer comment une contrainte d'émissions peut influencer le changement technologique, mais aussi, comment le changement technologique peut influencer le reste de l'économie.

Dans le chapitre 3, nous étudions ainsi comment la direction du progrès technique peut être affectée par une contrainte d'émissions ou d'utilisation d'énergie. En effet, l'exogénéité du changement technologique contraint la réactivité d'un modèle, alors que dans la réalité, on peut s'attendre à ce que le changement technologique accroisse l'efficacité énergétique de certains facteurs de production contraignant la croissance. C'est pourquoi, pour déterminer comment on peut s'attendre à ce que le changement technologique réagisse face à une contrainte, nous nous plaçons dans le cadre de travail de Nordhaus (1968). Nous travaillons avec un petit modèle théorique représentant une économie sur le sentier de croissance de long terme. Nous modifions la fonction de production de Nordhaus, et rajoutons un facteur de production supplémentaire, l'énergie. Dans cette nouvelle fonction de production, le capital physique et l'énergie sont reliés grâce à une fonction Cobb Douglas. Cet agrégat est ensuite relié au travail par une fonction CES, à élasticité de substitution constante. Le capital peut être accumulé, le travail est un facteur non reproductible, et l'énergie est produit chaque année (de la même manière que l'électricité par exemple).

L'objectif de notre travail dans ce cadre, est de mettre en lumière comment la direction du changement technologique est affectée quand il existe une contrainte sur l'utilisation d'énergie (cas d'une politique environnementale ou d'une contrainte d'émission). Nous montrons que, dans le cas où les émissions ne sont pas contraintes dans l'économie, le progrès technique reposera sur le facteur non reproductible, le travail. Le progrès technique sera donc neutre au sens de Harrod. Nous montrons ensuite, que dans le cas où les émissions sont contraintes, la direction optimale du progrès technique dépendra de la part du capital dans l'agrégat capital-énergie ; plus cette part est pe-

tite, plus le progrès technique tendra vers la neutralité au sens de Hicks. Ces résultats nous permettent de conclure que le progrès technique reposera sur le facteur de production contraint par des limitations, que ces limitations soient la non reproductibilité (comme les limitations inhérentes au travail) ou simplement des contraintes d'ordre environnementales. Enfin, nous montrons que la direction du progrès technique est entièrement indépendante de l'intensité de la contrainte environnementale. Ce chapitre nous permet de soutenir que modéliser le changement technologique comme un processus exogène et donc indépendant, est une méthode sous-optimale.

Dans le dernier chapitre de cette thèse, nous prenons note des conclusions de notre premier chapitre listant les différentes méthodes pour modéliser le changement technologique dans les modèles économie-énergie, ainsi que la limitation inhérente à modéliser le progrès technique comme un processus exogène, comme cela était fait dans le chapitre 2. Nous prenons note de plus des conclusions de notre modèle théorique, détaillé dans le chapitre 3, où le progrès technique est influencé dans sa direction par les contraintes énergétiques, et tend à reposer sur les facteurs de production qui sont soumis à des contraintes. Nous développons ensuite une méthode pour modéliser le progrès technique induit dans des modèles d'équilibre général, de façon à améliorer la précision des prédictions de ces modèles sur les impacts de contraintes, quelles qu'elles soient, sur l'économie .

Pour ce faire, nous fondons notre travail sur les travaux de Sue Wing (2001), et proposons une méthode pour modéliser le progrès technique induit à travers l'Approche du Stock de Connaissances. Nous supposons qu'il existe en effet un stock de capital humain dans l'économie, d'où proviennent des flux de services de capital humain, qui sont tout simplement des facteurs de production intangibles (non matériels). Ce stock de capital humain croît grâce à des investissements en capital humain (de la même manière que le stock de capital physique croît grâce à l'investissement en capital physique). Le progrès technique induit apparaît clairement à la suite d'une contrainte d'émissions,

comme les entreprises demanderont plus du bien intangible et moins des biens tangibles comme le travail, le capital physique ; l'énergie, les matériaux...).

Pour modéliser le progrès technique induit dans notre modèle d'équilibre général pour la France, nous créons une matrice technologique inter-industrielle grâce à l'utilisation de données sur les flux de brevets dans l'économie française provenant du "Johnson and Evenson Patent data set", ainsi que de valeurs sur l'investissement en R&D en France. Nous extrayons cette matrice, Proxy des flux de connaissance inter-industriels, de la matrice de comptabilité sociale (MCS) sur laquelle notre modèle pour la France a initialement été calibré. Après avoir extrait la connaissance de la valeur du travail de la matrice, nous modifions la MCS pour la France, et créons une colonne supplémentaire représentant les investissements en R&D et une nouvelle ligne représentant les services de capital humain.

Nous calibrons ensuite une version forward-looking du modèle pour la France détaillée dans le chapitre 2 de cette thèse, sur la nouvelle MCS. L'objet de ce travail est de pouvoir donner des conclusions quant aux effets d'une contrainte environnementale telle que le PNAQ sur l'économie française, dans le cas où le progrès technique est modélisé comme un processus induit.

Nous montrons que, similairement à Nordhaus (2002), dans le cas où le Plan National d'Allocation des Quotas est introduit, l'effet du progrès technique induit n'est pas aussi important que les effets de substitution entre les facteurs de production tangibles qui ont lieu les années qui suivent l'introduction de la contrainte.

Nous montrons, que similairement à Sue Wing (2001), dans le cas où l'ITC est modélisé, les secteurs qui ne sont pas soumis à la contrainte vont accroître leur demande de services de capital humain plus que les secteurs qui sont visés par la contrainte énergétique. Ce phénomène provient de l'effet de substitution qui permet à la production des secteurs non contraints de croître suite à l'introduction de la contrainte énergétique sur

les secteurs couverts. Cette croissance de leur production leur permet de mécaniquement accroître leur demande de facteurs de production et donc de services de capital humain.

Nous montrons qu'il existe un effet d'éviction ou effet de "crowding out", qui relie la demande de services de capital humain à la demande de services de capital physique. Quand l'investissement en R&D augmente ceci entraîne nécessairement une chute de l'investissement en capital physique.

Enfin, nous montrons que comme Popp (2002), il existe des pics de demande de services de capital humain les premières années de l'introduction du PNAQ, pour les deux types de secteurs, et qui disparaissent les années qui suivent alors même que la contrainte est encore active.

Nous concluons que le progrès technique est un processus à courte espérance de vie, qui ne peut être induit qu'à force de politiques de plus en plus contraignantes.

L'objet de cette thèse est d'étudier comment le changement technologique peut être affecté par une contrainte d'émission telle que le PNAQ, et comment cette contrainte influence le reste de l'économie. Pour chercher à répondre à ces questions, nous étudions les conséquences sur l'économie française de l'introduction d'une telle politique environnementale. Nous construisons un CGE pour la France. Nous étudions les résultats du modèle dans le cas où le progrès technique est modélisé comme un processus exogène et dans le cas où il est modélisé comme un processus endogène.



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# Chapitre 1

## Modeling Technological Change in Energy Economy Models : State of Art



## 1.1 Introduction

Today, due to political and social pressure, the solution to ever increasing carbon emissions is not to be found in the constraining of economic growth. While production is carbon emitting, all now agree on the fact that economic growth and the generation of emissions must be decoupled, in order to tackle the problem of climate change. For this reason, technological progress, the process by which fewer inputs are needed to produce the same amount of output, is now seen as the "saving grace" which allows for unconstrained economic growth, and controlled emissions. Views, however, on technological progress may differ quite significantly. Some are convinced that technological change has a "life of its own", and will kick in, in due time, to lighten the burden of environmental constraints. Others believe that technological change responds to an inducement process and is the result of well designed policies. Both schools of thought however converge on one aspect of technological change, namely that it is most certainly the "key" to attenuating the painful economic side-effects of environmental constraints. In other words, it is the source of the decoupling of economic growth and emissions.

These two views on technological change are echoed in the chosen modeling techniques. If technological change (TC) is considered an independent time trend entirely unaffected by any sort of constraint, whether economic or environmental, it will be modeled as an exogenous process. In this case, if emission restrictions are introduced in a energy-economy model, the model will yield no immediate reaction that may lead to technological progress, and the rate of abatement will stay unaffected. Mitigation of the economic costs incurred by environmental constraints will be obvious only once technological change kicks in, following a predefined and entirely independent exogenous time trend. For this reason, these types of models can only assess in which way technological progress can affect an economy, but never **how** technological change occurs. Therefore, such a modeling choice leads to the inaptitude of the energy-economy model to enhance any substitution process between inputs to production, and favors a

"wait and see" model reaction (Sue Wing I., Popp D. (2006)).

In the case where technological progress is expected to be driven by inducement or impulses deriving from a constraint, whether economic or environmental (Grubb et al. (1995)), technological change will be modeled as an endogenous process. Mitigation of economic costs due to environmental constraints will be visible as soon as the constraint is introduced, as abatement, or enhanced substitution reactions in the production function, are induced. As opposed to a "wait and see" model reaction, whereby no immediate response is given to the introduction of environmental constraints when technological change is modeled as an exogenous process, models with endogenous technological change will favor an "act now" strategy. In such model configurations, the very fact of introducing an emission restriction is the **solution** to the mitigation of its costs. It is to be noted, however, that the direction and bias of technological change may have to be fostered by appropriate policies, and not all technological change is environmentally friendly (see Carraro C., Galleotti M. (2004)). Indeed, the simple fact of constraining the economy on one side can lead to development of other industries or sectors leading to the production of new harmful pollutants. All the more so, the simple investing of research and development is not emission free.

In energy-economy models, whether the effect of technological change is sizeable enough to be relevant, does not only depend on the **type** of technological progress, namely exogenous or endogenous. Indeed, the impacts of technological change in energy-economy models will also depend on the chosen modeling method within these two types of TC, as well as on the category of the model itself, whether top-down, bottom-up or hybrid. In this paper, we will seek to assess the four main methods to model technological change, and seek to define more precisely the advantages and disadvantages to modeling technological change through the Autonomous Energy Efficiency Improvement parameter (AEEI), Backstop Technologies, the Learning by Doing process, or the Stock of Knowledge approach. For a thorough survey of the various methods to model

technological change see Löschel (2001).

In the following section, we will first seek to assess the uncertain impacts of environmental policies on technological change. Then, we will define exogenous and endogenous technological change in detail as well as the main four methods to model these processes in energy-economy-environment models. We will underline the implications of these methods on the models' behaviors facing an emission constraint.

## **1.2 Environmental Policies and the Effect of Technological Change : An Uncertain Outcome**

Joseph Schumpeter (1942) was the first to give a three step definition to the introduction on the market of a superior technology. According to his now widely-agreed-upon categorization, invention is the first step in the development of a new technological or scientific product or process. Then comes innovation, namely the introduction into the market of this new product or process<sup>1</sup>. Usually private companies with profit-maximizing goals are at the origin of these two first steps, invention and innovation, as a result of their investments in research and development. And finally, the third step is the diffusion of the new product or process which allows any individual or company to have access to it and to introduce it into their production process. The process of technological change is the cumulated effect of these three steps on the economy or the environment.

A first question that arises here is whether investment in research and development, the goal of which is always the increasing of the company's future profits, and therefore the technological progress that derives from this investment effort, reduces compliance costs to an environmental policy. Indeed, there is no certainty that the introduction of an environmental constraint (tax, norm, subvention etc..) will lead to investment

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<sup>1</sup>One can note, that a company can innovate simply by introducing on a market a product that is based on a technology that had simply not been previously commercialised.

in research and development the fruit of which will reduce compliance costs to it or the economy's emissions. A certain number of theoretical papers such as Milliman and Price (1989), Fisher, Parry et Pizer (1998), address different environmental policies such as taxes, subventions, tradable permits, command and control policies to assess their effect on environmentally-friendly innovations. Most of the theoretical papers show that market-based approaches<sup>2</sup> are preferable to induce more environmentally-friendly innovations, as opposed to command and control policies. But while uncertainties still remain as to the effects of such induced technological change on the economy, the diffusion of any new process may also not necessarily be straightforward, and the wide adoption of a new technology can be thwarted by other barriers.

### 1.2.1 Diffusion Barriers

In industrial countries, new technologies are the result of many phenomena. The companies' internal decisions, subventions to research and development, environmental regulations, policies of energy taxation are some examples (Climate Change 2001 : Mitigation). It is important, however, to note that there resides a tendency to want to optimise the utilisation of some well installed and widely used technologies in solid infrastructures. This creates entry barriers for new technologies. This entry barrier is the consequence of infrastructure changes as well as institutional developments or social developments that operate around the dominant technology in the system. For this reason, a new technology may not so easily be adopted, even if its advantages in terms of the firms' future productivity for instance are certain (see David (1985)).

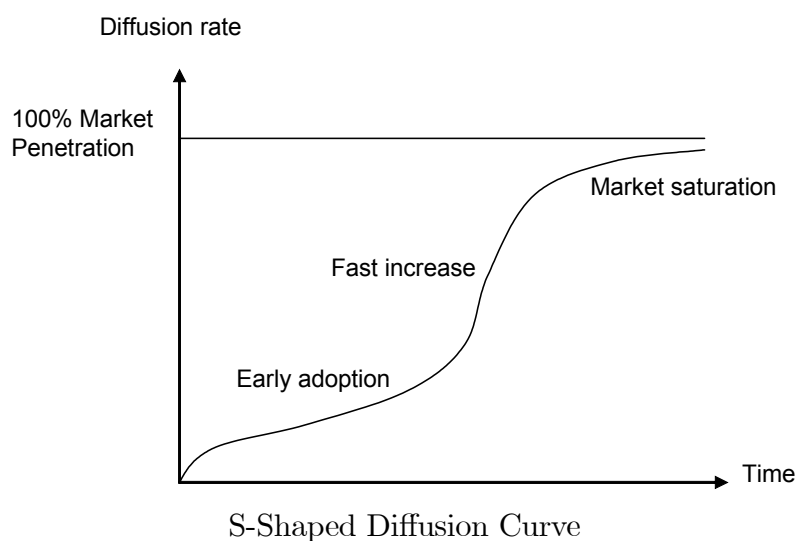
This so-called "lock-in" process leads to two effects. The first one, is that the older technologies that are already installed in the infrastructures will condition the choice and the entry of the future new technologies. Indeed, social habits and aptitudes can be so deeply embedded in an older and more widely used technology, that the choice

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<sup>2</sup>Market-based approaches are for instance taxes or tradable permits.

between two new technologies will not only result in the comparison between their performances, but will also depend on their "closeness" to the older technology. The second effect is relative to the fact that the productivity of a new technology is deeply linked to the infrastructure, the workers, the repairmen, the knowledge of employees in charge of the on-the-job training or education. All these institutional infrastructures are not easily replicated (Unruh (1999), (2000)). Such considerations support the "path dependence approach" to technological change (Weyant and Olavson (1999)), whereby once a dominant technology is chosen, it tends to be "locked-in", leading the economy on a path dependency, where the choice of the new technology then depends on historical facts and not on its competitiveness at all. Such "lock in" processes can refrain the economy from moving to a more competing path.

Another study by Rogers (1995), suggests that the rate of diffusion and adoption of a new technology is never straightforward but, follows an S-shaped curve. In the early stages, the fraction of users of this new technology increases slowly, then the number of users increases more rapidly as the technology matures with "learning by using" and "learning by doing". At the end of the technology's life cycle, when the technology is mature and approaches saturation, the increase of number of users slows down (see following figure).



Having acknowledged that the results of research and development can lead to technological change that is not necessarily going to be adopted, or will slowly be so, because of the deeply embedded institutional frameworks, or the S-shaped rate and diffusion of innovations over time, the questions of whether the technological change resulting from an environmental constraint can lead to the reduction in compliance costs, or in emissions, remains.

### 1.2.2 Cost Assessment

Today, all the research on the relationship between technological change and environmental policies is subject to two hypotheses : Social and economic activities have impacts on the environment, the evolution of which is linked to the direction and rate of technological change. And environmental policies create new constraints and incentives that affect the process of technological change (see Jaffe Newel Stavins (2002)). Although it may seem intuitive to assume that the induced innovations of an environmental policy lead to the reduction of the social costs of its implementation, some complexities need to be addressed. For instance, in the case where an environmental policy leads to the reduction of the marginal cost of depollution, then its implemen-

tation will be at a lower social cost than in the case where the policy induces no innovation<sup>3</sup>.

Goulder and Schneider (1999) study the case where a carbon tax incites firms to invest in R&D which could lead to technological progress. According to these authors, the impacts of a carbon tax on R&D differs significantly among industries. To take solely into account the sectors where the impacts on research and development are positive, leads to an over-estimation of the effect of environmental policies on the GDP. The authors therefore specifically show that the investment in R&D by some sectors might "crowd-out" the investments in R&D by other sectors therefore possibly leading to a slowdown of output and GDP. Moreover, Goulder and Schneider show that induced technological progress, while reducing the net costs of the emission reduction policies, leads to an increase in the gross costs (positive effects on the environment not yet taken into account) of a carbon tax.

Accounting for the general equilibrium effects, Schmalensee (1994) also suggests that it is necessary to question the effects on the innovations of the rest of the economy, of technological change induced by an environmental policy. Indeed, if innovations are the fruit of investments in research and development, it is important to evaluate the elasticity of the supply of inputs in R&D. In the case where the supply of inputs is inelastic, the innovations induced by the environmental policy will be done at the expense of other innovations in the economy. Schmalensee suggests that opportunity costs (or eviction costs) could therefore emerge, which could contribute to reducing the positive effects of environmental innovations on the economy.

Before tackling the methods of modeling technological change, we have chosen to take into consideration the different barriers that can be expected to thwart its induce-

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<sup>3</sup>In the case of a flat marginal benefit function evaluated at the optimum, the total spendings in depollution are increased although the marginal cost of depollution has decreased.(voir Jaffe et al. (2002))

ment, such as diffusion barriers, costs uncertainties, or crowding out effects. Taking note of these intricacies, we now take a closer look in the following two sections at the different methods for modeling technological change in energy-economy models. We will initially make a distinction between exogenous and endogenous technological change and then define the different modeling methods within these two groups.

## **1.3 Exogenous Technological Change**

While modeling technological change as an exogenous process has theoretically lost most of its popularity in the energy-economy field, it is still widely used in such models because of its relative simplicity. It therefore remains necessary to give an overview of the chosen methods to model technological change as exogenous. In this section, we will see that exogenous technological change can commonly be modeled either through an Autonomous Energy Efficiency Improvement parameter (AEEI) or through the introduction of Backstop Technologies.

### **1.3.1 The Autonomous Energy Efficiency Improvement Parameter**

In earlier models technological change was initially introduced as an exogenous process. The Autonomous Energy Efficiency Improvement parameter (AEEI) was therefore an earlier means to the decoupling of economic growth and energy use. More specifically, the AEEI reflected the rate of change in energy intensity (Energy Use / GDP) with energy prices held constant. Through such a specification, technology improvements are thus modeled independently of any price inducement, or scarcity constraint.

One of the main difficulties in adopting such a formulation is linked to the estimation the value that is attributed to the AEEI. According to the "Climate Change 2001 : Mitigation" its value ranges from 0.4% to 1.5% per year for all regions of the world, and lead to major differences between the baseline scenarios.



“Unfortunately there is relatively little backing in the economic literature for specific values of the AEEI (...) the inability to tie it down to a much narrower range (...) is a severe handicap, an uncertainty which needs to be recognized.” Dean and Hoeller (1992)

Indeed, whether the modeler’s choice of the value of the AEEI is closer to 1.5% or 0.4%, has major impacts on the model’s conclusions relatively to the cost of an environmental constraint. The higher the AEEI, the faster emissions will decrease over time, and the smaller the impact of an environmental constraint on the economy. Choosing a disproportionately high AEEI can therefore lead to the under-estimation of the costs of a climate policy. A study by Edmonds and Barns (1990) confirms the importance of the value of the AEEI on the estimation of costs. But, more than the value itself, uncertainties also reside on the AEEI’s supposed time trend, namely, whether it follows a linear or non linear time trend.

Formally, one can generally define the AEEI as in the equation 1.1. We suppose a production function  $F$  with two inputs to production, capital  $K_t$  and energy  $E_t$  used at time  $t$ . We define  $Y_t$  as the production that derives from the relation between  $K_t$  and  $E_t$  at time  $t$ . We have :

$$Y_t = \alpha_t F[K_t, \alpha_{e_t} E_t] \quad (1.1)$$

We note  $\alpha_t$  the neutral rate of technological change and  $\alpha_{e_t}$  the energy specific augmentation coefficient. Therefore, if we suppose that  $\frac{\dot{\alpha}_t}{\alpha_t} < \frac{\dot{\alpha}_{e_t}}{\alpha_{e_t}}$  then technological change is biased in favor of a lesser use of energy. The Autonomous Energy Efficiency Improvement is therefore  $\frac{\dot{\alpha}_{e_t}}{\alpha_{e_t}}$ .

There are a number of models that included the AEEI as a method for modeling technological progress. The most famous one might be the Integrated Assessment Model (IAM) RICE by Nordhaus and Yang (1996). More recently, the MIT-EPPA (Babiker et al. (2001)) and PACE (Böhringer (1999)), two computable general equilibrium models,

also incorporate an autonomous energy efficiency improvement parameter, to allow for technological change.

In top-down models, the AEEI is probably the most widely-spread method to model technological change as an exogenous process. However, another technique to account for exogenous technological change is through the introduction of backstop technologies. While entirely self-sufficient to address exogenous technological progress, this method may also be coupled to the AEEI. Usually used in bottom-up models, it's use is also subject to many assumptions.

### **1.3.2 Backstop Technologies**

A backstop technology is generally considered a technology that is available in unlimited quantities at a give time, but whose purchase price is initially very high. This high price reflects the research and development that is involved in producing it. Therefore, backstop technologies are usually seen as a pool of existing not yet commercialized technologies that are at a given price, easily available and widely accessible.

As prices of technologies are determinant of whether a production technology is chosen or not, the higher the price, the longer it will take before this technology will be chosen as a production technology. However, as new technologies mature over time, their costs fall. At the same time, older conventional technologies may become more expensive due to, for example, environmental policies that increase the prices of the conventional energy sources. Therefore, because of the price increases of conventional energy sources and the price decreases of backstop technologies, new technologies over time can become more competitive than conventional technologies. Introducing backstop technologies thus alleviates the consequences of the price increases of conventional technologies and mitigates the costs of an environmental policy. Through the existence of backstop technologies, increasing energy costs are hampered, as these technologies are often, in the long term, expected to provide significant amounts of energy.

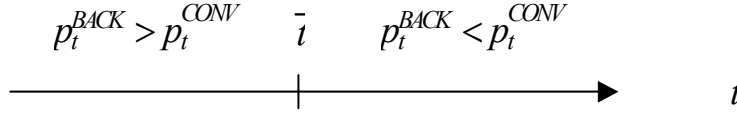


FIG. 1.1 – Relative prices of backstop and conventional technologies relatively to  $t$

Formally, modeling backstop technologies is a relatively easy task (see Sue Wing and Popp (2006)). Traditionally, to model the penetration of a backstop technology, one can define output as the outcome of two different production processes, a production process with conventional fuels  $F^{CONV}$  and one with the backstop technology  $F^{BACK}$ . The "bang-bang" behavior is such that, after a certain point in time, the output resulting from the backstop technology production technique "kicks in", as this technology becomes relatively cheaper and the conventional technology becomes relatively more expensive. The backstop technology then overtakes the **whole** market, and the conventional technology is immediately eliminated from production functions. Such model behavior is found in the DICE models. Formally, with  $Y_t$  the output at a time  $t$  and  $In_t$  inputs to production at time  $t$  :

$$Y_t = F_t^{CONV}(In_t) + F_t^{BACK}(In_t)$$

We note  $\bar{t}$  the point in time before which the price of backstop technologies is more expensive than the price of conventional fuels, and after which the price of backstop technologies is cheaper than the price of conventional fuels (see figure 1.1).

When  $t < \bar{t}$ , then one can determine the output as solely a function of the conventional techniques of production.

$$Y_t = F_t^{CONV}(In_t)$$

Similarly, when  $t > \bar{t}$ , then the output can be defined as solely the function of the backstop technique :

$$Y_t = F_t^{BACK}(In_t)$$

This specification can only represent the "bang-bang" behavior, by which one technique is used for production, entirely ruling out another technique. Indeed, in the case where the output of the old and new technologies are perfectly substitutable, then the newer technology will completely eradicate the older one once it has penetrated the market. In fact, as soon as the price of the backstop is lower than the price of the older technology it will take over the entire market and the older technology will become completely obsolete. The relevance of such a "bang-bang" behavior in energy-economy models is needless to say questionable especially in the light of our previous remarks on the slow and sometimes entirely thwarted diffusion of new techniques.

The unlikeliness of the "bang-bang" behavior was assessed recently by some authors who sought to eliminate the exaggerated model behavior due to the penetration of backstop technologies. Indeed, the way in which a backstop technology penetrates the economy, depends on the chosen elasticities of substitution between the outputs of the two production functions (Sue Wing and Popp (2006)). By setting an imperfect elasticity of substitution between the two activity outputs (one being entirely due to the older technology and the other one being entirely due to the backstop technology), a modeler can control the penetration rate of a backstop technology (Gerlagh and van der Zwaan (2003)) and thus hinders the "bang-bang" backstop effect. Popp (2004) also allows for such a "softer" entrance of backstop technologies by modeling these backstop technologies as imperfect substitutes to the fossil fuels, allowing for what he calls "niche markets", even when the price of the backstop technology is higher than the price of the conventional technology<sup>4</sup>.

Although the use of backstop technologies is widely criticized as being an exogenous process, hindering any reactivity of the model to an environmental policy, Popp (2004) suggests that the use of backstop technologies mitigates these policy costs much more

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<sup>4</sup>Such "niche markets" cannot exist in the case of the bang-bang behavior, as a backstop technology will be used only if it is cheaper than the conventional technique. If the price of the backstop is higher, the output of all goods will be subject to the conventional technique, solely.

effectively than induced technological change would. To show this, he introduces in the ENTICE-BR model two sorts of technological change. Exogenous technological change through a backstop technology, and induced technological change through investments in research and development. Popp shows that cost mitigation is greater with the modeling of the backstop technology than with endogenous technological change due to investment in research and development, simply because of the opportunity costs (or "crowding out" effects<sup>5</sup>) of research and development.

The main problem, however, with the backstop technology approach to modeling technological change, apart from its exogenous specification, is that it is often very closely linked to the personal assumptions of the modeler. Most of the time it depends on engineers' assumptions specifically relative to the availability date of the backstop as well as to its degree of penetration, its price and its emissions. Such choices can lead to great variations in the model's results and on the policy costs assessments. Moreover, due to their intrinsic specification, backstop technologies are not found in a social accounting matrix which is a snapshot of an economy at a time  $t$ .

A well known model that includes backstop technologies is the OECD GREEN Model (Burniaux, Martin, Nicoletti, and Martins (1992)). In this model, three backstop technologies are assumed to be available, a carbon based synthetic fuel, and two carbon free techniques. The model's main assumptions are linked to the timing of diffusion of each technology and their respective prices. Indeed, once the technologies are introduced, they become available over all the countries modeled in GREEN, in unlimited quantities and at constant marginal costs. One specificity of the model relies in the fact that technology innovation possibilities are supposed fixed at a present level of knowledge for the entire simulation period. What essentially drives the model's be-

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<sup>5</sup>Crowding out occurs when new investments in research and development hinder other investments in research and development, thus leading to opportunity costs. Such effects are expected to limit the potential positive contributions of R&D. Goulder and Schneider (1999) and Popp (2003) both point to this crowding out effect as a result of investments in research and development induced by an environmental constraint.

havior relative to the introduction of new technologies is the exogenously given price of the technological options. The evolution of prices of backstop technologies, are of course at the discretion of the modeler.

Apart from these questions, the main criticism that would be made to these two different modeling techniques, lies in the inaptitude of the model to react to any sort of environmental policy. This has lead modelers to explore different methods to endogenise or induce technological change so as to permit for such reactivity. In the following section, we will present the two modeling methods that allow technological change to be influenced by an energy policy.

## 1.4 Endogenous Technological Change

As our focus in this thesis is specifically on energy-economy models it is necessary to distinguish between energy-related technological progress and simple general productivity increases. In fact, in many energy-economy models, technological change is modeled separately and endogenously in the energy sector, total factor productivity remaining an exogenous process. Incorporating induced technological change in climate models allows for a more realistic approach of an economy's reactivity facing an environmental or energy restriction. In such a framework, an economy can then be expected to seek to adjust its reaction or technology choices to a new economic environment through an endogenous specification of technological change. In this section we will explore the two main different modeling methods to account for endogenous technological progress, and will seek to assess the advantages and limitations of both these methods.

Basically, the growth literature suggests that knowledge capital may accumulate either through investments in physical capital, or through research and development expenditures, or through a combination of both. It remains clear, however, that the

accumulation of knowledge capital is central to the inducement process of technological progress, and such accumulation will impact the production functions. Taking these considerations into account, induced technological change has until now been modeled, either through the learning by doing process (the main underlying hypothesis being that knowledge accumulates as a side effect of production) or through investments in research and development (knowledge accumulation being the outcome of R&D expenditures) or through a combination of both (knowledge accumulates as a side effect of production, as well as derives from expenditures in research and development).

However, the complexities linked to the process of technological change remain difficult to take into account in energy-economy models, and specifically the lack of certainty in the outcome of investments in research and development. Difficulties also lie in accounting for increasing market demands for new-high-priced-low-carbon products, which are the outcomes of research and development<sup>6</sup>. Moreover, slow diffusion of new technologies due to technology lock-ins and path dependence, are also difficult to assess. Finally, the existence of spillovers leading to sub-optimal investments in research and development may increase the models' complexities. While some of the aspects cited above can be assessed to a certain point, it is clear that the general method of inducing technological change in energy-economy models cannot take all these restrictions into account and suppose much clearer market reactions.

In this section we will seek to define more precisely both, the process of learning by doing, and the stock of knowledge approach as methods to endogenise technological change.

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<sup>6</sup>While the price of these low-carbon goods may be high, demand for these goods may still increase. Consumers will not simply base their consumption decisions on the price factor, but may desire the "environmental friendliness" of these goods, overlooking the cheaper more coal intensive products.

### 1.4.1 Learning by Doing

The concept of learning by doing was introduced by Arrow (1962) who was the first to suggest that unit costs decline over time as producers accumulate knowledge through the production process. Indeed, while new goods are initially expensive to produce, their production costs decline over time because of the emergence of new production methods that render its production easier and more straightforward. Therefore, the accumulation of a stock of knowledge is not a decisional factor, but is by-product or side-effect of the production of a good. Similarly, the concept of "learning by using" emerged, as a process whereby knowledge accumulates over time through the simple usage of a technology or a good<sup>7</sup>. Learning by doing is therefore simply a free "side-effect" of a growing economy.

It follows that investment in a new technology is initially more expensive than investment in widely-used technologies. But as the new technology's market share grows, its cost also declines and will become at some point in time cheaper than the older technology which is less subject to cost reductions, as it is more mature. Basically, learning by doing is therefore another "manna from heaven" as it links declining costs of a technology, with the expansion of its production.

Christer Berglund and Patrik Söderholm (2006) note three sources to the learning by doing effect. The first source of learning comes from the labor force. Indeed, labor force involved in producing a good, accumulates knowledge over time. The consequence is therefore that progressively less labor is needed to produce a given amount of output. A second source of the learning by doing effect can come from the management level who, over time, gains know-how and can rearrange the production processes and

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<sup>7</sup>Incorporating a new technology in a production function is expensive. The costs that it incurs count for instance learning costs for the workers involved in production, institutional costs (changes in production techniques needed for the incorporation of the new technology) as well as training costs for workers who will be using the new technique. The more workers get used to the technique, the less expensive it gets to incorporate it in the production methods, as workers are trained and infrastructures are adapted to the technology.



reassign jobs in a more efficient manner. Finally, technological change that derives from a repetitive use, can be seen as learning that was acquired by the production process infrastructure. These three sources simply lead to the enhancement of production efficiency or performance over time, through the experience gained in the production process.

Grübler et al. (1999) and Azar and Dowlatabadi (1999) argue for the relevance of using this method for modeling technological change in global energy models.

Sue Wing (2001) underlines three major problems to the modeling of learning by doing as a means of introducing endogenous technological change. The first one is the lack of empirical data as to specific estimated learning curves, and this being specifically the case for new technologies. Indeed, following their introduction, their declining costs are unknown and are often modeled following a "generalized" learning curve, result of an amalgam of other different learning curves. The second problem is relative to the partial equilibrium assessment of the learning by doing process. In fact, it is necessary to assess the different general equilibrium effects of a specific policy, leading to price or quantity variations in order to take into account all the possible feedbacks that may derive from these policies. It follows that ignoring the general equilibrium feedbacks and spillover effects of learning induced productivity improvements can seriously alter the general result and initial cost reductions in a sector. Finally, the process of learning by doing is a mechanistic process, where learning and cost reductions are immediate consequences of cumulative production.

### **The Single-Factor Learning Curve**

Formally, modeling technological change through the learning by doing approach is relatively straightforward. In this approach, costs decline as knowledge is accumulated over time, and as production increases. Therefore, one can model a good's production

cost function as the function of one single factor, the cumulative installed capacity :

$$C = C_0 * Ex^{-\alpha}$$

With  $C$  the cost of a specific technology or good,  $C_0$  the cost at unit cumulative capacity,  $Ex$  the cumulative (installed) capacity (a proxy for experience and only explanatory variable to the cost of the specific technology), and  $\alpha$  the learning elasticity or learning index. Therefore, if the cumulative capacity doubles then the cost of the technology increases only by  $2^{-\alpha}$ . This is called the progress rate. The learning-by-doing rate is  $1 - 2^{-\alpha}$ , which is the complementary of the progress rate. Basically, the progress rate simply determines how fast one learns. The learning-by-doing rate, on the other hand, is determined in percentages and is the percentage of cost reduction that derives from the doubling (in our case) of the installed capacity.

Argote and Epple (1990) suggest that learning-by-doing rates can be very different according to sectors and to technologies that are studied, even if they belong to the same industry. In fact they estimate that this rate can range from 5% to 35%! Leading to similar results, Köhler J. et al (2006) surveyed the literature quantifying learning curves, and adapted work previously done by McDonald and Schrattenholzer (2001) suggesting that the learning-by-doing rates for energy technologies could range between 3% and 35%. However, learning rates that are incorporated in models are often not the result of serious econometric studies. Its value can often be chosen to influence the models' results.

Regarding the impacts on the optimal timing of abatement of modeling technological change through learning by doing, all three papers Messner (1997), Grübler and Messner (1998) and Mattson and Wene (1997) reach similar conclusions : with learning curves as a means for introducing technological progress, *early* investment in energy technologies are necessary to stimulate learning and ultimately cost reductions<sup>8</sup>. Most

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<sup>8</sup>In these models, the choice between different energy technologies is optimized given different costs of abatement and emission targets.

bottom up models in fact study the optimal abatement over time, and suggest that modeling learning by doing leads to *early* action in the timing of abatement<sup>9</sup>, compared to the exogenous technological change case.

Regarding environmental policy cost assessments, Manne and Richels (2004) assess the costs of stabilising  $CO_2$  emissions in the case where technological change is the consequence of LBD. They study in particular the case of the electricity sector and seek to determine the impacts of taking the learning by doing process into account on the costs of abiding by environmental constraints. Their major finding is that learning by doing does indeed reduce the costs of the environmental policy. The main reason behind this result is the fact that the business as usual emissions are lower in the case where learning by doing is introduced in the model. It is therefore much easier to abide by environmental constraints as the additional constraints that are necessary to reach the emission stabilization policy are much smaller when the business as usual emissions are low. Manne and Richels do not strictly speaking study the "policy induced" effects of learning by doing. In fact, they assess the cumulative effects of business as usual learning by doing, and policy induced LBD. To isolate the policy induced LBD, Goulder (2004) suggests comparing two scenarios with the model. One, with the two learning by doing effects cumulated, and one constraining the model so as not to allow for additional policy induced learning by doing. However, Manne and Richels do show that incorporating learning by doing in energy-economy models does in fact reduce costs significantly.

Learning by doing is more often modeled in bottom-up rather than in top-down models. Two well known bottom-up models incorporating learning by doing are the MESSAGE model (Messner (1997)) and the MARKAL model (Barreto and Kypreos (1999)). In these models technological progress derives from a learning or experience

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<sup>9</sup>Note that Manne and Richels (2004) suggest the contrary : early abatement is not necessarily the result of modelling learning curves.

curve which is a function of experience that accumulated through production or through the use of a technology during its diffusion.

### The Two-Factor Learning Curve

Recently, modelers have tried to incorporate another explanatory variable to the cost function. Indeed, they incorporate cumulative investments in R&D or an R&D based knowledge stock as a factor impacting the production cost of a good (see Söderholm, P. Sundqvist, T. (2003)). In this setting, two rates are taken into account : the "learning by doing" rate, and the "learning by searching" rate, which derives from the investments in research and development. Formally, one can model the two-factor learning curve as in equation 1.2 :

$$C = C_0 * Ex^{-\alpha} * R^{-\beta} \quad (1.2)$$

With, as above,  $C$  the cost of a specific technology,  $C_0$  the cost at unit cumulative capacity,  $Ex$  the cumulative (installed) capacity,  $\alpha$  the learning elasticity or learning index,  $R$  the cumulative investments in research and development or R&D based stock of knowledge, and  $\beta$  the searching index. Similarly to the single-factor learning curve, a doubling of R&D based knowledge stock, will lead the technology cost to increase by  $2^{-\beta}$ .

Controversies remain concerning the learning by searching approach. Kouvaritakis et al. (2000) in the POLES model, Barreto and Kypreos (2003) with the ERIS model, and Klaassen et al., (2003) all prefer the two-factor learning curve, and take research and development into account in their models. However, Miketa and Schratzenholzer (2002) and Criqui et al. (2000) suggest that this additional term to the learning function, increases rather than decreases the investment costs!

One critic that can be made towards choosing the learning by doing method to incorporate induced technological change, is that it does not assess the opportunity

costs of acquiring new knowledge as eviction effects are not accounted for (see Goulder and Schneider (1999)).

In the two factor learning curve, technological change may partly result from investments in research and development. Assuming that such investments can be the source to cost alleviation, some energy-economy modelers have considered that the accumulation of the stock of knowledge may be the only source to endogenise technological change. They consider knowledge as a stock which accumulates over time through R&D investments, and the services of which are used as production inputs. In the following section we address the stock of knowledge approach to modeling technological change.

#### **1.4.2 The Stock of Knowledge Approach or Investments in R&D**

Modeling technological change through a learning by doing process has been more commonly found in bottom up models than in top down models. In top-down models, technological change can be modeled through the accumulation of knowledge as a result of investments in research and development. Indeed, industries choose to invest in R&D as a response to an environmental constraint, which leads to the increase in the stock of knowledge, which in turn affects technological progress. In this framework, firms are profit-maximizing, and investment in research and development will be undertaken only if it is a profitable activity.

Modeling technological change with this method proves to be a complex task, partly due to the difficulty in attributing a value to knowledge, as such information is not available in a social accounting matrix. However, it builds on the macro-economic growth theory by which technological change innovation is a decisional factor, as opposed to the "free side-effect" aspect of learning by doing. The stock of knowledge approach is therefore a more attractive formulation to an economist who sees technological change as the result of a decision.

### **Intricacies in the Innovation Literature**

The literature on innovation is now quite exhaustive, and underlines the many intricacies linked to modeling it theoretically. A major underlying difficulty is that innovation is not a straightforward process, whereby investment in research and development always leads to a certain outcome such as a new technology or a blueprint etc... Indeed, not all investments in research and development necessarily lead to increases in the knowledge stock. Therefore, in energy-economy models, introducing induced innovation as the result of investments in research and development, and assessing the uncertainties that derive from this specification, may prove to be somewhat difficult. Precisely, spillovers and uncertainties as to the outcome are two major issues in the innovation literature that are often assessed in these models<sup>10</sup>.

**Uncertainty** Uncertainties have important implications on the modeling of endogenous technological change in energy-economy models, as the price of future technologies are unsure and may not necessarily become cheaper than conventional technologies. Montgomery et al. (forthcoming) refer to the aspects of uncertainty that are specifically linked to climate research and development. They suggest that markets do not necessarily prefer low-carbon products to conventional products. Very often in fact, the price of the conventional (carbon intensive) products does not reflect the externalities that derive from its use, and are cheaper than low-carbon products. The natural consequence is therefore a sub-optimal investment in research and development by profit-maximizing firms to develop low-carbon products, simply because of the high uncertainties of the market preferences and of the concept of climate change.

Moreover, there are also uncertainties as to the outcome of investments in research and development. Taking such uncertainties into account is a difficult task. In fact, very

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<sup>10</sup>Köhler et. al (2006) discuss four issues to be taken into account when modeling induced technological change with the stock of knowledge approach, namely path dependency, uncertainty, spillovers, and technology diffusion.

often, modelers choose to model the outcome of investment in research and development as a "certain" process as does Otto et al. (2005) who argue that uncertainty matters less at an aggregate level when averaged out (see Romer (1990))<sup>11</sup>.

**Spillover Effects** Apart from the uncertainties linked to the R&D process and market preferences, the literature on innovation suggests that spillovers are an important factor to take into account when assessing the impacts of investments in research and development. Indeed, spillovers allow for the dissemination of knowledge intra-sectorally, inter-sectorally and internationally through many different channels such as patent flows, published materials or even simply through the learning by doing process. Otto et al. (2005) for instance choose to assess the spillovers effects from a stock of blueprints (resulting from some manufacturer's investment in knowledge capital) that lead to productivity increases in other production sectors.

Spillovers allow knowledge to cover the general economy at a very low cost, and R&D investments may allow the economy to grow infinitely<sup>12</sup>. Not all industries, however, will be interested in the knowledge of one particular industry, and spillovers may therefore be profitable to the industries that are technologically closer or simply more able to apply it. Also, as spillovers can disseminate the knowledge resulting from private investments in research and development by one firm, this destroys the full appropriability of the resulted knowledge, leading to a possibly lessened incentive to invest in R&D. In fact, whether the stock of knowledge accumulated through investments in research and development is firm specific, or not, will determine the existence or magnitude of spillovers in an economy. As noted previously, spillovers affect the magnitude of investments in research and development, in the sense that it affects the rate of return of these investments. Indeed, the difference between private and social returns

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<sup>11</sup>Wehrli and Saxby (2006) however model such an effect by postulating that the results of R&D are indeed uncertain and innovations therefore occur following a Poisson process.

<sup>12</sup>Although they may also be subject to decreasing marginal returns.

of research and development have often been assessed through empirical models. Due to the existence of spillovers, private returns to R&D are estimated to be significantly smaller than social returns to R&D. Empirical studies estimate private returns to be between 20% to 50% the size of social returns (Bosetti et al (2006)a). Whether the knowledge that derives from these investments is appropriable or not, and conditionally to the relative magnitude of the appropriability, the rate of return of investments in research and development will be affected, and R&D may be under-invested.

Therefore, three cases are possible (see Sue Wing (2003) for an in depth discussion). A first case supposes that firms invest in research and development which increases their respective stocks of human capital. These stocks are appropriable, and therefore firms cannot benefit from the knowledge stocks of other firms. Consequently, there are as many prices of human capital as there are firms, and there are no inter-sectoral or intra-sectoral knowledge spillovers. Each firm benefits solely from the knowledge services that derive from its own investments in research and development. A firm cannot benefit from other firms' R&D efforts.

In the second case, knowledge spillovers exist and suppose that investments in research and development by one firm can benefit other firms. All firms have access to a general pool of research and development, which is then allocated to the firms' different knowledge stocks according to their capacity to "absorb" research in development. In this case, knowledge is not appropriable, and different firms can benefit together from the same pool of research and development. Therefore, through the non-excludability of knowledge, firms can allocate a certain amount of resources to research and development, but see their knowledge stocks increased by more than their investment.

In the third case, firms invest in R&D, which increases an economy-wide stock of human capital or knowledge. The knowledge that derives from it is therefore not an



appropriable fruit of the investment in R&D. In the same way that capital services are allocated to the firms according to its price and the way in which it enters the production function, firms demand a certain amount of knowledge services as inputs to production, according to its price and how it enters the production function<sup>13</sup>.

### **The Stock of Knowledge Approach**

**Biased Technical Change** Often in energy-economy models, when technological change is induced, modelers seek to assess how the productivity of energy relative to the productivity of other production factors is affected by an environmental policy. Technological change can however influence the productivity of all factors of production or simply the energy factor.

Endogenous technological change can be specified formally as in the equation 1.3.

$$Y_t = A_t H S_t F(K S_t, L_t, E_t) \quad (1.3)$$

$Y_t$  is the value of production at time  $t$ , and  $F$  the production function.  $K S_t$ ,  $L_t$  and  $E_t$  are respectively capital services, labor and energy inputs used at time  $t$ <sup>14</sup>. Productivity increases are defined by the value of  $A_t$  which is the Hicks-neutral exogenous technological progress parameter at time  $t$ . Moreover, in this specification, increases in the use of human capital services  $H S_t$  in the production function automatically lead to a lesser use of all the factors of production : their productivity increases, and technological progress is Hicks-neutral. Basically, firms facing an environmental or emission constraint, may choose to increase their demand for human capital services  $H S_t$  (the intangible production factor) and decrease their demand for tangible inputs such as capital services, labor and energy.

In climate models, some modelers seek to address how investments in research

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<sup>13</sup>We choose such a specification in our model in the chapter 4 of this thesis, to account for inter and intra-industry spillovers.

<sup>14</sup>The FEEM-RICE model has such a production function specification.

and development, following an environmental constraint, will lead to an increase in energy efficiency, and therefore a more clear-cut decrease in emissions. Put differently, they try to address how technological change induced by a policy will lead to the decreasing of the emission/output ratio. In this specification, knowledge services reduce the level of carbon emissions that flow from the use of energy. Formally, human capital services can enter the production function as simply increasing the energy factor's efficiency (see equation 1.4). Investments in research and development, being the firms' response to environmental constraints, lead to energy efficient technological change, the productivity of other factors remaining unaffected.

$$Y_t = A_t F(KS_t, L_t, HS_t E_t) \quad (1.4)$$

Facing an environmental or emission constraint, firms may increase their demand for knowledge services (the intangible input to production) and thus limit their demand for energy. In this specification, technological change is biased and favors of a lesser use of energy.

Modelers may model induced technical change through one or the other process, or also through both as in Buonnano et al.(2003).

**Models Incorporating the Stock of Knowledge Approach** Goulder and Mathai (2000) allow for a smooth transition between the learning by doing process previously described and the stock of knowledge approach as they take investments in research and development into account to study the optimal dynamics of carbon emission reduction. Indeed, they use a partial equilibrium model where technological progress is either the result of investment in research and development and consequently the accumulation of the stock of knowledge (in their specification, the stock of knowledge is a function of the level of emission reduction), or the result of a learning by doing process in carbon abatement. A central planner facing an emission constraint, chooses time paths of abatement and efforts in research and development, that minimize the present value

cost of abatement. The cost function is therefore a function of both the accumulated stock of knowledge (that grows with R&D efforts) and the abatement (learning curve). The authors underline that the optimal dynamics of emission reduction as well as the dynamics of carbon taxes depend on the **form of the technological progress**, i.e. whether it derives from the learning effect or from the investments in R&D, but also on the criteria of analysis, whether it be a criteria of cost-efficiency or cost-benefit. Through analytical studies they show that in the case where knowledge derives from investments in R&D, it is optimal to reduce the emissions in the future. However, in the case where the knowledge derives from a learning effect, the impact on the dynamics of the optimal reduction is ambiguous.

Goulder and Schneider (1999) use a general equilibrium simulation model to study the effects of induced technological change on the costs incurred by abiding by environmental constraints. In their model, there is no learning by doing process and technological change is solely the result of investments in research and development. As environmental policies are introduced, profit-maximising firms are affected by changing relative prices, and they adjust their level of investment in research and development so as to maximise their profits in this new framework. As opposed to the Goulder and Mathai model, induced technological change reduces the costs of abatement by about 15% which is half of what Goulder and Mathai predict in the middle cases. There may be many reasons for such differing results, but one may be linked to the fact that in the Goulder and Mathai case, the environmental policy is more aggressive or more stringent, which thus leads to higher abatement costs. Another explanation to these different results may lie in the marginal abatement cost functions in these two models. Indeed, the producers' marginal abatement cost functions in the Goulder and Schneider model increase faster with higher abatement levels, than in the Goulder and Mathai model (Goulder (2004)).

Otto et al. (2006) study with a forward looking CGE of the Dutch economy the

cost-effectiveness of an environmental constraint such as a cap and trade constraint. In their model knowledge capital is sector specific which cause positive technology externalities on the production of sectors leading profit maximizing firms to underinvest in R&D. The authors find that it is more cost effective to direct  $CO_2$  constraints towards  $CO_2$  intensive sectors rather than impose a uniform  $CO_2$  constraint on all sectors. Moreover, they show that differentiated  $CO_2$  prices bias technological change towards non  $CO_2$  intensive industries. Indeed,  $CO_2$  intensive sectors see their growth "discouraged" by differentiated  $CO_2$  prices while non  $CO_2$  intensive sectors see their growth "encouraged". The authors also find that it is better to direct R&D subsidies towards non  $CO_2$  intensive sectors as it reduces emissions and increases welfare compared to the BAU, concomitant with an R&D *tax* on  $CO_2$  intensive sectors to slowly disappear.

Kemfert (2004) uses the WIAGEM model, a multi-regional, multi-sectoral integrated assessment model, to introduce induced technological change as the result of investment in research and development, the spending of which influences the productivity of the energy input. In such a framework, investments in research and development therefore increase energy efficiency. While, knowledge is here not modeled as a stock but as a flow. The model results suggest that induced technological change due to investments in research and development diminishes the compliance costs to an environmental policy. Kemfert shows that in the case of no technological change, abiding to environmental constraints can be managed only through a reduction in output leading therefore to welfare losses. Inducing technological change thus allows for the decoupling of emissions and output, and mitigates the costs of climate policies without leading to output reductions.

### **A Relatively Small Impact of R&D Induced Technological Change**

This method is not without controversies. Nordhaus (2002) using the RICE model incorporates induced technological change through investments in R&D. His paper is often cited by opponents to induced technological change as his results suggest that induced technological change is not as effective as simple input substitutions. Indeed, input substitutions in his framework of the RICE model reduce carbon intensity twice as much as induced technological change does. He thus concludes that, when needing to reduce carbon intensity, investing in research and development is not as important as input substitutions. While his work with the RICE model supposed a rigid framework (there were no investments in physical capital and therefore no economic growth in the induced technological change version of the RICE model), Popp (2003), who allows for such optimal economic growth, still argues that the overall impacts of modeling technological change through investments in research and development tends to have relatively small impacts. Although the effects on the economic and environmental variables do exist, in comparison to the case where technological change is exogenous, they stay relatively small<sup>15</sup>.

SueWing (2001), incorporates the stock of knowledge approach as a method to model technological change in a computable general equilibrium model for the US economy. In his model, a general economy-wide knowledge stock increases through investments in R&D, the services of which are used as inputs to production. The knowledge stock grows in the same way as the physical capital stock does. Sue Wing seeks to assess the effects of ITC on the costs of limiting carbon emissions, and shows that, similarly to Goulder and Schneider (1999) and Nordhaus (2002), the effect of technological change is small.

Although a small effect, the "crowding out" effect, can lead to unexpected modeling

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<sup>15</sup>In our model for the French economy, we also show that modeling technical change through the stock of knowledge approach has small effects on the economy.

results. Modeling technological change through the stock of knowledge approach, where industries invest in research and development when facing a constraint, leading to productivity increases due to the accumulation of the knowledge, does not necessarily suggest that research and development "as a whole" increases over time in the economy. Such environmental constraints may lead to the contraction of general (or economy-wide) R&D. Two papers support in fact the notion of a "crowding out effect", whereby research and development is supplied inelastically, and investment in R&D in one sector of the economy, may lead to reductions in the amount of R&D investments in the rest of the economy. Goulder and Schneider (1999) and Popp (2004) argue in this direction.

## 1.5 Conclusion

As determined in the previous sections, technological change can be modeled either as an exogenous or as an endogenous process. In the following table we display a certain number of models and their method for modeling technological change.

Omitting to account for technological progress in a climate model may lead to great overestimations of the costs of a climate policy. But, if one wants to account for such progress, choosing between an endogenous process or an exogenous process is not without consequence and can lead to very large differences in model results. The choice of the modeling method, i.e. Autonomous Energy Efficiency Improvement parameter, Backstop Technologies, Learning by Doing, or the Stock of Knowledge Approach implies many hypothesis and modeling constraints, which in the essence hinder rigorous model comparison. Also, the choice of parameter values within one unique modeling method affects short and long term predictions quite sensitively. Indeed, as we have seen in the previous chapter, as the autonomous energy efficiency rate can range between 0.4 and 1.5, the learning by doing rate for energy technologies can range between 5% and 35%, and may not be rigorously determined by econometric analysis. Choosing to incorporate backstop technologies in the modeling process, also leads to great varia-

tions in modeling results because of the differences in the modelers' sensitivity relative to the timing of incorporation of technologies, their estimated price, as well as the future use of a disputed technology<sup>16</sup>. Finally, the modeler's assessment of the different inter-sectoral, intra-sectoral, international spillovers, as well as outcome uncertainties following investments in research and development, and possible crowding-out effects, lead to a wide range of modeling results.

For these reasons, comparing energy-economy model results in the case of environmental constraints remains a very tricky task.

In the table 1.1, we give an overview of the most recent energy-economy models and the modeling methods chosen.

In the chapter 4 of this thesis, we build a forward-looking model for the French economy, and incorporate induced technological change through the stock of knowledge approach. Our goal is to assess the impacts on the economy of an environmental constraint. Our work builds on the knowledge of the state of art of technological change modeling techniques, and describes the intricacies of modeling endogenous technological change through this approach, when the value of embodied knowledge is unknown, and must be estimated.

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<sup>16</sup>Some modelers may or may not, for instance, consider the use of hydrogen or fusion power as possible production techniques in the next decade.

Technological Change in Energy-Economy Models			
Model Name	Type	Techn. Change Specification	References
RICE	IAM	AEEI	Nordhaus et Yang (1996)
DICE	IAM	R&D	Nordhaus (2002)
FEEM-RICE	IAM	R&D, LBD	Bosetti et al. (2006)
ETC-RICE	IAM	R&D, LBD	Castelnuovo et al. (2003)
WIAGEM	IAM	R&D	Kemfert (2004)
ENTICE	IAM	R&D, backstop	Popp (2004)
DEMETER - 2E	ES	LBD, R&D	Gerlagh et Lise (2003)
ERIS	ES	two fact. Learning curve	Klaassen et al. (2003)
POLES	ES	two fact. Learning curve	Kouvaritakis et al. (2000)
MESSAGE	ES	single fact. Learning curve	Messner (1997)
MARKAL	ES	single fact. Learning curve	Barreto et Kypreos (1999)
MIT-EPPA	CGE	AEEI, backstops	Babiker et al. (2001)
PACE	CGE	AEEI, backstops	Böhringer (1999)
MERGE	CGE	backstop, LBD	Manne et Richels (2004)
OECD GREEN	CGE	backstop	Burniaux et al. (1992)
MODEL for USA	CGE	R&D	Sue Wing (2002)
MIND	IO	R&D	Edenhofer et al. (2006)
IAM : Integrated Assessment Model, ES : Energy System Model			
CGE : Computable General Equilibrium, Model, IO : Input-Output Model,			
AEEI : Autonomous Energy Efficiency Improvement, Backstop : Backstop technologies			
R&D : Investment in Research and Development			
LBD : Learning by Doing,			

TAB. 1.1 – Technological Change in Energy-Economy Models





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## **Chapitre 2**

# **A CGE Model for France with Exogenous Technological Change : Conclusions on the French National Allocation Plan**

## 2.1 Introduction

The goal of this chapter is to study the impacts of an emission constraint in a computable general equilibrium (CGE) model for the French economy, with technical change modeled as an exogenous process. We seek to show how the economy reacts to the introduction of an environmental policy, in the case where technological change cannot be influenced in its rate of direction.

To carry out this analysis, we construct our own recursive dynamic CGE model for the French economy, and model technological change with the autonomous energy efficiency improvement parameter (AEEI)<sup>1</sup> described in the chapter 1 of this thesis<sup>2</sup>. In this framework, technological change will be entirely unaffected by the constraint, and will simply increase the efficiency of energy according to this predetermined rate independently of any framework changes. Therefore, studying the effects of an emission constraint in such a framework, may lead to underestimations of the firms' reaction to a policy change.

Applied general equilibrium (AGE) models have been the principal tool used to analyze the welfare effects of climate change mitigation. However, these simulations are typically constructed on the premises that all of the economy's markets are in equilibrium and all of its factors are fully employed, thus involuntary unemployment is rarely modeled. Indeed, there have been numerous studies on the general equilibrium effects of carbon abatement in Europe, but a comparatively small number have sought to investigate the effects of mitigation policies on employment. In this chapter we account for the relative scarcity of studies on employment effects in single countries<sup>3</sup>. Indeed, these last two decades, the French labor market has been characterized by relatively

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<sup>1</sup>In fact we use the inverse AEEI, which render the same results.

<sup>2</sup>The value of the AEEI that we introduce in the model is that of 0.75%, which is relevant considering that in most studies the value of the AEEI is between 0.4% and 1.5%.

<sup>3</sup>Indeed, very few papers (for Holland, Bovenberg, A. et al (2000), for Germany, Böhringer, Boeters and Feil (2002)) have addressed the employment impacts of an environmental reform within individual European countries.

high unemployment rates. This has lead policy makers to estimate the quality of different policies according to their effect on employment (i.e., the law reducing the number of working hours, environmental taxation etc..). In light of the specificities of France's labor market, it appears that modeling unemployment as solely voluntary, leads to major general equilibrium biases. We therefore model unemployment as involuntary, the rates of which we determine as skill specific. What distinguishes our approach here is our treatment of unemployment as an involuntary and skill differentiated process.

We apply a policy similar to the National Allocation Plan to this model for France with exogenous technological change and skill differentiated unemployment. Indeed, in June 2004, France released its National Allocation Plan, a proposal describing how the country had planned to allocate emissions trading allowances to different individual emitting operators. The goal of this allocation plan is to determine a cap on the greenhouse gas emissions of the sectors that participate in the European Emissions Trading System (E.U. E.T.S.) and to allow the country to begin reducing its carbon emissions.

The E.U. E.T.S. entered into force on January 1<sup>st</sup> 2005. Participating entities in the trading system are all the European countries whose National Allocation Plans (NAP) have been approved by the European Commission. These NAPs are to be implemented during the period 2005 to 2007, and are designed as the first step for each participating country towards meeting its target under the burden sharing agreement. In fact, France's carbon emissions are expected to increase until 2012 generally due to the country's economic growth. The Energy Information Administration (International Energy Outlook 2004) suggests that the country's emissions in 2012 in the reference case, will be above the 1990 threshold emissions for France in the Kyoto agreement by some 4 Mt C. A constraining of France's emissions is therefore necessary to help France reach its burden sharing agreements. For this reason it is relevant for France to abide by a National Allocation Plan (NAP), as the country will be unable to satisfy the burden sharing agreement in the reference case without a specific constraint.

Under the NAP, France's Energy producing sectors, which in the simulations of the paper cover the coal, oil, gas and electricity sectors, are constrained to emit a maximum of 17.96 mega tons of carbon (Mt C) per year<sup>4</sup>. Energy intensive sectors, which we here treat as ferrous and non ferrous sectors, chemical products and other energy intensive sectors, may not emit more than 15.49 Mt C each year until the end of 2007. The French National Allocation Plan indeed does not constrain all the sectors in the economy. In fact, even sectors such as the transportation sector are not covered by the NAP and are therefore not issued any allowances that would constrain their emissions. For the sake of clarity in the analysis and conclusions, we choose to call "covered sectors", all energy intensive and energy producing sectors whose carbon emissions are constrained by the NAP and "non covered sectors" all other sectors that are not mentioned in the NAP and that are not expected to reduce their emissions to any required predetermined level during the first period the plan is enforced<sup>5</sup>.

Therefore, starting 2005, all covered sectors received this pre-specified amount of allowances, that they can now trade on the market for tradeable permits. The price of the allowances is determined according to the stringency of the NAP, as well as the demand and supply of allowances. From 2008 onwards, the Kyoto protocol is expected to enter into force<sup>6</sup>. In this second period, the NAP will be reevaluated and possibly made more stringent. Moreover, previously "non-covered" sectors will be required to reduce their emissions, in order for the country's emissions to fall back to its 1990 levels.

In this paper we analyze three different environmental policies, and study the econ-

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<sup>4</sup>That is, the sum of all emissions of all four energy producing sectors may not be greater than 17.96 MtC.

<sup>5</sup>The National Allocation Plan entered into effect on January 1st 2005. Between 2005 and 2007, the plan is enforced as is. Starting 2008, the caps on the covered sectors can be reevaluated, most possibly made more stringent in order to reach France's Kyoto target. Therefore "another" NAP is expected to be issued. Also, while they were not constrained in the NAP, non covered sectors starting 2008 will be constrained by the enactment of the Kyoto protocol.

<sup>6</sup>The Kyoto protocol requires France to reduce its average emissions between 2008 and 2012 to its 1990 level of 103 MtC.

omy's reactions to such constraints, in the case where technological change is not malleable.

In the first policy, although the proposed NAP is only supposed to be implemented during the first period (2005-2007), we suppose that it will be extended unchanged to the next period. Our goal in modeling such a policy is to assess the stringency of the NAP, to get a closer look at its impacts on permit prices, as well as to assess the importance of the need for further emission constraints to attain the Kyoto limits. We therefore initially ignore the Kyoto agreements that are to constrain the economy's emissions starting 2008, and we solely study the effects of a possible further implementation of the NAP during the next period (2008-2012) as is. We show that the model predicts a slight increase in carbon prices, which will be over these five years close to \$9 per metric ton of carbon. The sectors that will sell their excess allocations are the coal, ferrous and non ferrous and electricity sectors. The oil, gas, chemical products, and other energy intensive sectors, whose emission reductions are insufficient, will buy these allowances on the market for tradeable permits.

In a second step, we implement the NAP as is until 2012, concomitant to which we take the Kyoto constraints into account in the model starting 2008 and constrain both covered and non covered sectors to limit their emissions to France's 1990 level<sup>7</sup>. We derive conclusions as to the effects of these two policies on the economy and specifically in terms of permit prices. We find that when Kyoto constraints are taken into account between 2008 and 2012, non covered sectors' emissions fall. Covered sectors' emissions are thus mechanically reduced, as their use as inputs to production of the now less polluting non covered sectors' goods, falls mechanically. This emission reduction slightly relaxes the constraint on covered sectors, as they effortlessly emit less (because they are simply less demanded and therefore less produced), and carbon prices fall to \$3.4 per metric ton of carbon between 2008 and 2012. The sectors that sell their permits on the

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<sup>7</sup>The NAP implemented alone until 2012, did not allow France to attain its Kyoto limits.

market for tradeable permits, are the coal, oil and gas sectors. The oil and gas sectors were not sellers of permits in the previous policy. This change is due to the fact that non covered sectors, whose emissions are taxed, choose to demand less highly polluting fossil fuels (coal, oil and gas) as inputs to their production. The law of supply and demand therefore constrains the production of fossil fuels to be equally reduced which mechanically leads to a reduction in their emissions. Their reduction in emissions is such that they have an excess of pollution permits, which they sell on the market for tradeable permits.

In the third policy, we suppose that the NAP will be made more stringent in the second period (between 2008-2012). But as we still ignore the degree of the possible contraction, we first model the implementation of the NAP until 2007 unchanged, and then constrain total covered sectors' emissions to a maximum of 32 Mt C in the second period. While this third policy is dependant on the fact that we were compelled to make a hypothesis as to the importance of the additional constraint, it remains of interest to the reader in that it gives insights on the interactions that reside between the NAP and the Kyoto constraints (and the relations between permit prices and taxes), and the effects of their concomitant implementation on the economy. Under our projections of baseline emissions the proposed cap is not very constraining the first period (2005-2007) and permit prices are close to \$1.2 per metric ton of carbon, as was the case in the first period in the first policy. In the second period, a further constraining of the NAP after 2008, coupled with the introduction of the Kyoto constraints until 2012, induces the covered sectors' permit price to jump up to \$25 per metric ton of carbon between 2008 and 2012, while it was that of \$3.4 in the previous policy. Sectors that choose to sell pollution permits are now coal, ferrous and non ferrous sectors and electricity. This change is now due to the fact that the Kyoto constraints are negligible compared to the constraints on covered sectors. Therefore, the general equilibrium effects on the production of coal, oil and gas, are not strong enough to counter the direct effect of the

covered sectors' constraint, and the market situation is the same as in the case where the Kyoto constraints are not taken into account.

In the next section, we describe the model<sup>8</sup>, then we lay out the different policies we study linked to France's National Allocation Plan, finally we underline the conclusions on the French economy as a whole. The object of this chapter is to get a clear idea of the impact of an emission constraint on the substitution possibilities of the French economy when technical change is modeled as exogenous. Indeed, in this framework, the only reaction of the firms to an emission constraint is through input substitutions, the mechanisms of which we determine here.

## 2.2 Description of the Static Model

In this section we define the different theoretical modeling choices on which our model is based. We follow the standard formulation of a CGE model representing a small open economy in complementarity format (e.g. Boehringer and Vogt (2003)). There are seventeen sectors, seven of which will be constrained by the French NAP.

### 2.2.1 Database and Calibration

We model France as a small open economy and calibrate the model on data for the French economy in 1995. The data source used for calibration was extracted from a Social Accounting Matrix (SAM) for France compiled by EUROSTAT and GEM-E3 researchers (see National Technical University of Athens).

#### The Production Sectors

Seventeen sectors are accounted for in this model.

Agriculture

Coal

---

<sup>8</sup>A formal description of the model is to be found in the Annexes A and B.



Oil  
Gas  
Electricity  
Ferrous and non ferrous metals  
Chemical Products  
Other Energy Intensive Goods  
Electric Goods  
Transport Equipment  
Other Equipment Goods  
Consumer Goods Industries  
Construction  
Telecommunication Services  
Transport  
Service and Credit insurances  
Other Services

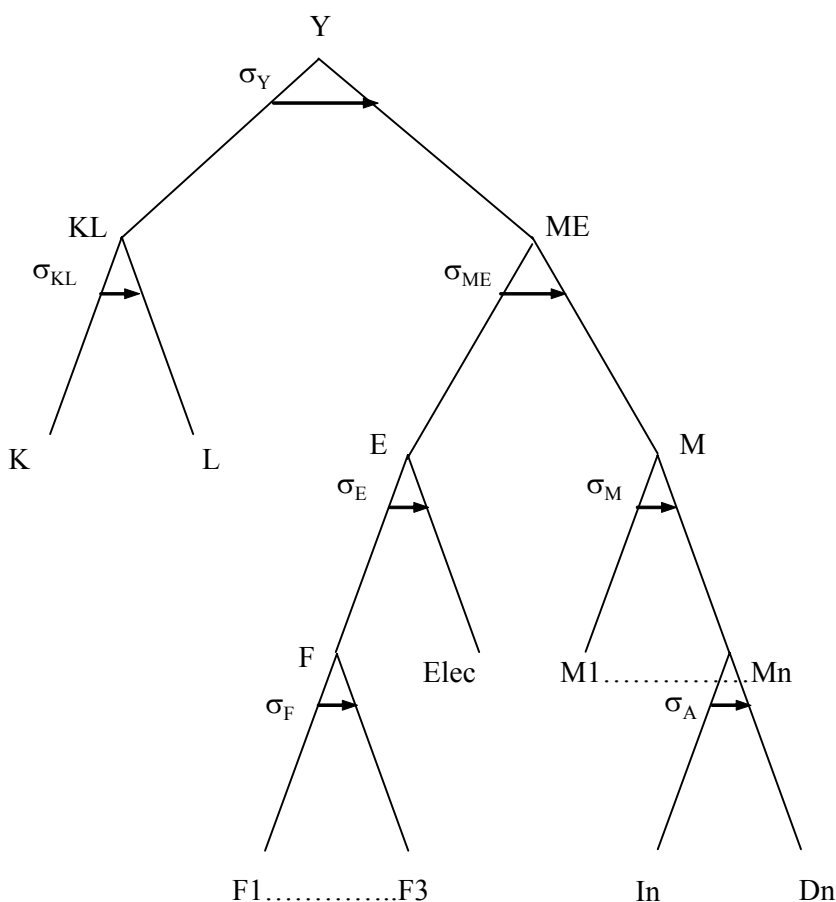
Each sector is modeled as a representative firm that combines inputs of primary factors, fuel and non fuel intermediate goods according to a nested Constant Elasticity of Substitution (CES) production function. Four of the model's sectors are energy sectors (coal, oil, gas, electricity). The model accounts for three production factors, physical capital services, skilled labor and unskilled labor.

The produced good  $Y$ , is a CES function linking  $KL$ , a bundle of physical capital services  $KS$  and labor  $L$  (labor itself being a CES function of skilled and unskilled labor<sup>9</sup>), and  $EM$  which is a CES function of energy inputs  $E$ , and materials  $M$ . The bundle of energy goods  $E$  links  $F$  the fossil fuel bundle and *elect* electricity also according to a constant elasticity of substitution function, while  $F$  is a similar function of

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<sup>9</sup>Skilled and unskilled labor are related through a Cobb Douglas function, which we have not represented on the graph.

coal oil and gas ( $F_1...F_3$  in the graph). The bundle of material inputs  $M$  is a function of all the material inputs in the economy<sup>10</sup>. Finally, each intermediate input in this graph is in fact an Armington good (Armington P. (1969))<sup>11</sup>, relating domestic goods produced in the economy and the imported goods produced in the rest of the world<sup>12</sup>, and all goods are produced for both the export and domestic market. The detailed formulas of the different functions and bundles making up the production function are described in the Annexes A and B of this chapter.



<sup>10</sup>It is a bundle of all the goods produced in the economy by all sectors that are used as inputs to production in one sector.

<sup>11</sup>The only inputs that are not Armington goods are the factors of production capital and skilled and unskilled labor.

<sup>12</sup>This armington good relationship is in fact described in the graph only for the  $n$  th good of the material bundle.  $I_n$  is the value of the imported good  $n$ , and  $D_n$  is the value of the domestically produced good  $n$ . However, all intermediate inputs are Armington goods.

### Substitution Elasticities

The production function in the model being a standard KLEM model it relates bundles of inputs according to elasticities of substitutions that are defined in the following table.

Values of elasticities of substitution		
$\sigma_Y$	Top layer armington	0.7
$\sigma_{KL}$	Capital versus labor	1
$\sigma_{ME}$	Materials versus energy	0.75
$\sigma_E$	Electric versus fossil fuel	0.7
$\sigma_M$	Between materials	0.6
$\sigma_F$	Between fossil fuels	1
$\sigma_A$	Armington elasticity	2
$\sigma_L$	Elasticity skilled vs. unskilled	1

### The Tax System

The SAM for the French economy in 1995 assesses the major relevant taxes for that year. We can thus describe the total tax burden for all sectors in the French economy in 1995, as well as their relative share in the government budget (see figures 2.1, and 2.2).

Factor taxes (taxes on capital and labor taxes) represent close to 60% of the total tax revenues for the government, and is therefore the major source of revenue. It follows from these simple statistics, that further study relative to revenue neutral green tax reforms, consisting in the introduction of an energy tax, the revenues of which are redistributed to the economy through the reduction of labor taxes, are relevant in the French economy.

The fact that both coal and agriculture have a negative tax burden simply suggests that they are subsidized sectors.

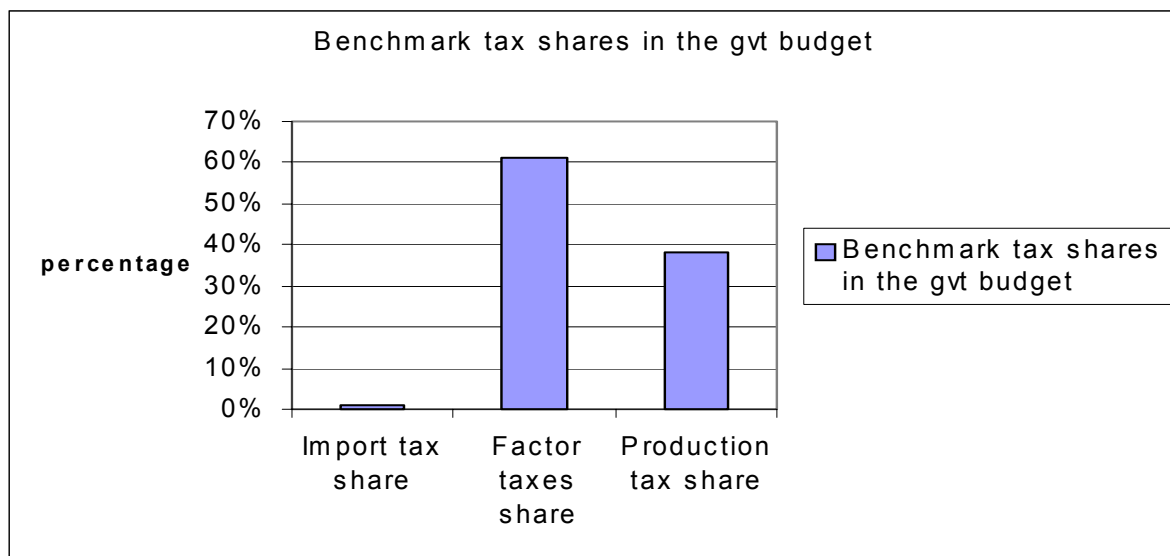


FIG. 2.1 – Benchmark tax shares in the government budget

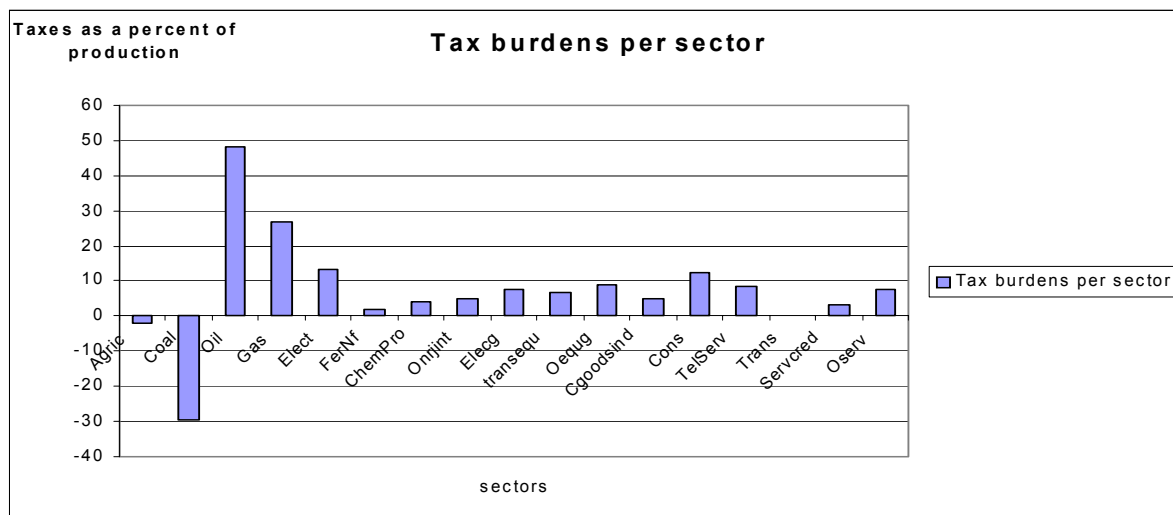


FIG. 2.2 – Tax burden per sector as a percentage of production

## 2.2.2 Labor Market Differentiation and Unemployment

### Two Types of Qualifications

The model's key innovation is its disaggregation of the labor input into skilled and unskilled labor for each sector, and the modeling of unemployment for these two types of labor. Indeed, the social accounting matrix for France does not separate between skilled and unskilled labor, as it gives a general value of total labor used in the economy. We therefore use data from the Enquête Emploi, a French household level employment survey (INSEE (2002)), to disaggregate the labor input to each sector in 1995 into the separate contributions of skilled and unskilled workers<sup>13</sup>. By so doing, we specify unemployment for skilled workers to be determined differently than for the unskilled. It follows that each group of workers will be subject to a different unemployment rate. With additional data from Audric-Lerenard et al (2000), we estimate<sup>14</sup> the relative unemployment rates for qualified and unqualified working agents in France in 1994<sup>15</sup>.

We then model unemployment for the skilled workers with a wage curve specification, and model unemployment for the unskilled as the result of the existence of a minimum wage.

### The Reasons for Unemployment Depend on Workers' Qualifications

**The Wage Curve Specification for High Skilled Workers** In this model, we chose to model involuntary unemployment for qualified workers through a wage curve specification as in Blanchflower and Oswald (1994). The wage curve hypothesis as-

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<sup>13</sup>We chose to follow the INSEE's definition of skilled and unskilled labor.

<sup>14</sup>Audric Lerenard et al (2000) report unemployment rates for five categories of labor, namely skilled employees and skilled workers, managerial employees, as well as unskilled workers and unskilled employees. Following this disaggregation, we estimate two unemployment rates for the unskilled and the skilled, without making a distinction between employees and workers.

<sup>15</sup>Audric Lerenard et al (2000) determine the unemployment rates for 1994. We did not have access to data for 1995. We therefore chose to consider that the unemployment rates had not changed dramatically over the year, we approximate them to be equal in 1995 to their estimation of them in 1994. Our estimation leads to an unemployment rate for non skilled workers to approximately 20.4 %, while the unemployment rate for skilled workers is close to 10.4 %.

sumes that wages are determined according to the local unemployment level. Indeed, local unemployment is negatively correlated to the wage rate. This phenomenon reflects efficiency wages or bargaining : if unemployment is high, then competition for job opportunities is stronger, enabling companies to offer lower wages, and if unemployment is low, then high skilled workers have their pick of a range of job opportunities, forcing each firm to offer higher wages in order to attract qualified labor. In the case where unemployment is high, firms do not have an incentive to induce workers to high efficiency, as they fear losing their job. On the contrary, when unemployment is low, firms must offer high wages in order to incite workers to high efficiency, and also because trade union bargaining power is higher when unemployment is low.

In the graph 2.3, the real wage rate that would clear the market, that is to say would allow the supply of labor to equal the demand of labor, is  $w_0$ . However, the demand of labor intersects the wage curve and leads to a real wage  $w_1$ , where  $w_1 > w_0$ . The result is the existence of unemployment, viewed on the graph as the difference between the actual labor that would have been supplied for a wage equal to  $w_1$  and the labor that is in reality supplied by the wage curve function. The consequences for the labor market are shown in figure 2.3.

Blanchflower and Oswald estimate that at the local level, the elasticity of annual labor earnings with respect to the local unemployment rate is in fact equal to  $-0.1$ . Montuenga, Fernández, and García (2004) estimate the elasticity for France to be  $-0.106$ . We follow Rutherford, Miles Light and Hernandez (2002), and Boehringer et al. (2001) to model the wage curve specification in our CGE model.

**A Fixed Minimum Wage for Low Skilled Workers** In this model, unemployment for low skilled workers is modeled through the existence of a minimum wage rigidity which does not allow the labor market to clear. Unemployment for unskilled workers is thus also modeled as involuntary. This is particularly relevant for France.

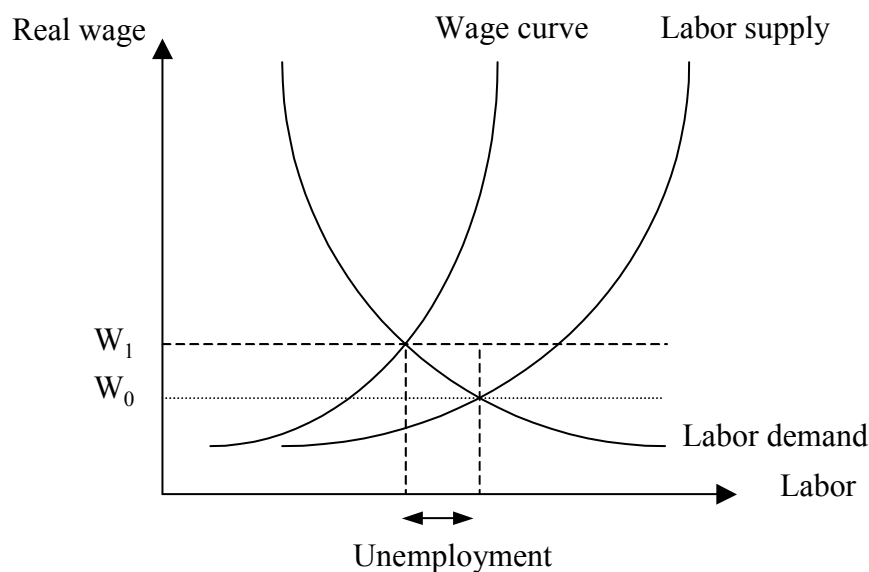


FIG. 2.3 – Wage curve specification

Indeed, workers in France are guaranteed a minimum wage (SMIC : Salaire Minimum Interindustriel de Croissance) under which it is illegal to employ a worker<sup>16</sup>. Following the classical unemployment theory, in the case where the minimum wage is higher than the wage allowing the labor market to clear, that is to say, allowing supply to equal demand, then, unemployment is the difference between the amount of labor supplied to the economy for that wage and the amount of labor demanded by firms. The existence of the SMIC is considered by some to be one of the causes to unemployment of non qualified workers in France however this view is not generally shared by all<sup>17</sup>. Indeed, some political parties or activist groups do not recognize this minimum wage to be too high for the labor market to clear. In our model, however, we choose as a hypothesis

<sup>16</sup>The minimum wage in France called the SMIC (Salaire Minimum Interprofessionnel de Croissance) is determined by the government. While, adjustments in the SMIC are usually due to administrative procedures taken each year, the government has sometimes enacted additional increases in the SMIC.

In 1995, the minimum wage was that of 958.53 ecus per month.

<sup>17</sup>Work by Laroque et Salanie (2000), suggests that 20 % of the french unemployed between 25 and 49 years of age, are cast out of the market because of their productivity being too low for the SMIC (while 57% of the unemployment is voluntary). On the contrary papers such as Machin et Manning (1997) or Dolado et al (1996), suggest that there is little evidence of a negative impact on employment.

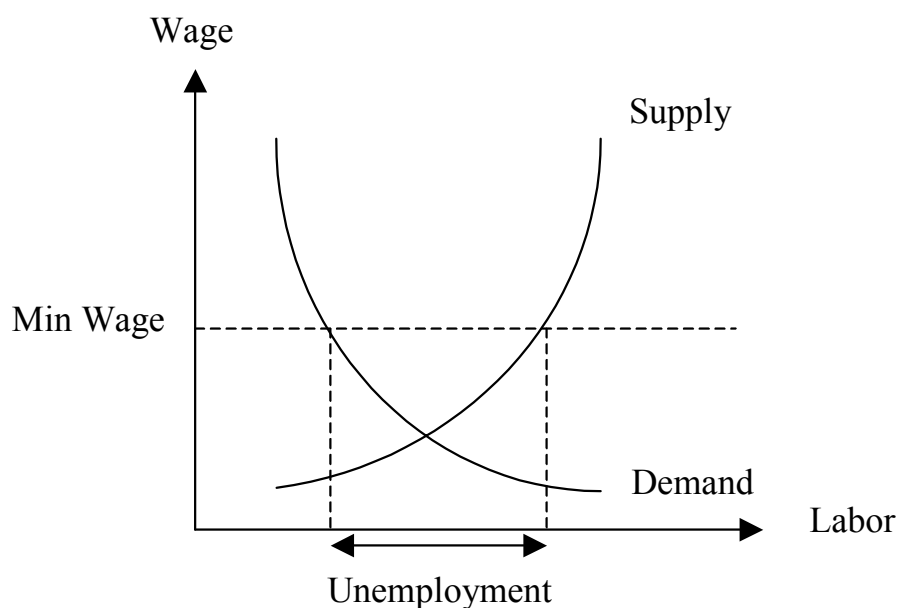


FIG. 2.4 – Classical unemployment

to recognize that for the low skilled workers, this lack of wage flexibility could be the cause for unemployment. The following figure shows how unemployment in a classical framework is created because of a minimum wage that is higher than the one allowing supply to be equal to demand (see figure 2.4).

### A Relative Concentration of Skilled Labor in the Non Covered Sectors

We derive statistics from the data from the Enquête Emploi (INSEE 2002) - exploitation DARES 1982 - 2002, in order to assess the relative shares of the value of skilled and unskilled labor within the economy<sup>18</sup> (see graph 2.5).

Labor, whether skilled or unskilled is more concentrated in non covered sectors than in covered sectors. As we distinguish between these two types of labor, it follows that their relative unemployment rates are also different<sup>19</sup>. The relative con-

<sup>18</sup>We multiply the "quantity" of skilled and unskilled labor in the economy by an estimation of their average wages.

<sup>19</sup>Indeed, we derived relative unemployment rates from Audric Lerenard et Alice Tanay (2000), such



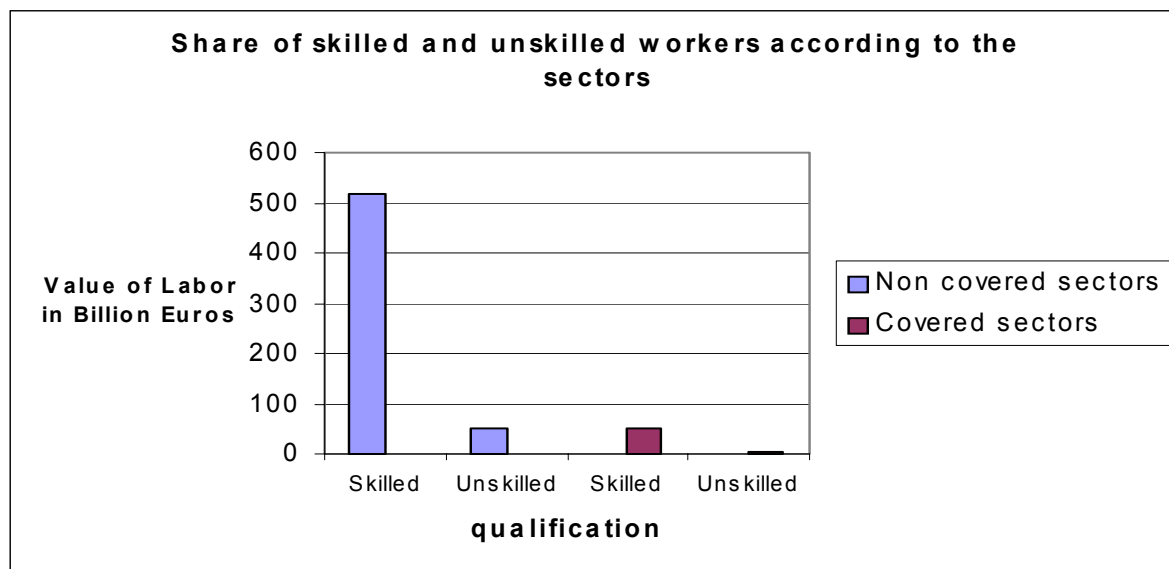


FIG. 2.5 – Concentration of workers per category of sector and per qualification

centration of labor in the non covered sectors will have important effects on the effects on unemployment of the introduction of the National Allocation Plan and the further implementation of Kyoto constraints.

### 2.2.3 The Government

In our specification, the government is a tax collector, who collects the revenues of all taxes on the economy, and uses these revenues to demand part of the consumption goods.

## 2.3 Policy Descriptions

In this section we present our projections of the impact on the French economy of the French National Allocation Plan. To do so, we first describe the Business as Usual (BAU) scenario, which is a forecast of the French economy's growth in terms of GDP (Growth Domestic Product), unemployment and emissions, when no policy is intro-

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that we estimate the unemployment rates in 1995 for unskilled labor to be that of 20.43 % and the unemployment rate for skilled workers to be that of 10.38 %.

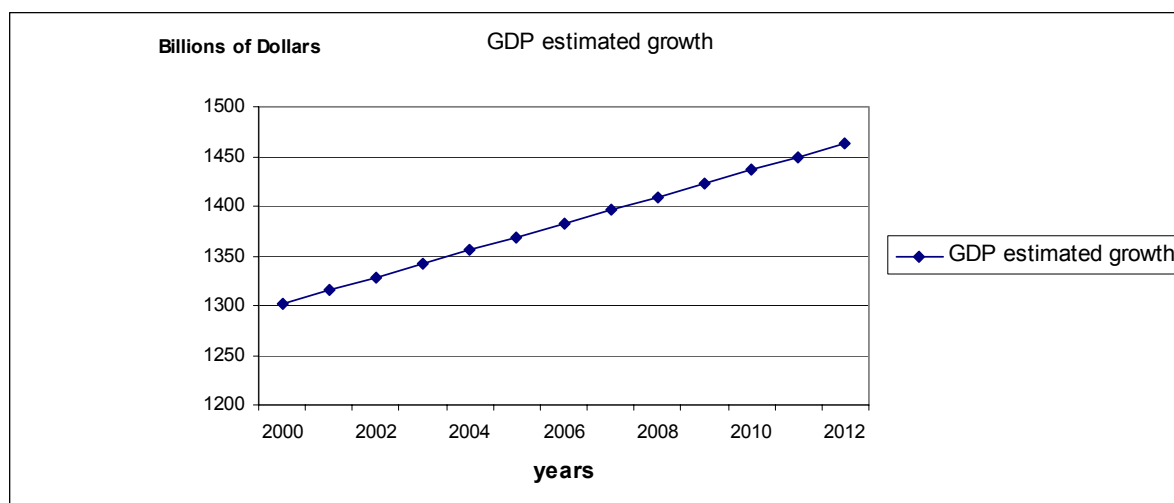


FIG. 2.6 – Business as Usual growth of GDP

duced, that is when the economy simply grows as is. This forecast, shows that the economy grows due to an increase over time in active population, capital, as well as due to the autonomous energy efficiency improvement parameter.

### 2.3.1 Business as Usual General Forecast

#### Economic Variables Trends in the Business as Usual Setting

We here present the model's business as usual projections of GDP, unemployment and emissions. We calibrate the model such that the growth of GDP follows OECD projections<sup>20</sup> (see figure 2.6).

Unemployment rates change slightly over the two periods. Indeed, over time, the unemployment rate of skilled workers decreases due to the wage curve specification. As the economy grows, the price of skilled labor increases leading the unemployment rate of skilled workers to mechanically decrease over time (see figure 2.7). Such a mechanism flows from the wage curve specification that was introduced in the model.

<sup>20</sup>We estimate the average growth rate according to the past GDP growth rates for France. We calibrate our model on the GDP growth rate from tables in the Annex 1 of "Sources of growth in OECD countries" in OECD, Economic Outlook n° 70.

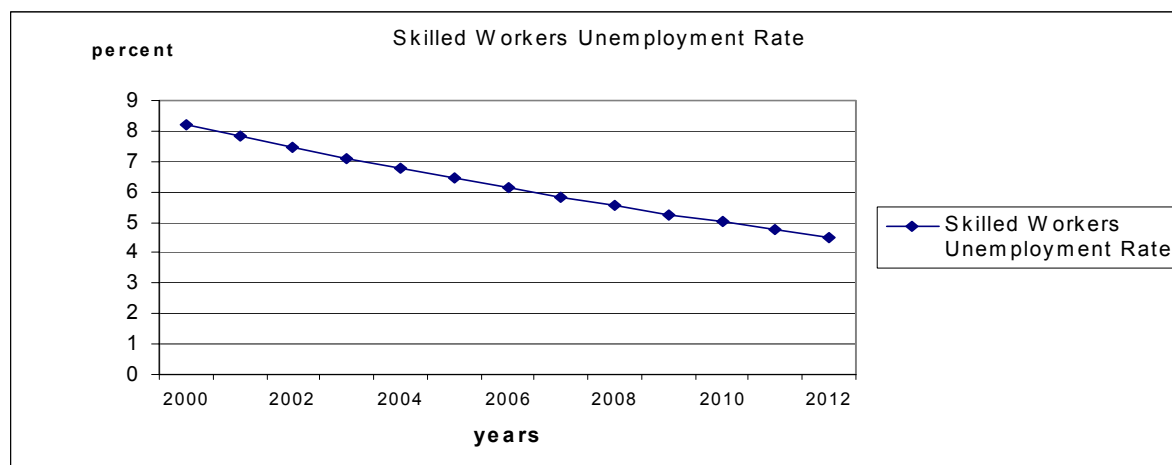


FIG. 2.7 – Skilled workers unemployment rate general trend

On the contrary, unskilled workers' unemployment rate increases generally during the same periods of time, as simply more skilled workers are used in the economy, and therefore less unskilled are necessary for production (see figure 2.8).

### Estimated Emissions Trends in the Business as Usual Setting

Emissions follow an increasing trend as seen in the following figure<sup>21</sup> (see figure 2.9), and replicate the Energy Information Administration / International Energy Outlook (2004) reference case emissions forecast for France.

Indeed, between 2005 and 2012, France's carbon emissions are estimated to increase steadily mainly due to the country's economic growth. However, on average between 2008 and 2012, France's carbon emissions are expected to be higher than the 1990 Kyoto threshold<sup>22</sup>. Indeed, the Kyoto protocol ties France's average yearly carbon emissions during that period to be no greater than its level of emissions in 1990, i.e. 103 Mega

<sup>21</sup>We calibrate our model such that the emission predictions follow a trend very similar to what is predicted by the International Energy Outlook 2004 / Energy Information Administration's emissions reference case for France.

<sup>22</sup>Our model predicts France's carbon emissions to be close to 107 Mega tons of Carbon (MtC) in 2012 while Kyoto constraints suggest that France's total emissions must not be greater than 103 MtC. This is coherent with the projections of The Energy Information Administration (International Energy Outlook (2004)) that suggest that the country's emissions in 2012 in the reference case, will be above the 1990 threshold emissions for France in the Kyoto agreement by some 4 Mt C.

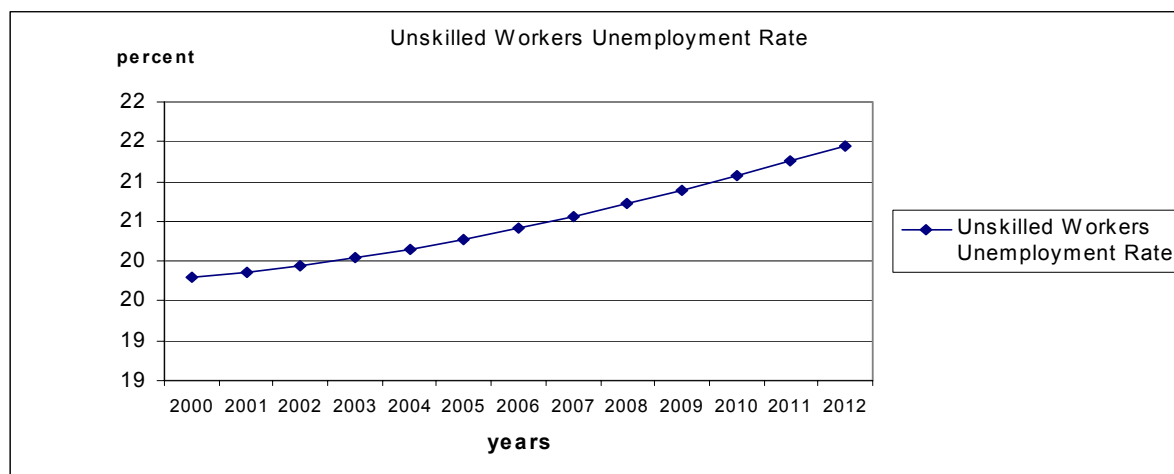


FIG. 2.8 – Unskilled workers unemployment rate general trend

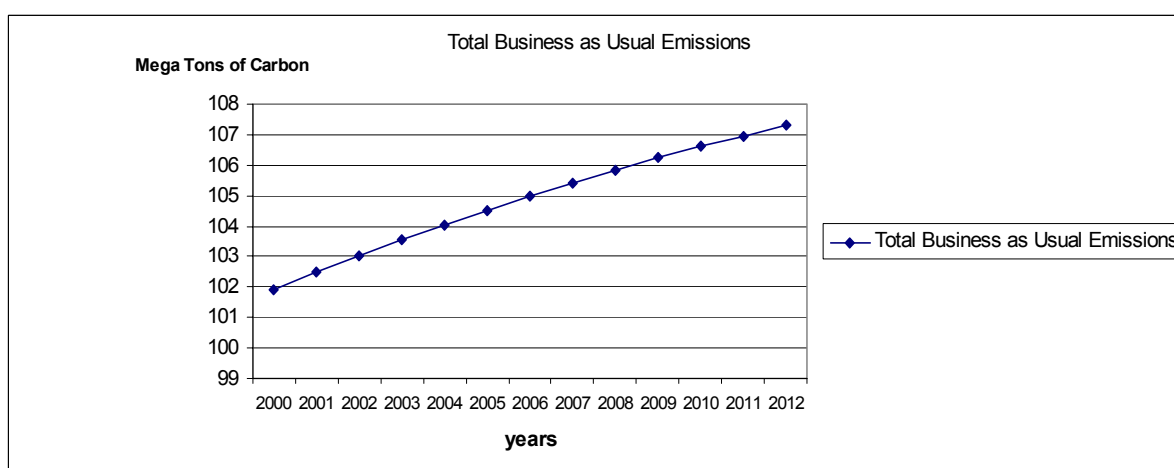


FIG. 2.9 – Business as Usual emissions for France

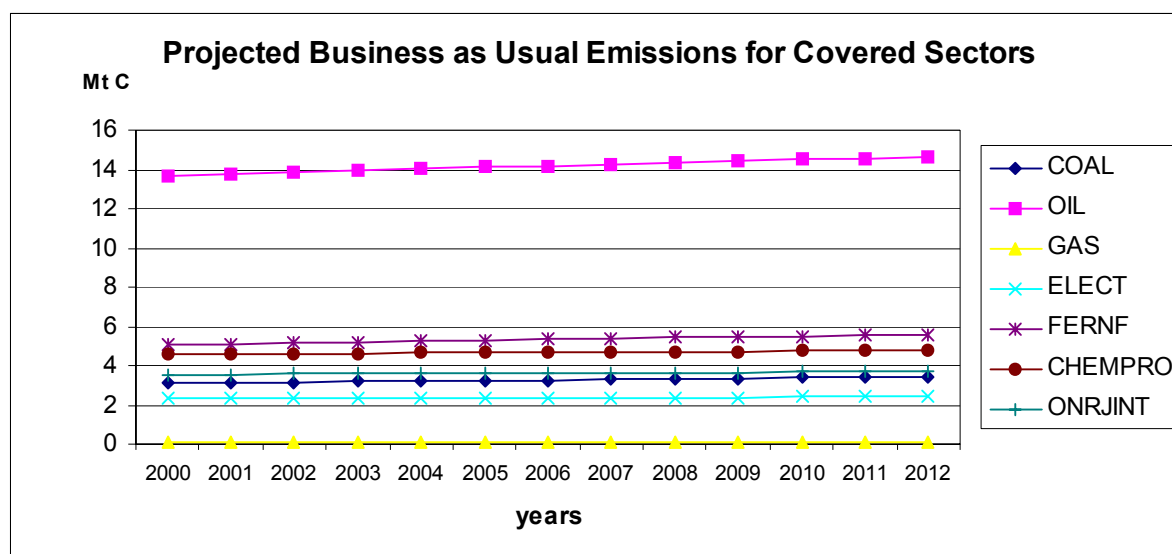


FIG. 2.10 – Benchmark sectoral emissions

tons of carbon.

In order to study the sectoral effects of the National Allocation Plan, we initially define the benchmark sectoral emissions for all covered sectors (see figure 2.10). As seen on the following graphs, the emissions of all these sectors are expected to increase steadily in the baseline scenario.

The following chart presents the model's projections of the share of each covered sector's emissions the first year of the introduction of the NAP, namely in 2005. In 2005 the oil sector is expected to have emitted much more than the other sectors covered by the plan, while coal, chemical products, and other energy intensive sectors and ferrous and non ferrous sectors are responsible as a whole for close to a half of France's emissions in 2005 (see chart 2.11). The electricity sector, in France, mostly representing the production of nuclear energy emits very little due to its fundamental characteristics.

Similarly, we specify the estimated benchmark emissions for non covered sectors as well as the energy producing and energy intensive sectors covered by the NAP.

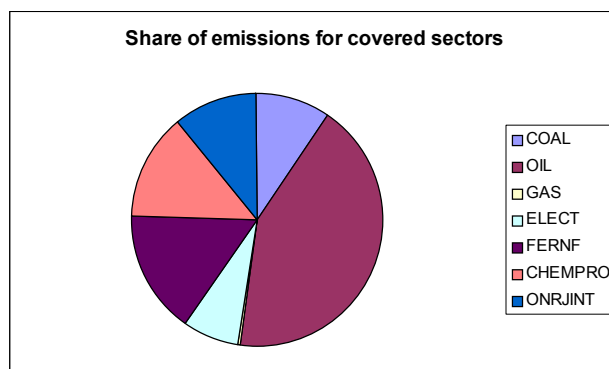


FIG. 2.11 – Estimated business as usual relative emissions for covered sectors in 2005

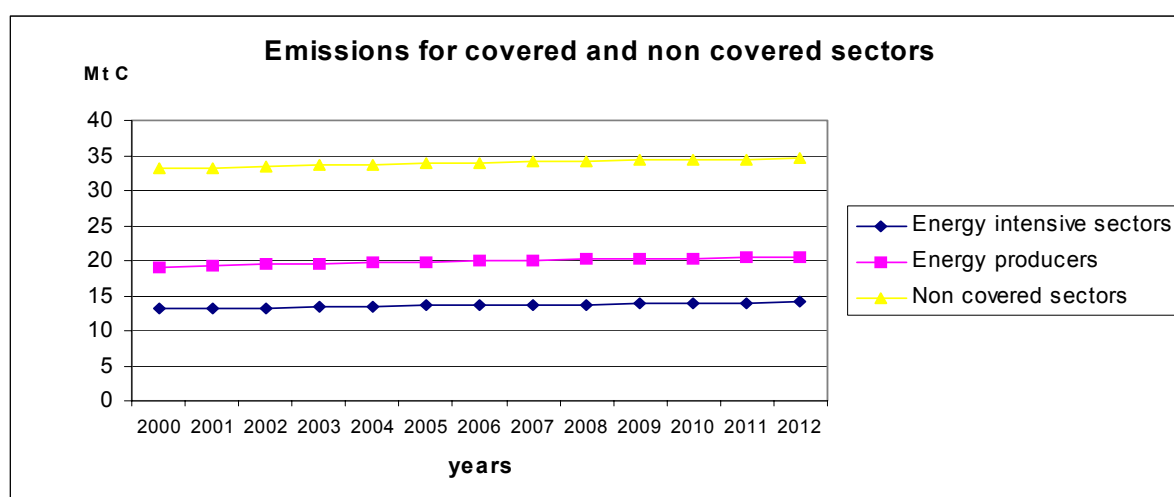


FIG. 2.12 – Covered and non covered sectors benchmark emissions

Non covered sectors' emissions keep increasing over time as there is no constraint on them (see figure 2.12). It is worthy to note that non covered sectors' emissions are relatively high considering the fact that they are not taken into account in any way by the National Allocation Plan.

In the following sections we will assess how an emission constraint affects the different sectoral specificities we specified in the benchmark.

### 2.3.2 The French National Allocation Plan

The National Allocation Plan was first implemented in January 2005 and is supposed to be enforced for three years until the beginning of the Kyoto protocol in 2008. After 2008, the plan will either continue to be implemented as is<sup>23</sup> if it is considered a relevant policy to enable France to meet its Kyoto target, or will be made more stringent. As is, the plan limits the total amount of emissions of all energy producing sectors (i.e. coal, oil, gas and electricity) to 17.96 Mt C a year during the three years the plan is to be implemented. It also requires that the total amount of emissions of energy intensive sectors (i.e. in our specification we suppose that energy intensive sectors are ferrous and non ferrous metals sectors, chemical products producing sectors, and other energy intensive sectors) does not exceed 15.45 Mt C a year<sup>24</sup>.

#### The Mechanism of the Emission Trading System

When the National Allocation Plan came into effect in 2005, all sectors constrained by the NAP received the amount of permits predetermined in the plan. In the new market that has now emerged, permits are priced simply according to law of supply and demand. Therefore, the more stringent the policy, the higher the price of the emission permits. In fact, if the policy is stringent the supply of permits will be small and therefore the price of emission permits will be high, as demand is greater than supply. Therefore, we can expect a small permit price when the NAP hardly constrains the sectors, and a high permit price when the policy is very stringent.

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<sup>23</sup>The first period of the implementation lasts three years, starting January 1st 2005. After that, the plan is implemented for five year periods running consecutively. The allocation of the permits is done before the beginning of each period. Once a period is started, the amount of permits to be allocated cannot be altered, such that industries may not rely on specific lobbying action within a period in order to be allocated more permits.

<sup>24</sup>It is important to note that only the sectors concerned by the NAP (covered sectors) will receive permits, and sectors that are not covered by the plan will not be given any allowances. However, non covered sectors can buy these allowances to covered sectors, if they choose to do so, as can any person. In our paper, for the sake of simplicity, we do not take into account the possibility for non covered sectors to buy allowances from covered sectors.

Moreover, not all sectors covered by the NAP will manage or choose to reduce their emissions identically. In fact, sectors will theoretically compare their marginal abatement costs to the permit prices, and choose to abate as long as the cost of abating one metric ton of carbon is smaller than the pollution permit price for one metric ton of carbon. Those whose marginal abatement costs are greater than the emission permit prices, will stop abating and choose to buy the permits from sectors whose marginal abatement costs are lower than the permit prices. Indeed, in the case for example where the energy producing sectors as a whole manage to reduce their emissions without using all the emission permits that they are allocated (case where these sectors found that abating was cheaper than buying emission permits), they will be able to sell their supplementary emission permits to the energy intensive sectors if the cost of abating for them is more expensive than buying an emission permit.

### **Banking**

Banking is allowed in the National Allocation Plan. Indeed, firms can choose to allocate emission permits as they wish, over the two periods that we are studying<sup>25</sup>. We therefore suppose that in 2005, as all sectors know the number of permits they will receive in 2005, 2006 and 2007 (the first period), they are allowed to allocate their permits over these three years as they wish. Similarly, firms over the second period (2008 - 2012) can allocate their allowances over the five years as they wish in order to level their emission reductions over time. During the first period, firms will therefore choose to level their efforts such that the price of emission permits the first year equalizes the permit price the second year corrected by the interest rate, which will also be equal to the price of the third also corrected by the interest rate. Namely, firms seek to allow

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<sup>25</sup>While banking is allowed over the two periods by the french NAP, it is the only country that has allowed such a mechanism. We here suppose that these are two distinct periods and we do not allow for such banking procedures.



permit prices over time to follow the following equalities.

$$p_1 = \frac{p_2}{(1+r)} = \frac{p_3}{(1+r)^2}$$

Where  $p_1$  is the price for an emission permit in 2005,  $p_2$  its price in 2006, and  $p_3$  its price in 2007. In this specification  $r$  is the interest rate. Banking, basically levels the prices of permits over the three years, as firms will choose each year the level of abatement that can allow for this equality. For the sake of simplicity we choose to set the interest rate to one, and we constrain the model to derive the emission reductions such that the price of carbon is the same each year.

### Three Environmental Policies

In this chapter we shed light on the consequences of the NAP on global emissions, permit prices, GDP, as well as on unemployment rates for both skilled and unskilled labor. We address three different policy situations :

- We first derive preliminary conclusions on the stringency of the NAP. We suppose that the NAP will be implemented from 2005 until 2012 without being made more stringent in 2008. By so doing we ignore the additional constraints that are necessary, in order for France to abide by the Kyoto levels. As the NAP supposes that the allowances are to be allocated at the beginning of each period, i.e. in 2005 and in 2008, we therefore suppose that banking is possible during these two periods.
- Then we model the introduction of the National Allocation Plan until 2012 unchanged, but also take into account the constraints determined by the Kyoto protocol which we model through the introduction of a second carbon tax this time on non covered sectors<sup>26</sup>. We therefore study the impact of the NAP on the first period, and then of both the NAP and an additional tax on non covered

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<sup>26</sup>As our model represents one single region (France) we cannot model the exchange of permits from one region to another in the Kyoto process. We therefore proxy the price of the new emission permits with a fixed carbon tax.

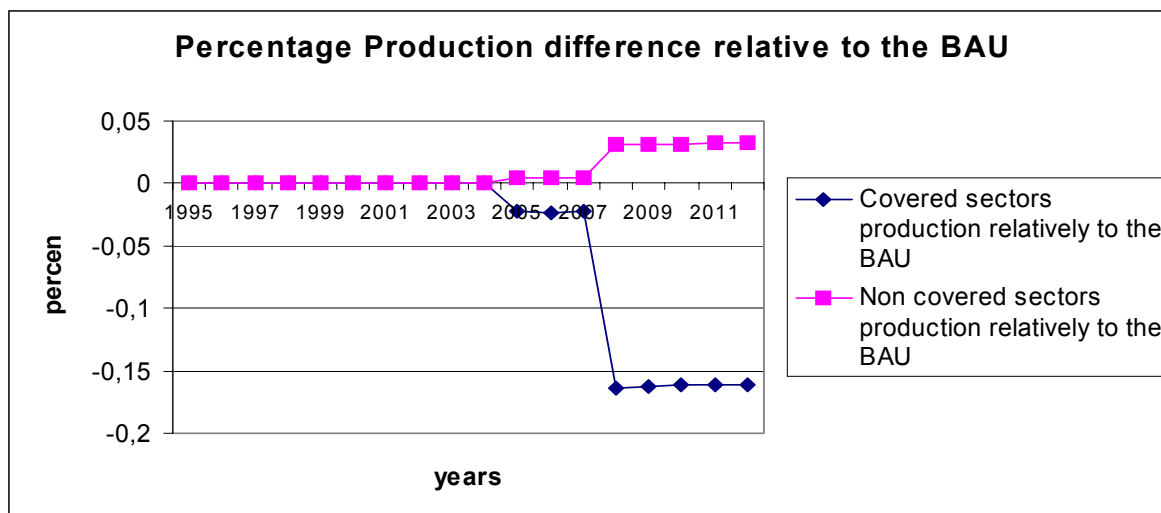


FIG. 2.13 – Percentage production difference relative to the BAU.

sectors, in the second period. We choose the necessary value of the tax on non covered sectors in order to allow for the burden sharing targets to be met over the five year period from 2008 to 2012.

- Finally, we assess the impacts of the NAP between 2005 and 2007, the stringency of which we increase starting 2008, and couple with a tax on non covered sectors that is necessary to satisfy the Kyoto targets.

### **First Policy : The National Allocation Plan is Implemented Until 2012, the Kyoto Constraint is Not Introduced in the Second Period**

In this section, we choose to study the effects of the National Allocation Plan on condition that it is extended until 2012 unchanged. We do not take into account the fact that starting 2008 the Kyoto protocol is to enter into effect<sup>2728</sup>.

**Effect on Production** We here study the effects of the introduction of the NAP on the production of both covered and non covered sectors, between 2005 and 2012.

<sup>27</sup>This hypothesis will be relaxed in the following sections.

<sup>28</sup>We address these policies independantly in order to single out the different effects linked to the policies.

Following the introduction of the NAP, the production of covered sectors falls, while the production of non covered sectors increases relative to the BAU. Indeed, as all sectors reduce their demand for the production of covered sectors as a consequence of the emission constraint on them, the production of covered sectors falls mechanically to satisfy the law of supply and demand. In fact, both covered and non covered sectors substitute between their inputs to production and demand more goods produced by the non covered sectors (leading to an increase in the production of non covered sectors as seen on the graph) and less goods produced by the covered sectors, as inputs to production. Such a drop in the demand for covered sectors' goods leads to a drop in covered sectors' production.

**Proposition 1** *Non covered sectors' production increases following the introduction of the NAP constraining covered sectors.*

**Effect on Total Emissions and Carbon Price** Following the introduction of the NAP in 2005, France's total emissions decrease relative to the BAU as seen in the graph 2.14. It appears however, that the NAP is not sufficient for France to reduce its emissions to the level that is required in the Kyoto agreements (average of 103 MtC over the second period).

More precisely, in the figure 2.15, we determine the percentage differences of total emissions between the policy case and the BAU, once the NAP is introduced. During the first period, the graph shows that France's total emissions fall by close to 0.12 % during the first three years. For the sake of analysis, we suppose that the NAP is not further constrained during the second period 2008 - 2012, that is to say, that the caps that are determined in the NAP for the first period, are not modified. Therefore, in the second period the percentage difference of total emissions between the policy case and the BAU reaches almost 1%<sup>29</sup>.

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<sup>29</sup>The increase in this percentage difference in the second period is simply due to the fact that the economy is growing. Therefore, a stable emission constraint over the two periods acts as a tighter constraint in the second period in comparison to the first period.

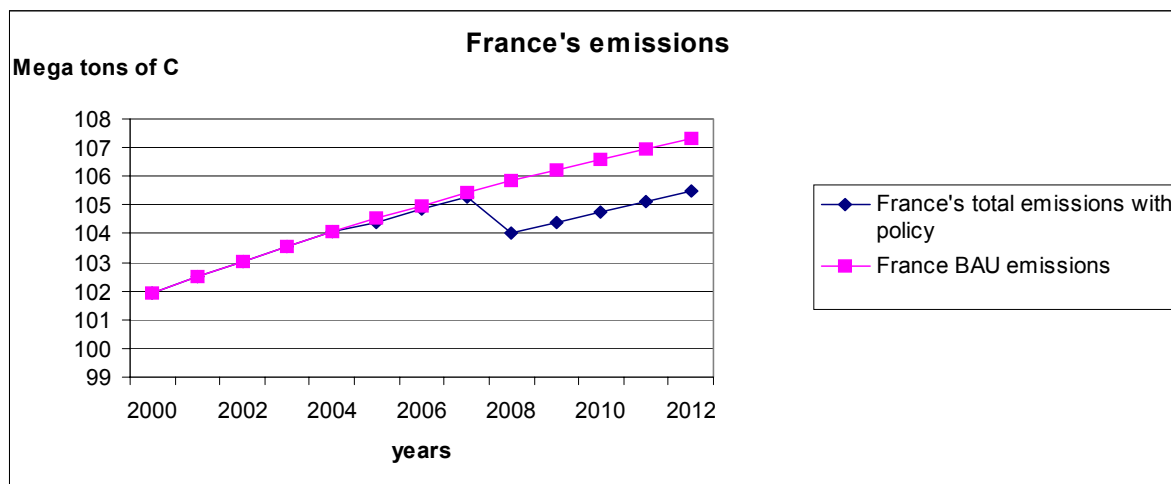


FIG. 2.14 – France’s total emissions

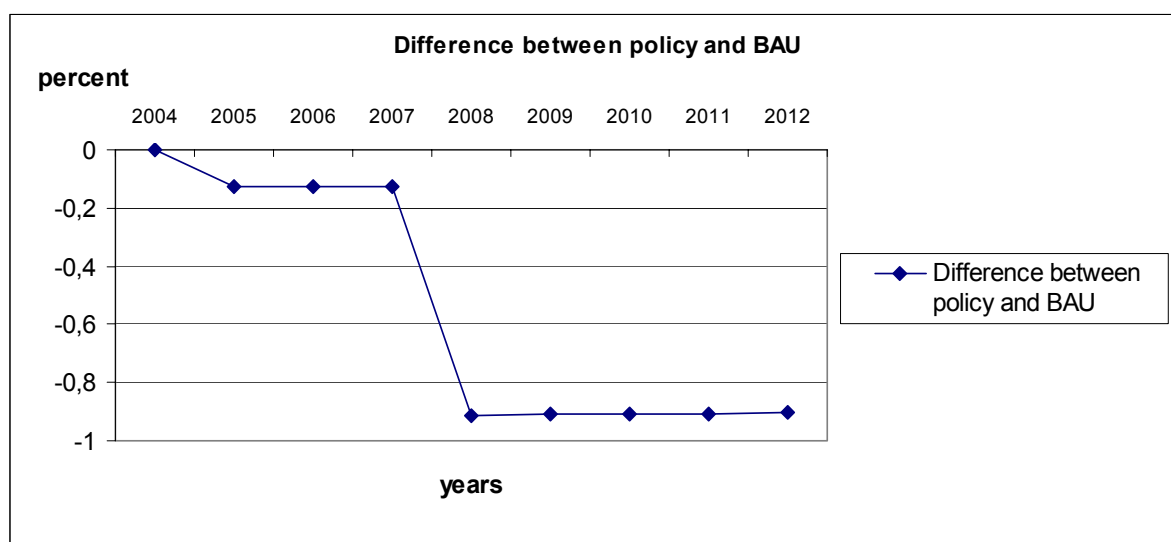


FIG. 2.15 – Percentage total emissions reductions for France relative to the BAU

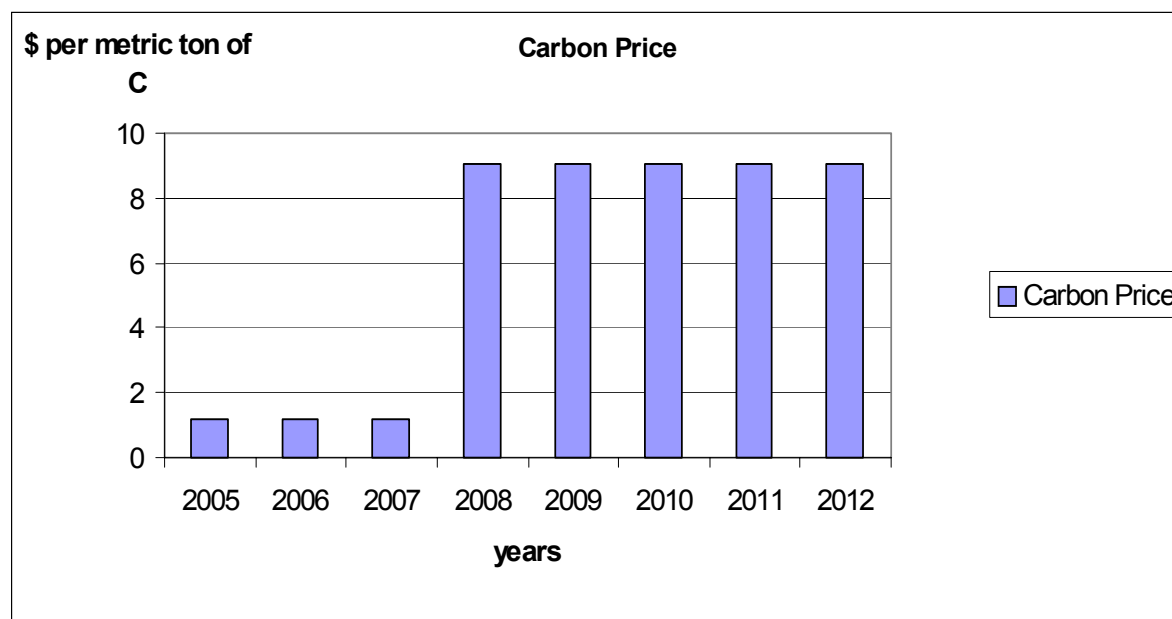


FIG. 2.16 – Carbon price in dollars per metric tons of carbon

As the constraints are tighter in the second period (because of the natural increase in emissions over time in the business as usual setting), the prices for emission permits will be very small during the first period and greater during the second period (see figure 2.16). Indeed, during the first period, the permit price is close to \$1.2 per metric ton of carbon, and the second period, it reaches \$8.5 per metric ton of carbon.

**Effect on Sectoral Emissions** It appears moreover, that both covered and non covered sectors see their emissions fall because of the NAP, while covered sectors' emissions fall more than non covered sectors emissions.

In fact, although only covered sectors are required to reduce their emissions to satisfy a constraint, non covered sectors also see their emissions fall very slightly. These non covered sector's emission reductions occur due to the price increases of the covered sectors' production and specifically of the energy sectors. Indeed, the new costs that derive from the constraints and the permit prices, increase the price of the energy goods, from which emissions flow, and which are delivered by the energy sectors (coal,

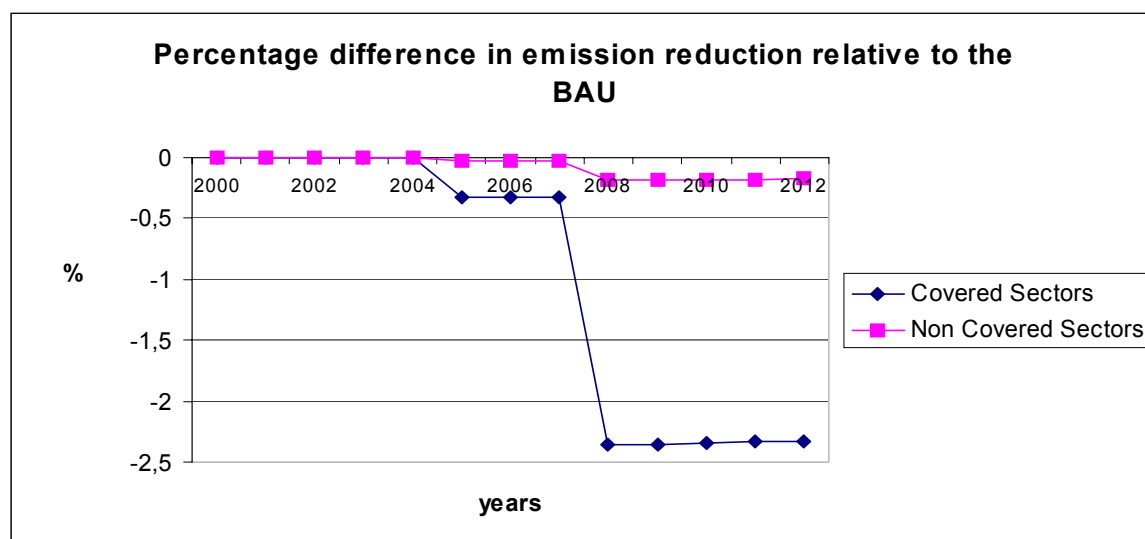


FIG. 2.17 – Emission reductions for covered and non covered sectors relative to the BAU

oil and gas). The price increases lead non covered sectors to reduce their demand for these energy goods as inputs to production as they are more expensive and increase the use of other factors that are relatively cheaper. For this reason, non covered sectors use less energy goods as inputs to production, which mechanically reduces their emissions.

**Buying and Selling Sectors** Theoretically, following the introduction of the constraints defined by the NAP, not all sectors covered by the NAP manage, or choose to reduce their emissions identically. In fact, sectors compare their marginal abatement costs to the permit prices, and choose to abate as long as the cost of abating one metric ton of carbon is smaller than the pollution permit price for one metric ton of carbon. Those whose marginal abatement costs are greater than the emission permit prices, stop abating and choose to buy the permits from sectors whose marginal abatement costs are lower than the permit prices.

The graph 2.18, gives a precise idea of which sectors covered by the NAP manage to reduce their emissions enough to sell their permits on the market for tradeable

permits, and which become buyers of permits. In this graph, the bold blue line, is the average emission reduction percentage that is necessary for covered sectors to satisfy the constraint given by the NAP<sup>3031</sup>.

Sectors that reduce their emissions less than the average, are buyers of emission permits, while sectors who manage to reduce their emissions more than the average, will become sellers of pollution permits on the market for tradeable permits. The graph 2.18 shows that the electricity sector as well as the coal and ferrous and non ferrous metals sectors, in this policy case, will reduce their emissions above what is required of them by the NAP, and will sell their excess permits on the market for tradeable permits. Indeed, the SAM shows that these sectors are all more intensive in coal and electricity (which has the highest carbon coefficient) than they are in oil and gas. Therefore, the demand for these goods falls, and their emissions fall proportionnally. On the contrary, sectors such as oil, gas, other energy intensive sectors, and chemical products all use oil and gas (with smaller carbon coefficients) intensively as inputs to production. The demand for these inputs falls less, and they must therefore buy emission permits on the market for tradeable permits.

**Effect on Unemployment** The effect on the unemployment rates of the implementation of the NAP, without any additional constraint or any increase in its stringency over time, are to be studied while keeping in mind that all results are very small due to the non stringency of the plan.

The effects of the NAP on unemployment for skilled and unskilled workers, although very small, remain of interest. Indeed, both the unemployment rates of skilled and unskilled labor decline (see figure 2.19), that is more labor is used as inputs in the

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<sup>30</sup>In the case where there is no market for tradeable permits, all covered sectors would have to reduce their emissions at that exact level, whatever their cost of abatement.

<sup>31</sup>Covered sectors indeed must reduce their emissions in average by 2.34 % over the first period in order to satisfy the Kyoto constraints. Those who have abated more than 2.34 % can sell their excess permits to sectors who have abated less then this average percentage.

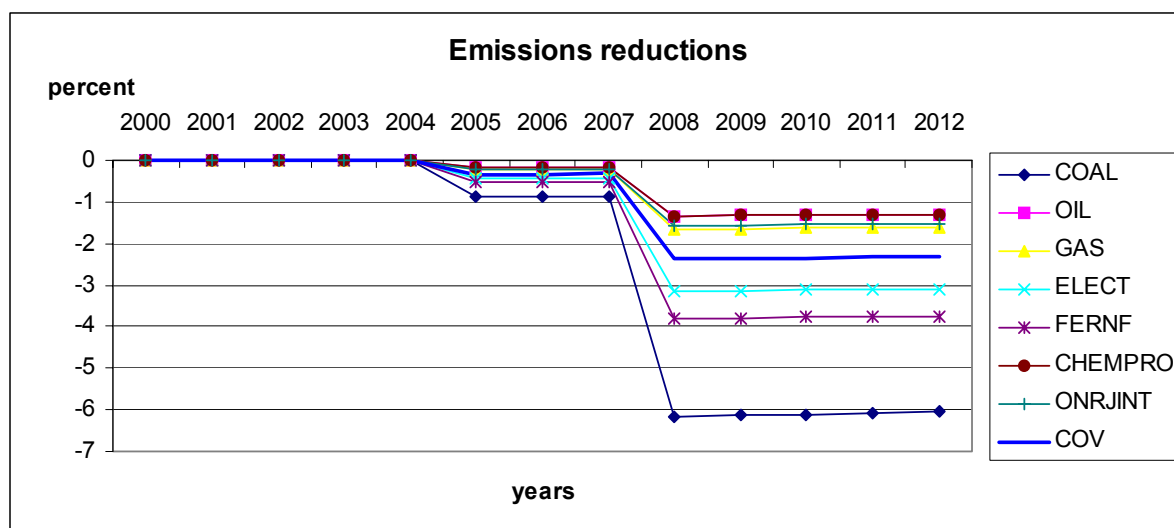


FIG. 2.18 – Sectoral emissions reductions due to the introduction of the NAP.

production functions. Two effects explain this decrease in unemployment rates : a substitution effect, and a general equilibrium effect.

- The first effect leading to these decreases in unemployment rates, is the substitution effect following the increase in the prices of the goods produced by the covered sectors. As the prices of these inputs go up due to the new constraints, firms choose to use inputs relatively cheaper and increase their demand for labor, both qualified and unqualified (while reducing their demand for covered sectors goods).
- The other effect leading to a decrease in the unemployment rate of both types of workers, is the general equilibrium effect that increases the production of a majority of non covered sectors, as the demand for their goods as inputs to production increases<sup>32</sup>. These production increases lead to a higher demand in labor as inputs to production. The key issue to the decrease in the unemployment rates lies in the heavy concentration of both skilled and unskilled workers in non

<sup>32</sup>The demand for non covered sectors' goods as inputs to production increases as they are not taxed or constrained, and their price therefore becomes competitive relatively to covered sectors' goods. Therefore, a constraint on covered sectors increases non covered sectors' production.



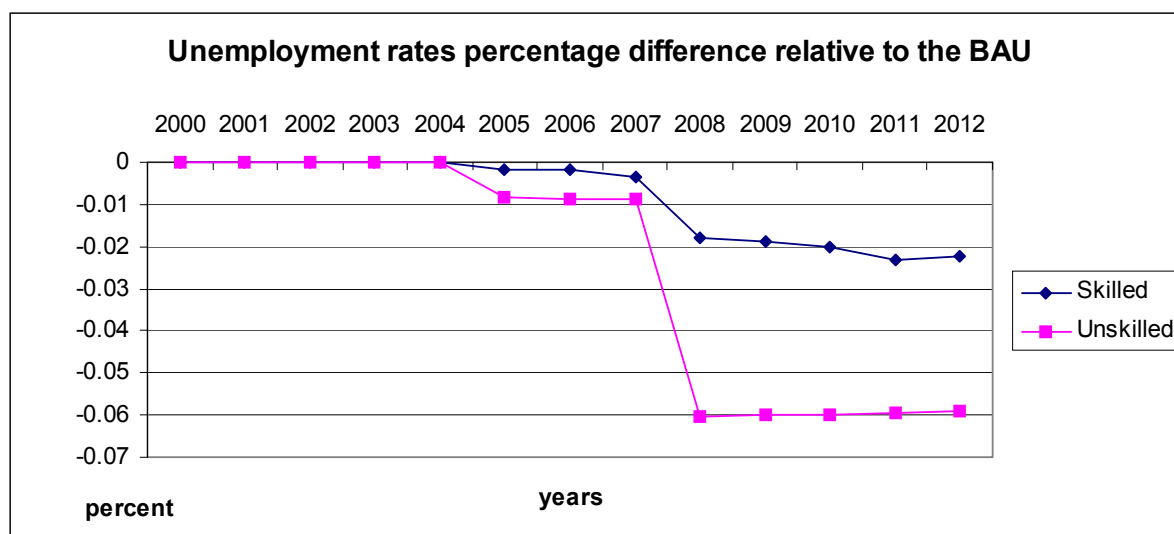


FIG. 2.19 – Unemployment rates for skilled and unskilled workers relative to the BAU

covered sectors (see graph 2.5). If non covered sectors see their production increase following the introduction of the NAP, this will decrease both skilled and unskilled unemployment rates, as they need more inputs to satisfy the production increase. It follows that, had there been a decrease in non covered sectors production, this would have led to the contraction of their demand for labor. As labor is concentrated in non covered sectors, this would have led to a general increase in France's unemployment rates.

Therefore, the effect of the different policies on non covered sectors' production, will be crucial to assess in order to understand the unemployment variations.

In this scenario, the effect on the economy of the introduction of the NAP, is a small decrease in the unemployment rates<sup>33</sup>. However, the unemployment rate for unskilled labor decreases faster than for skilled labor. This is due to our modeling choices. Indeed, as the wages for unskilled labor are lower than the wages for skilled labor, and because the elasticity of substitution between both types of labor, is equal to one, firms choose

<sup>33</sup>The decrease in the unemployment rates are very small however and could be close to not being significant.

to demand more unskilled labor than skilled in order to counter the effects of the price increases of their inputs. These percentages are very small however, due to the non stringent characteristic of the policy, and are hardly noticeable in the first period for skilled workers.

These preliminary conclusions rely on multiple hypotheses as previously noted, specifically on the non existence of the Kyoto constraints. In the following section we choose to take into account the Kyoto constraint aiming at reducing France's average emissions over the five year period of 2008 to 2012 to be equal to France's emissions in 1990.

### **Second Policy : The National Allocation Plan is Implemented Until 2012, Kyoto Constraints are Modeled**

In this section, we take into account that the Kyoto protocol enters into effect in the beginning of 2008. According to the Kyoto protocol, France is to reduce its total emissions to its level in 1990, that is between 2008 and 2012, France's average emissions cannot be greater than 103 Mega tons of carbon<sup>34</sup>. We therefore model the NAP as well as the Kyoto constraints.

We suppose that France's NAP is extended as is until 2012. That is to say each year the covered sectors are constrained to not emit more than what is determined in the plan. According to the plan however, non covered sectors are not required to reduce their emissions in any way. However, the plan in itself does not enable France to reach the Kyoto target of an average of 103 MtC between 2008 and 2012. It appears necessary for non covered sectors to be constrained to reduce their emissions over the period 2008-2012 in order for France to satisfy the Kyoto targets. As a member of the protocol, France will receive in 2008 a certain number of emission permits that the non covered sectors can choose to use or sell to other countries in order to meet its target.

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<sup>34</sup>103 Mt C is the amount of carbon that was emitted by France in 1990. In our benchmark simulations, we consider France' average emissions between 2008 and 2012, to be close to 106.6 Mt C.

In order to study the protocol and the way in which each country chooses to buy or sell their permits, it is necessary to have an integrated model for all European countries. However, our model describes the French economy alone. To counter the difficulty in modeling the Kyoto constraint with a single country model, we introduce an additional tax on non covered sectors. This serves as an approximation of the effect of the allocation of European pollution permits on the French economy. The policy we now study is the implementation of the National Allocation Plan until 2012, coupled with the introduction in 2008 of a "pollution tax" on the non covered sectors, of a value of \$26 per metric ton of carbon<sup>3536</sup>.

**Effect on Production** It appears here that the effect of the Kyoto constraint increases the positive impact on the production of non covered sectors, and worsens the negative impact on the production of covered sectors (see figure 2.20). Indeed, in the case of the NAP alone, covered sectors' production falls by  $-0.2\%$  relative to the BAU, while its production falls by  $-0.5\%$  in the case where the Kyoto constraints are taken into account.

The introduction of a tax on non covered sectors' emissions, leads these sectors to further decrease their demand for fossil fuels as inputs to production. Total covered sectors' production therefore decreases even more than in the case of the NAP alone, as non covered sectors turn away from the production of covered sectors, and reduce their use as inputs. Moreover, the demand for non covered sectors goods increases even more following the introduction of the Kyoto constraint, and this because non covered sectors demand more of their own goods as inputs to production (through the

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<sup>35</sup>The carbon tax that will affect non covered sectors will necessarily have to be, in our framework, \$26 per metric ton of carbon. It is the only tax price that allows France's emissions to average 103 metric tons of carbon over 2008 and 2012.

We derive this price by simply simulating the country's emissions with different tax prices, until we find a carbon price that allows France's emissions to average 103 MtC over the second period.

<sup>36</sup>The pollution tax affects non covered sectors as well as the demand sectors also responsible for emissions. Therefore, consumption as well as investment are taxed at the same rate as non covered sectors.

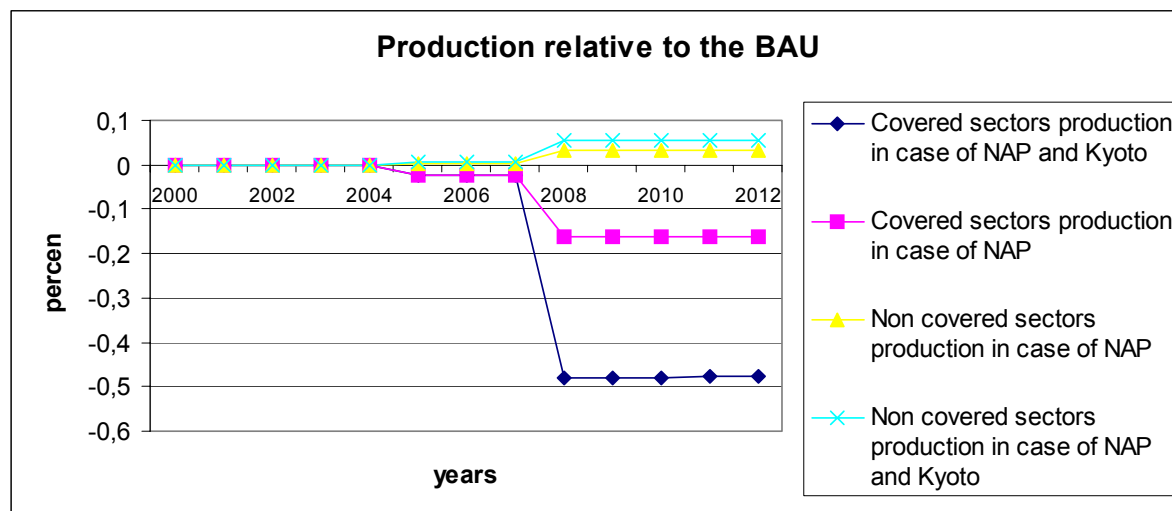


FIG. 2.20 – Sectoral production change relative to the BAU.

substitution effect), as their demand for fossil fuels decreases.

However, while the total production of covered sectors decreases due to the Kyoto constraint relative to the BAU, the production impacts are not uniform among all the covered sectors. The graph 2.21, determines how the tax on non covered sectors affects the production of covered sectors. To isolate the effect of the Kyoto constraint, we compare the production variations for all sectors in the case where the NAP is introduced with the Kyoto constraint, to the case where only the NAP is introduced. We see that the production of coal, oil and gas, decreases due to the Kyoto constraint, while the production of ferrous and non ferrous, chemical products, electricity and other energy intensive goods see their production increase slightly or remain stable. The production reductions derive from the fact that the demand for these fossil fuels by non covered sectors decreases, as non covered sectors who are taxed according to their emissions, prefer inputs that are not fossil fuels. As the demand for coal, oil and gas decreases, their production also decreases, to satisfy the law of supply and demand, which mechanically pulls total emissions downwards. The other sectors' productions increase slightly relative to the case where the NAP is introduced, simply due to the

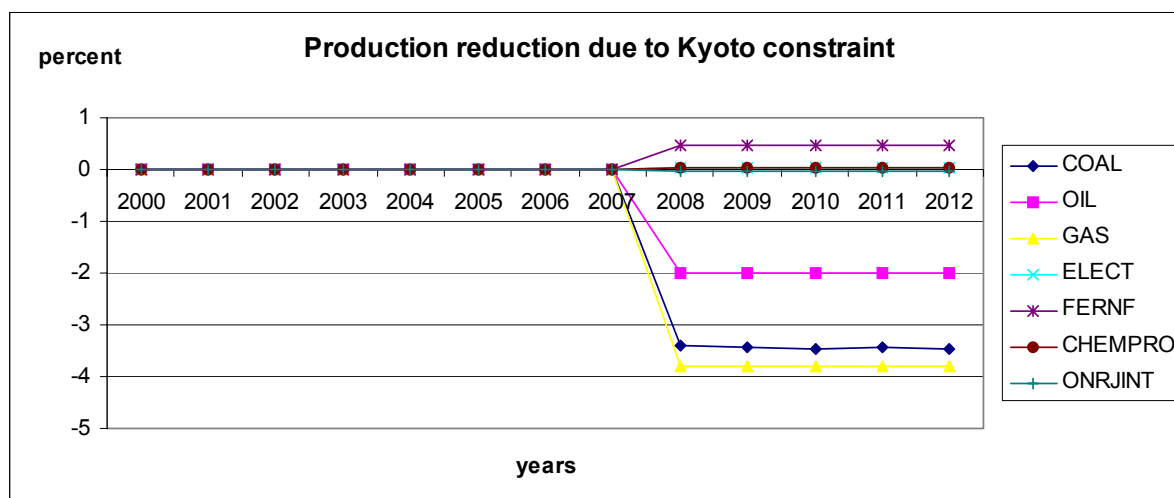


FIG. 2.21 – Effect of the Kyoto constraint on the production of covered sectors

substitution effects that lead to a strong decrease in the demand for the fossil fuels, which need to be substituted by other less emitting inputs.

**Effect on Total Emissions and Carbon Price** The effect of the Kyoto protocol on France's total emissions is predicted to follow a pattern close to the figure 2.22. The pink line reflects France's business as usual emissions, while the yellow line is the Kyoto constraint fixed at 103 Mega tons of carbon. The blue line is France's emissions following the introduction of the National Allocation Plan in 2005 and the entering into effect of the Kyoto constraints in 2008. In 2005, France's emissions are lower but parallel to its Business as Usual emissions, as banking is allowed and sectors level out their emission reductions over the first period. However, in 2008, the Kyoto constraint enters into effect, and France's emissions are severely constrained by both the NAP and the Kyoto constraints. Indeed, a tax on non covered sectors is introduced in order for France's average emissions between 2008 and 2012 to be equal to the country's emissions in 1990.

The effect of these two policies impact the emissions for covered and non covered sectors. Indeed, we represent the impacts of the NAP and the tax on non covered

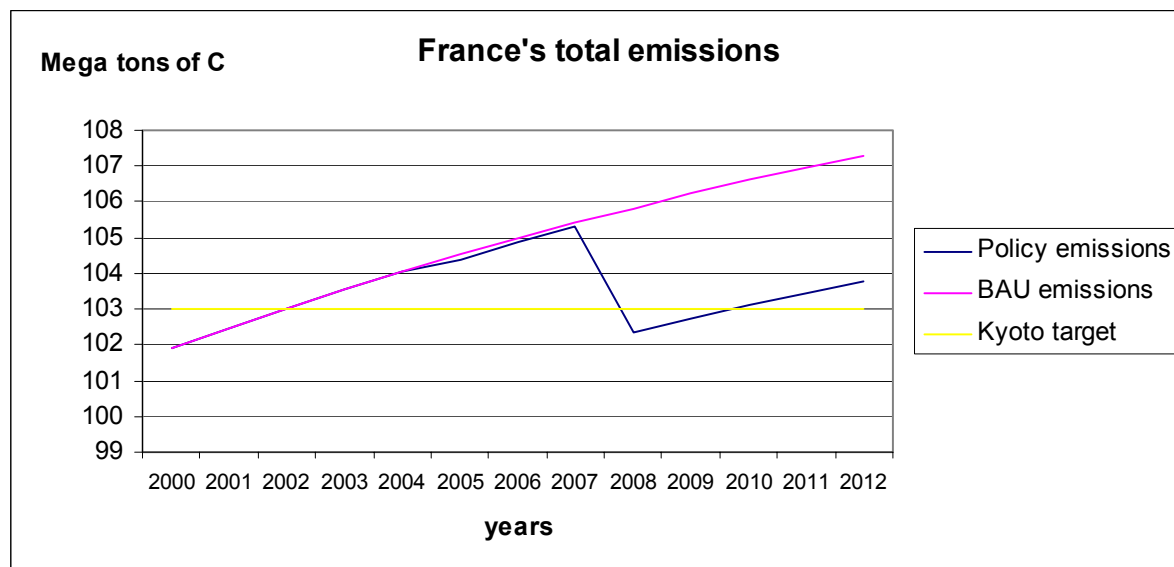


FIG. 2.22 – France's total emissions with NAP and Kyoto constraints

sectors for emissions for both types of sectors (see figure 2.23).

The figure 2.23 describes the different effects of the introduction of the Kyoto constraints on both covered and non covered sectors.

In 2005, the NAP enters into effect, and covered sectors' emissions are slightly lower than in the baseline. Non covered sectors' emissions are also slightly reduced due to the general equilibrium effect and substitution effect previously described.

In 2008 the Kyoto protocol enters into effect, and non covered sectors are subject to a carbon tax. Covered sectors' emissions are now further reduced by the unconstrained NAP as well as by the introduction of the Kyoto constraints (which affect the covered sectors' emissions mechanically as the demand for fossil fuels as inputs to production decreases).

The first period, as policies are unchanged, the permit price stays at \$1.2 per metric ton of carbon (see figure 2.24). The following period sees an increase in the prices of permits such that it stays during the five years starting 2008 at \$3.4 per metric ton of

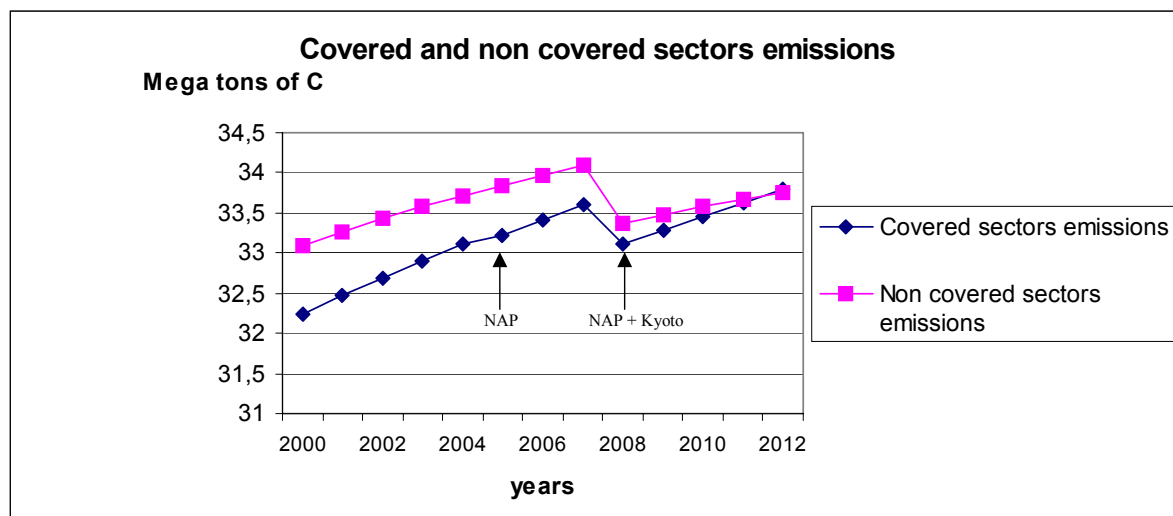


FIG. 2.23 – Covered and non covered sectors emissions with the NAP and Kyoto

carbon (this is however lower than the permit price of \$9 for the second period in the previous policy). The price of permits exchanged by the covered sectors is therefore reduced following the introduction of the Kyoto constraint on non covered sectors. This price reduction is due to the fact that the production of covered sectors falls relative to the first policy. Indeed, in the second period, non covered sectors are taxed at the level of \$26 per metric ton of carbon emitted. Covered sectors' production falls as seen in graph 2.20. Therefore, it becomes less difficult for covered sectors to abide by the NAP, and the demand for permits falls, which leads to a fall in permit prices.

**Proposition 2** *Due to general equilibrium effects, the enactment of the Kyoto protocol, although solely concerning non covered sectors, reduces the price of permits that covered sectors will exchange on the market for tradeable permits by almost two thirds.*

**Effect on Sectoral Emissions** A closer look at the effects for both covered and non covered sectors of the NAP coupled with the Kyoto constraints, shows how emissions fall relative to the BAU in approximately the same proportions.

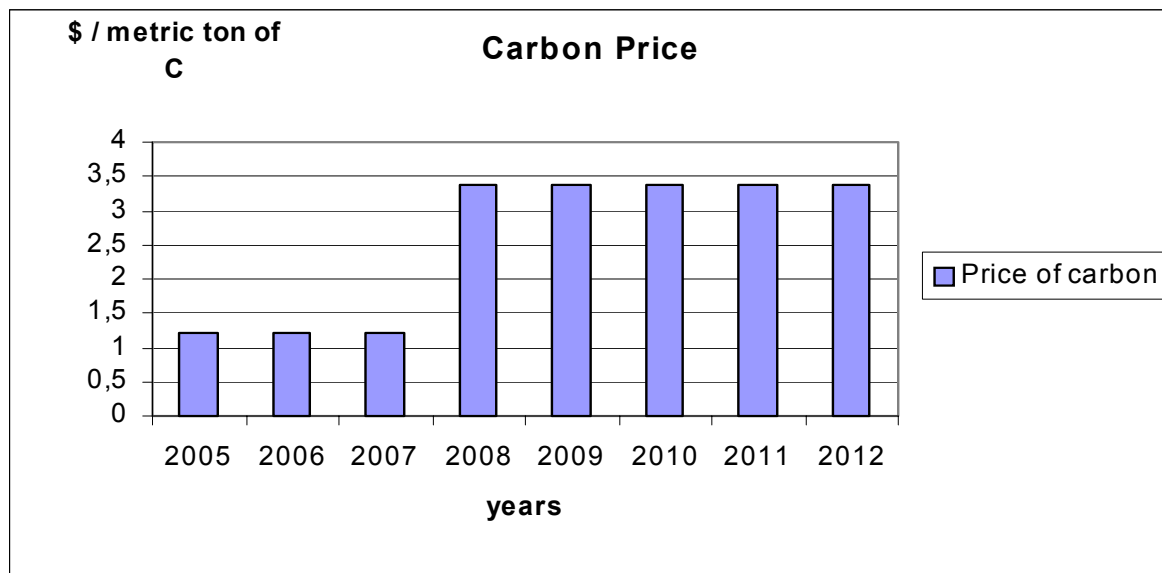


FIG. 2.24 – Covered sectors permit price after the introduction of the Kyoto protocol

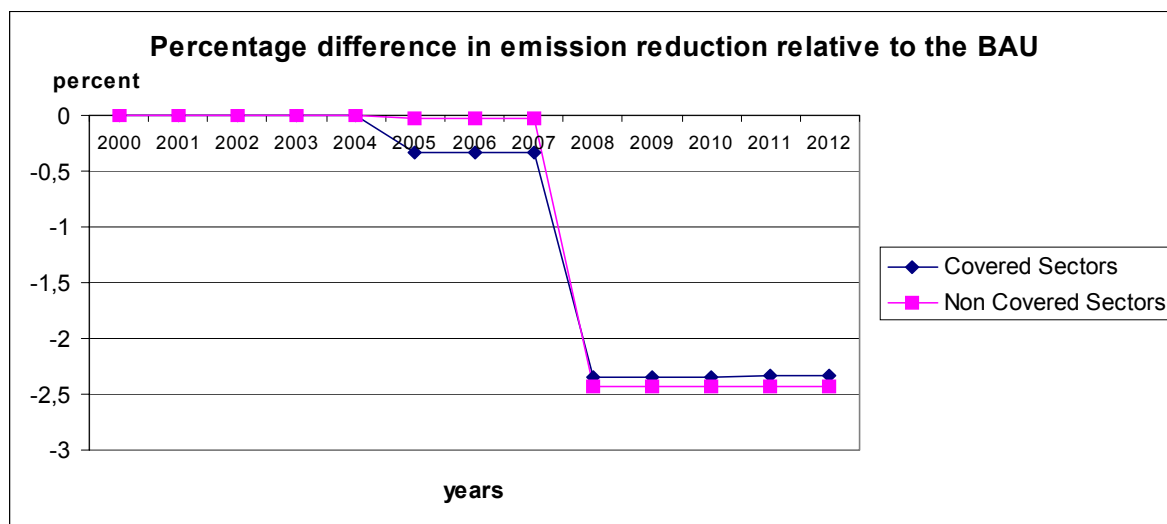


FIG. 2.25 – Covered and non covered sectors emission reductions



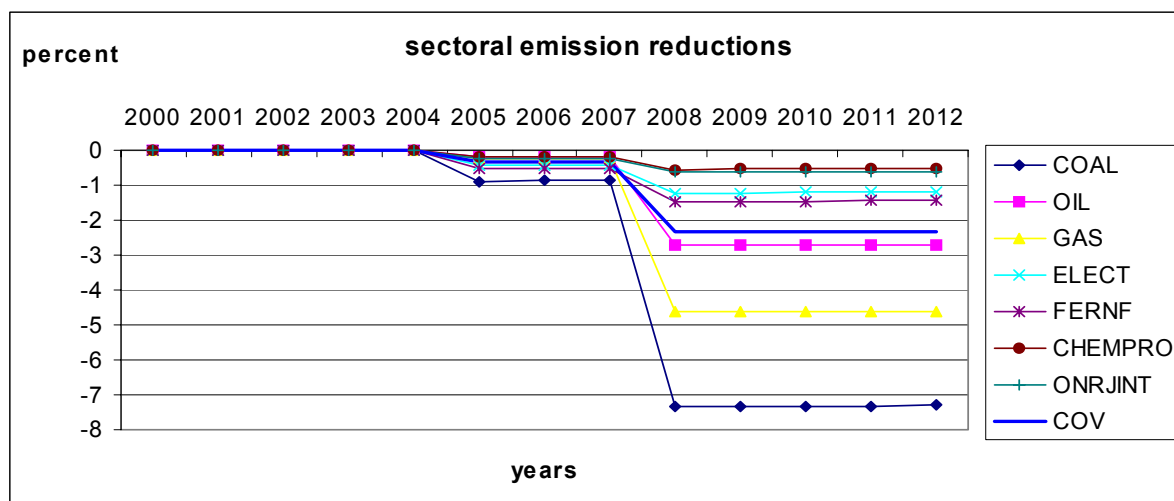


FIG. 2.26 – Covered sectors' sectoral emissions changes with the Kyoto and the NAP

**Buying and Selling Sectors** In the case where the National Allocation Plan is implemented as is, and the Kyoto constraints are taken into account in order for the country to satisfy the burden sharing agreements, the sectors that reduce their emissions more than the average necessary reduction are not the same as in the case where the Kyoto constraints are not taken into account (see graph 2.26). Indeed, the sectors that reduce their emissions more than the average emission reduction necessary to satisfy the target, are now the oil, coal and gas sectors, which are the fossil fuel sources of energy<sup>3738</sup>. All sectors that buy the pollution permits are now the electricity, ferrous and non ferrous metals, other energy intensive goods, and chemical product sectors<sup>3940</sup>.

We therefore see that the oil and gas sectors, who were buyers of emission permits

<sup>37</sup>When the Kyoto constraints were not taken into account, sectors that sold emission permits on the market for tradeable permits, were the coal sector as well as ferrous and non ferrous metals and the electricity sector.

<sup>38</sup>These were precisely the sectors whose production fell further following the introduction of the Kyoto constraints.

<sup>39</sup>These were precisely the sectors whose production increased slightly or stayed stable following the Kyoto constraints.

<sup>40</sup>In the case where the Kyoto constraints were not taken into account, sectors that bought emission permits were chemical products, oil, gas and other energy intensive goods.

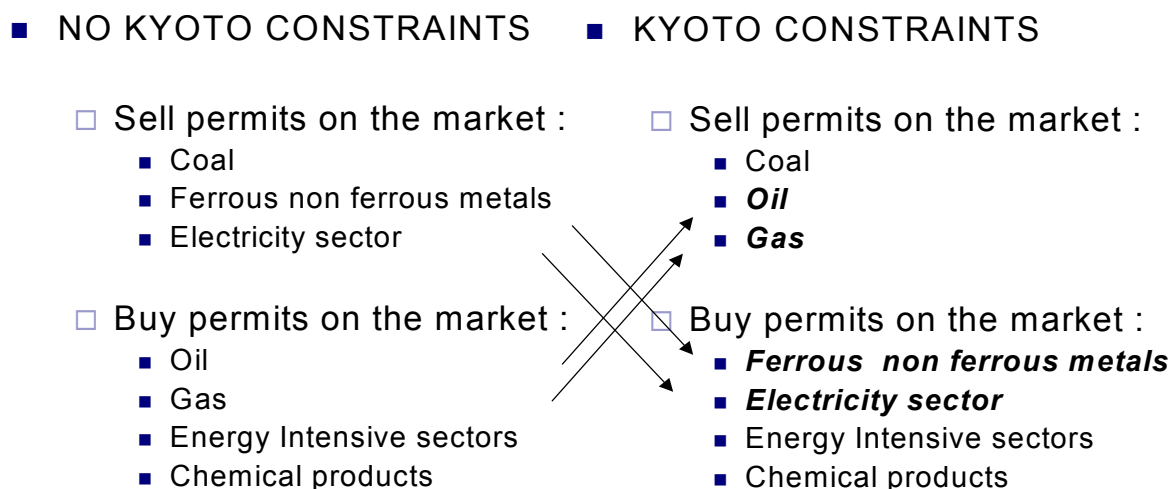


FIG. 2.27 – Sectoral effects of the Kyoto constraints on the buyers and sellers of pollution permits

in the case where the NAP is introduced without the Kyoto constraint, now sell them. Now also, the electricity sector, who initially sold permits when the Kyoto constraints were not taken into account, is now a buyer of permits (see figure 2.27).

The reason behind this change lies in the fact that the introduction of the Kyoto constraint leads to a reduction in the demand for fossil fuels as inputs to production (their production falls relative to the case where only the NAP is introduced). Indeed, non covered sectors see their emissions now taxed. They therefore choose to reduce their demand for fossil fuels as inputs to production, which leads to a contraction in the production of coal, oil and gas as seen in graph 2.21. As this production fall mechanically reduces the emissions of these sectors, these three fossil fuel sectors have a surplus in emission permits, and become sellers of emission permits on the market for tradeable permits. The other four covered sectors see their production increase slightly or stay relatively stable following the introduction of the Kyoto constraint, which forces them to have to demand more permits on the market for tradeable permits.

**Effect on Unemployment** According to the graph 2.28, both unemployment rates decrease slightly between 2005 and 2007, in the same proportions as in the case where the NAP is implemented without the Kyoto constraints. These decreases in unemployment rates are due to substitution effects favoring the use of labor instead of more expensive inputs following the introduction of the NAP. They are also due to the revenue effects following the introduction of the NAP. These revenue effects, are such that covered and non covered sectors use more non covered sectors goods as inputs to production, as these are not exogenously constrained, which leads to an increase in non covered sectors production, and therefore an increase in their demand for labor<sup>41</sup>.

In 2008, as we introduce the additional constraint on non covered sectors in order to reproduce the effect of the enactment of the Kyoto protocol, the unemployment rate for both skilled and unskilled workers keeps decreasing, but much less than in the case where the NAP is implemented alone<sup>42</sup>. Indeed, the introduction of the Kyoto constraint has a negative effect on the unemployment rates. To assess this, we isolate the effects of the enactment of the Kyoto protocol in 2008, by simply comparing the unemployment rates of both skilled and unskilled workers in the case where the NAP is implemented without the Kyoto protocol and the case where the NAP is implemented with the Kyoto protocol. The graph 2.29 underlines the impact of the Kyoto protocol, that is the additional tax on non covered sectors.

Indeed, the figure 2.29 shows that the unemployment rates for unskilled and skilled workers in the case where the Kyoto protocol is enacted are greater than when the NAP is implemented alone. The Kyoto protocol has a negative effect on skilled and unskilled unemployment rates. Nonetheless, skilled workers seem to be slightly less

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<sup>41</sup>As labor is concentrated in non covered sectors, an increase in non covered sectors' production leads to an increase in the demand for labor as an input to production, and therefore a decrease in their unemployment rates.

<sup>42</sup>In the case where the NAP is implemented alone, the unemployment rates of skilled labor and unskilled labor fall by 0.02% and 0.06% respectively in 2012. In the case where the Kyoto constraints are introduced with the NAP, the unemployment rates of skilled and unskilled labor only fall by 0.012% and 0.015% respectively in 2012.

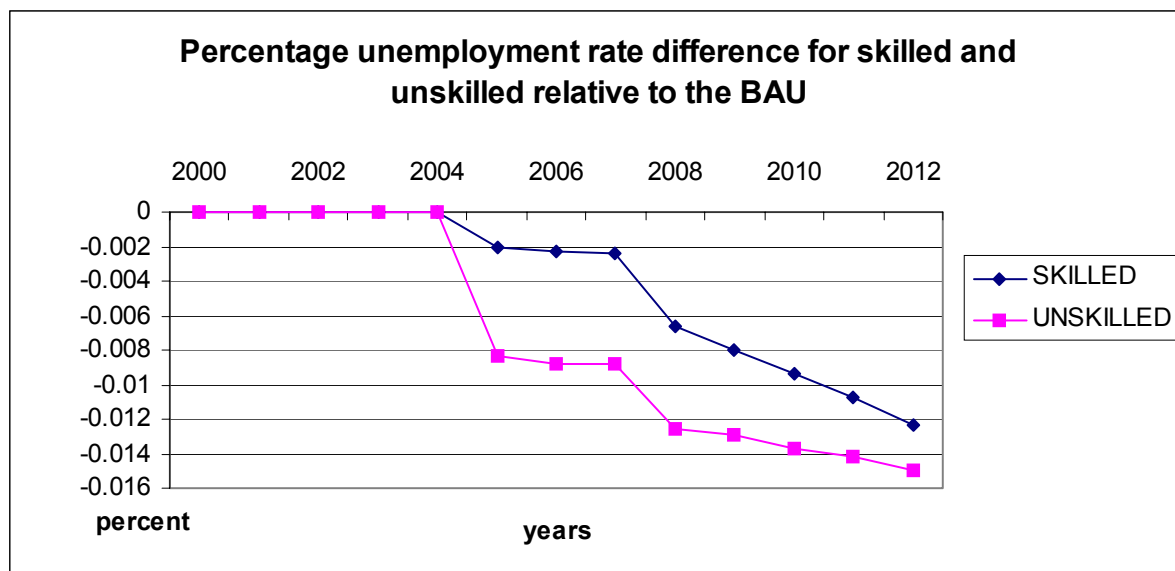


FIG. 2.28 – Percentage difference in unemployment rates relative to the BAU

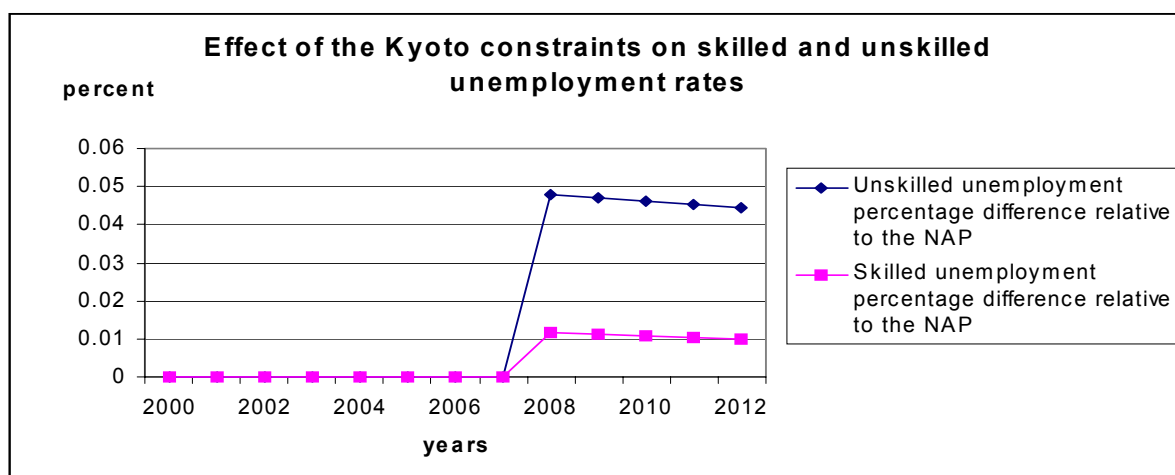


FIG. 2.29 – Unemployment rates percentage difference between the NAP without the Kyoto constraints and the NAP with the Kyoto constraints starting 2008

affected than the unskilled whose unemployment rate is higher than its rate when the NAP is implemented alone, by close to 0.05 % in 2008<sup>43</sup>. Indeed, the unemployment rate for skilled labor is very strongly related to its specification.

The introduction of the Kyoto constraint in 2008, leads to a strong contraction of covered sectors' production (see figure 2.29). The production reduction in the case of covered sectors is much stronger than the production increase in the case of non covered sectors. Indeed, covered sectors' production falls by 0.48% in 2012 in the case where the Kyoto constraints are implemented compared to 0.16% in the case where the Kyoto constraints are not implemented. Non covered sectors' production increases by 0.054% relative to the BAU in the case where Kyoto is taken into account, compared to 0.031% in the case where Kyoto is not implemented<sup>44</sup>. It is clear that the covered sectors' production contraction is greater than the non covered sectors' production gain from the Kyoto constraints.

The effects of the Kyoto constraints on the unemployment rate of unskilled workers, are more drastic than those for skilled, because its value is not guided by a relation similar to the wage curve, which controls the skilled unemployment rate.

These conclusions are given in the case of the implementation of the National Allocation Plan until 2012, coupled with the enactment of the Kyoto protocol in 2008 until 2012. The major hypothesis behind this policy is that the NAP will not be modified or made more stringent after 2007. We relax this hypothesis in the following section in order to specify the effects of making the NAP more stringent between 2008 and 2012, coupled with the enactment of the Kyoto protocol until 2012<sup>45</sup>.

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<sup>43</sup>Of course these increases are very small and marginal, and have to be taken with precaution, but they do reveal general tendencies given by the model.

<sup>44</sup>This is not clearly visible on the graph, but these values derive from the tables that were used to make these graphs.

<sup>45</sup>The value of the tax on non covered sectors that is needed to reduce France's emissions to its level in 1990, will thus be smaller than \$26 per metric ton of carbon, as smaller constraints will be needed to attain the Kyoto objectives due to the further constraining on covered sectors of the emission limits.

### **Third Policy : The National Allocation Plan is Implemented as is Until 2007, Made More Stringent Between 2008 and 2012, Kyoto Constraints are Modeled**

In this policy, we suppose that the NAP will be made more stringent after 2008. We are forced to make a hypothesis ad hoc concerning the additional constraint because of the lack of information on the amount that will be constrained. We therefore suppose, as a means to study the behavior of the economy, that starting 2008, non covered sectors cannot emit as a whole more than 32 Mega tons of carbon a year<sup>46</sup>. In order for the country to abide by the burden sharing agreement, the level of the tax on non covered sectors will therefore not need to be as high as previously, and a tax equal to \$8.5 per metric ton of carbon allows for the Kyoto constraints to be satisfied<sup>4748</sup>.

**Effect on Production** In the second period, when the NAP is constrained and the Kyoto protocol is introduced, it appears that covered sectors' production falls even more relative to the BAU than in the case of the two previous policies and non covered sectors' production increases more relative to the BAU than in the case of the two previous policies. This is simply due to the fact that the greater constraint on covered sectors' emissions leads non covered sectors to demand even less covered sectors production (as the price of their goods increases) and to favor their own goods as inputs. Moreover, the tax on non covered sectors being now 8.5\$ per MtC, non covered sectors' production becomes even more attractive than in the case where the tax on emissions was of 26\$ per MtC.

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<sup>46</sup>This represents a constraint of 1.45 Mega tons of carbon a year, as the total of all permitted emissions is that of 33.45 Mega tons of carbon in the initial French NAP. This is a very optimistic constraint.

<sup>47</sup>\$8.5 per metric ton of carbon is the tax on non covered sectors, investment and consumption, that, coupled with the National Allocation Plan, constrains France's emissions to its 1990 level.

<sup>48</sup>We recognize that this is evidently somewhat constraining, as we here "force" the French economy to not emit more than its Kyoto limit. Therefore we do not take into account the fact that France, as a member of the European Community, can also buy emission permits from other European countries, in the case where it cannot, or will not, satisfy the Kyoto constraints.

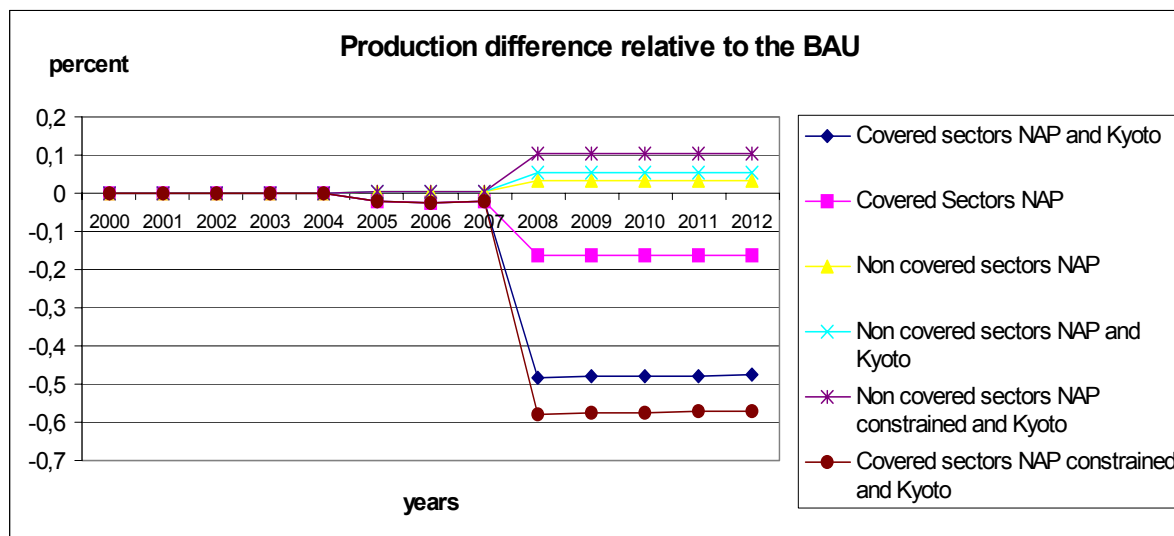


FIG. 2.30 – Covered and non covered sectors production variations relative to the BAU

**Effect on Emissions and Carbon Price** These two constraints generate important emission reductions (see graph 2.31).

In graph 2.32, we report the permit prices that derive from this new constraint. In this graph we compare the prices of the emission permits that were allocated to the covered sectors between 2005 and 2012. Two scenarios are taken into account. The first one, in which we derive the price of the pollution permits in the case where the NAP is implemented as is, and Kyoto is enacted starting 2008 (red batons). The second one derives the prices of the pollution permits in the case where the NAP is implemented as is until 2007, and starting 2008 is constrained by 1.45 Mega tons of carbon a year, concomitant with the enactment of the Kyoto protocol (blue batons).

In 2007, before the plan is made more stringent, the price of emission permits is close to \$1.2 per metric ton of carbon. The prices of pollution permits increase drastically starting 2008. Indeed, as the NAP is made more stringent, the demand for these permits increase while their supply is smaller than in the case where the NAP is unconstrained. The constraint on the NAP in 2008 creates a jump in the prices that reach \$25 per metric ton of carbon during the period 2008 to 2012. This price increase

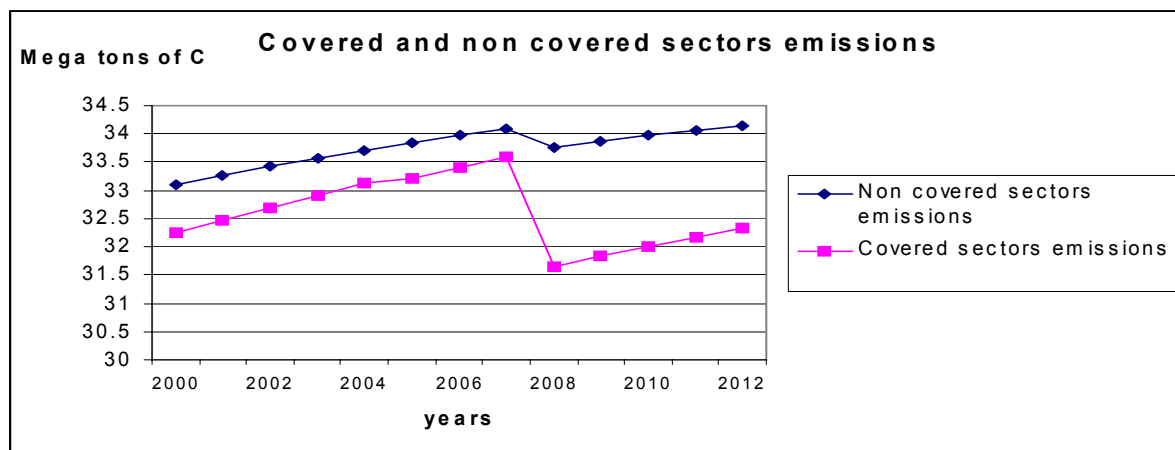


FIG. 2.31 – The effect on the emissions of covered and non covered sectors in the case where the NAP is made more stringent in 2008

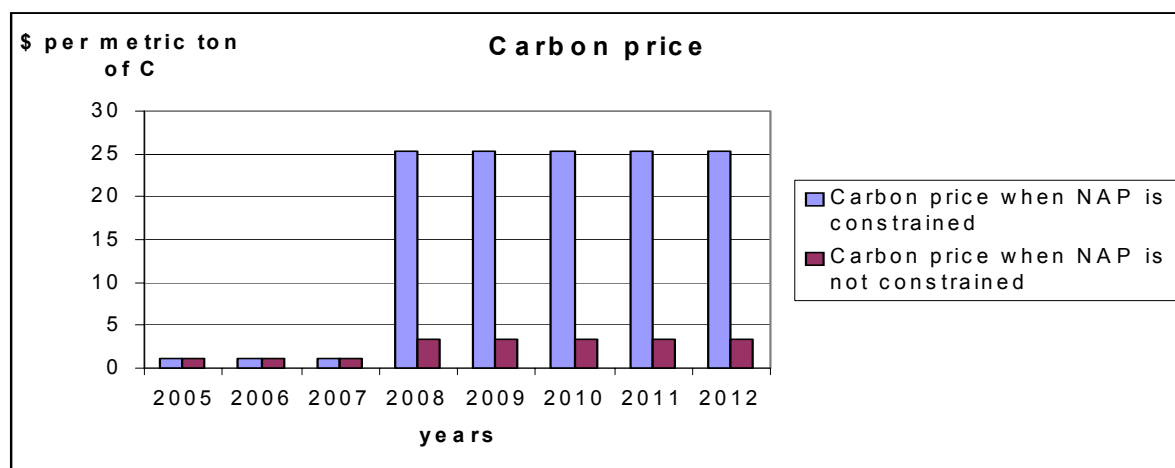


FIG. 2.32 – Pollution permit price comparison with Kyoto : NAP forever and NAP constrained after 2008



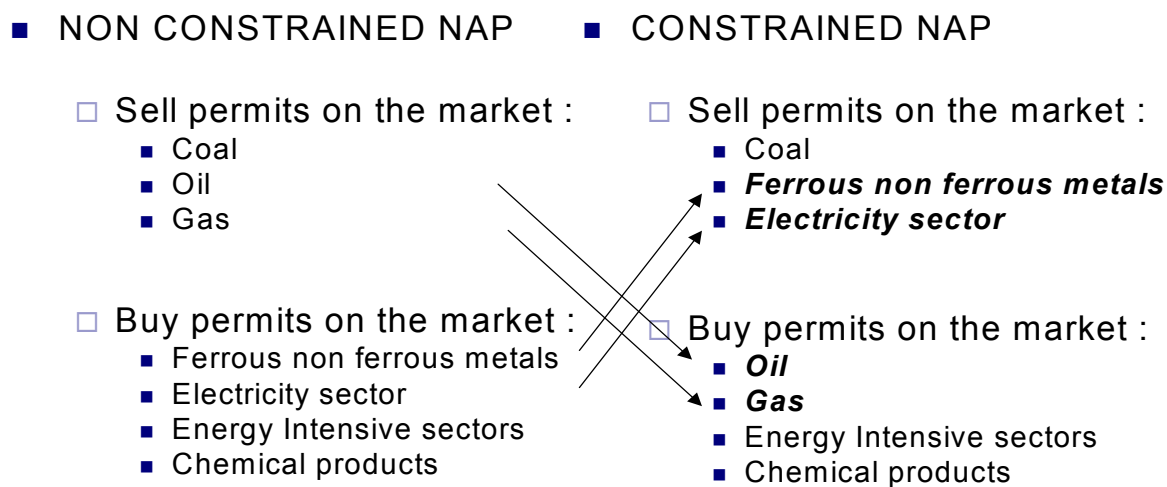


FIG. 2.33 – Sectoral effects of the NAP constraint on the buyers and sellers of pollution permits

follows directly from the increase in the stringency of the NAP, making it harder for the covered sectors to attain the caps that they are submitted to.

**Effect on Sectoral Emissions** Covered sectors’ emissions decrease rapidly following the constraining of the NAP in 2008. Indeed, the sectors that decrease their emissions more than the necessary average to satisfy the constraints, choose to sell their permits on the market of tradeable permits to those who do not reduce their emissions sufficiently (see graph 2.34). This policy, is very similar to the policy where the NAP is implemented as is, and the Kyoto constraints are not taken into account.

Indeed, the figure 2.34 shows that the coal, electricity and ferrous and non ferrous metals sectors are those that sell their excess emission permits to the oil, gas, chemical products and other energy intensive sectors. And this for the same reason as in the first policy. Indeed, the SAM shows that the coal, electricity and ferrous and non ferrous metals sectors are all more intensive in coal and electricity, (and coal has a higher carbon coefficient) than they are in oil and gas. Therefore, the demand for the coal,

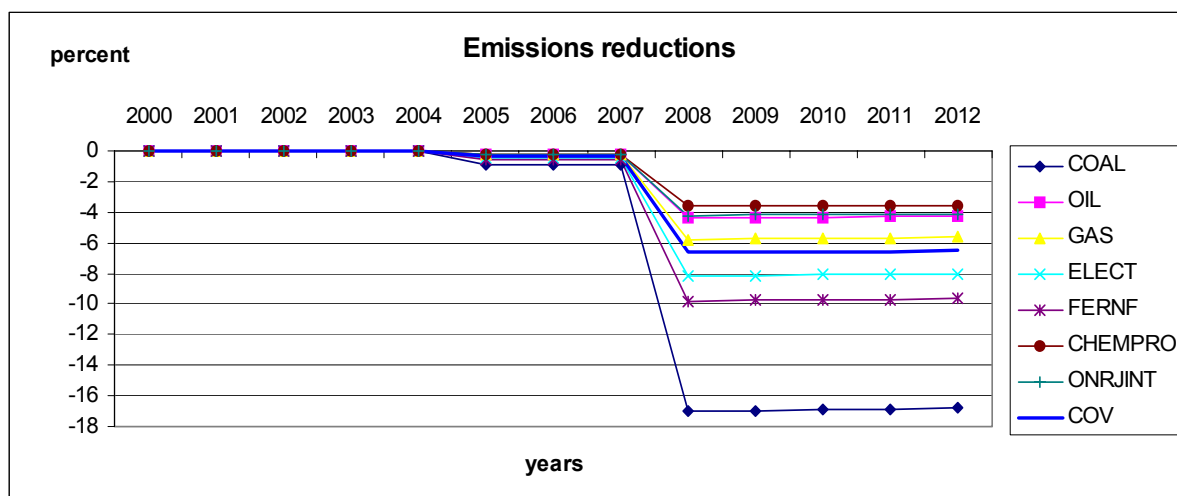


FIG. 2.34 – Sectoral emission reductions in the case where the Kyoto protocol is implemented and the NAP is constrained

electricity and ferrous and non ferrous metals sectors falls which leads their emissions to falls proportionally. On the contrary, sectors such as oil, gas, other energy intensive sectors, and chemical products all use oil and gas (with smaller carbon coefficients) intensively as inputs to their production. The demand for these inputs falls less and they must therefore buy emission permits on the market for tradeable permits.

Basically, the further constraining of the NAP, leads to a greater decrease in covered sectors' emissions therefore only a very small tax on non covered sectors is necessary to satisfy the Kyoto constraint. It follows that the general equilibrium effects that arise from a tax on non covered sectors are too small to have a real visible effect on the situation of the trading system.

**The Effect on Unemployment** The constraints having changed, the effects on unemployment are once more considered. Over the two periods, the unemployment rates for unskilled workers decrease relative to the benchmark (see graph 2.35). In order to understand the changes more precisely we compare the policy where the NAP is constrained after 2008 and we introduce no additional tax on non covered sectors,

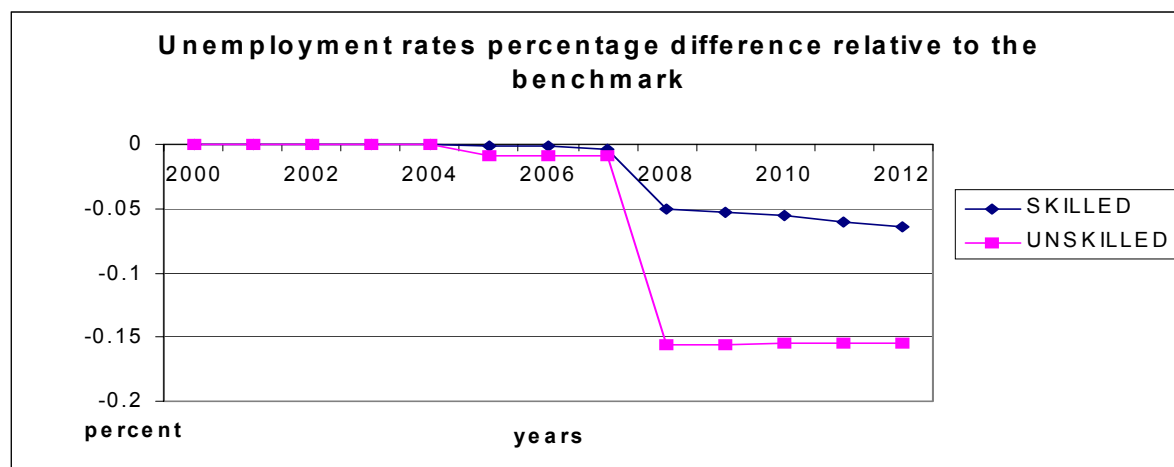


FIG. 2.35 – Unemployment rate percentage difference relative to the BAU

to the policy where the NAP is constrained, taking into account the Kyoto tax on non covered sectors to allow France to reach its Kyoto objectives (see graph 2.36).

The graph 2.35, shows how the introduction of the NAP in 2005, further constrained in 2008, and coupled with the Kyoto constraints in 2008, affects the unemployment rates of both the skilled and unskilled workers.

In the case of both skilled and unskilled workers the unemployment rate begins to fall in 2005, due to the substitution effects and general equilibrium effects that follow from the introduction of the NAP. Non covered sectors' production increases which leads to an increase in the demand for labor as inputs into their production. A comparison of the unemployment rates for both skilled and unskilled labor, sheds light on the fact that in the case where the NAP is constrained further in 2008 and the tax on non covered sectors is \$8.5 per metric ton of carbon, the unemployment rates decrease more than in the case where the NAP is unconstrained in 2008 and the tax on non covered sectors is close to \$26 per metric ton of carbon.

The constraining of the NAP has a positive effect on the production of non covered sectors (as can be seen in the case of figure 2.30). The introduction of the Kyoto

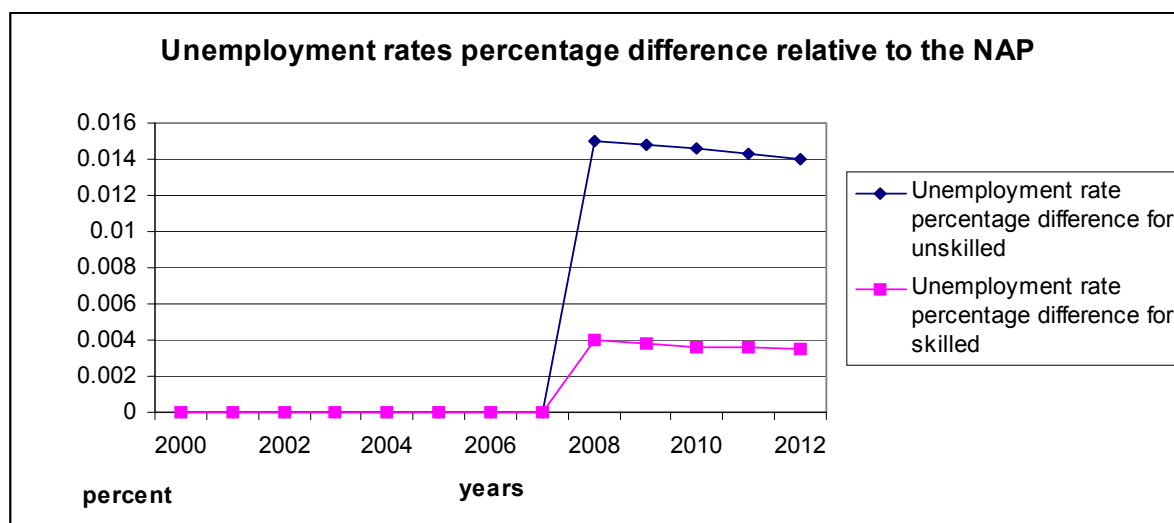


FIG. 2.36 – The impact on unemployment rates of the introduction of the tax on non covered sectors

constraints leads to an increase in the unemployment rates of both skilled and unskilled labor, due to the fact that the contraction of covered sectors' production is greater than the increase in non covered sectors' production. The final impact on both unemployment rates is the result of the constraining of the NAP (which reduces the unemployment rates) and the Kyoto tax on non covered sectors (which increases the unemployment rates). These two effects influence the unemployment rates in opposite directions. However, the constraining of the NAP will lead to a permit price of \$25 per metric ton of carbon which will have more weight than a \$8.5 per metric ton of carbon tax on the emissions of non covered sectors. The effect of the constraining of the NAP is greater than the Kyoto constraint. For this reason the unemployment rates fall more in the case of the constraining of the NAP with the Kyoto constraints modeled, than simply in the case where the Kyoto constraints are modeled without any further constraining of the NAP. Indeed, the positive effect on the production of non covered sectors, of the constraining of the NAP is greater than the negative effect on the production of covered sectors following the introduction of the Kyoto constraints.

## 2.4 Conclusion

In this paper we studied the effects of the implementation of the National Allocation Plan on the French economy with a Computable General Equilibrium Model for the French economy, with exogenous technological change. We show that the NAP is hardly constraining as permit prices during the first period are close to \$1.2 per metric tons of carbon.

Indeed, the NAP leads to very low permit prices and therefore very minor effects on the economy. Allowing for the National Allocation Plan to be implemented as is in the second period, between 2008 and 2012, leads to carbon prices close to \$9 per metric ton of carbon. Unemployment rates for both types of labor, decrease in this scenario relative to their benchmark values, mainly because of substitution effects in their favor, and an increase in the production of non covered sectors, in which labor is concentrated. The electricity, coal, and ferrous and non ferrous metals sectors sell their excess permits on the market for tradeable permits.

To reach the Kyoto objectives, the introduction of a carbon tax on non covered sectors and the continuous enforcement of the NAP, continues to reduce the unemployment rates of both skilled and unskilled labor, but the unemployment rate reduction is not as strong as in the case where the NAP is implemented alone. Carbon prices fall relative to the case where the NAP is implemented alone, and attain \$3.8 per metric ton of carbon, in the covered sectors market for tradeable permits. This decrease is the consequence of the contraction in the use of fossil fuels by non covered sectors, leading to a mechanical reduction of their production, and their emissions. This time, the coal, oil and gas sectors sell their excess permits on the market for tradeable permits, as their production drops mechanically. They therefore need less permits.

Finally, a possible further constraining of the NAP in the second period, coupled with a tax on non covered sectors, lead carbon prices to attain \$25 per metric ton of

carbon. The unemployment rates still fall relative to the BAU, due to the fact that the NAP has greater effects on the non covered sectors' production than the Kyoto constraints have on covered sectors' production. Again, the electricity, ferrous and non ferrous metals and coal sectors sell their excess permits on the market for tradeable permits.

In this version of our model for France, technological change is modeled as an exogenous process, it is therefore unaffected by the emission constraints. It simply over time, increases the efficiency of energy. However, in the first chapter of this thesis we suppose that modeling technological change as an exogenous process may lead to underestimating some of the economy's reactions. Indeed, in this model, we have showed that the only way firms may react to the NAP and the Kyoto constraints is to engage in substitutions between their tangible inputs (capital, labor, and intermediate inputs). We detailed such substitutions. But, in this framework, we are simply underestimating all the possible reactions of the firms. In fact, in the reality, firms may react differently to the effects of an emission constraint, and may want to direct technological change such that it releases the constraint of the environmental policy. In the following chapter, we will seek to study how an emission constraint will affect the direction of technological change. We will then model endogenous technical change in this model for France to determine the other possible reactions of firms.

## ANNEXE A : Main Functions of the Model

In this appendix we formally determine the static and dynamic model.

The production functions in this model are Constant Elasticity of Substitution (CES) functions. There are 17 sectors in the economy, each sector producing one unique good  $i$ , with  $i=(1,..,j,..n)$ , and  $n = 17$ . In our specification, each sector uses as inputs to production its own output, a fraction of all other sectors' outputs, as well as capital and labor.

### A1 - The Production Function

We determine in this subsection, the following production function for all sectors  $i$  with  $i = (1 \dots n)$ .

$$\left\{ \begin{array}{l} y_i = \left( \alpha_{ME,i} ME_i^{1-\frac{1}{\sigma_Y}} + \alpha_{KL,i} (KS_i^k L_i^{1-k})^{1-\frac{1}{\sigma_Y}} \right)^{\frac{1}{1-\frac{1}{\sigma_Y}}} \\ \alpha_{ME,i} + \alpha_{KL,i} = 1 \end{array} \right.$$

We note  $y_i$  the production of the good  $i$ . We define  $a_{ME,i}$  as the share of  $ME_i$  (the materials-energy bundle), and  $\alpha_{kl,i}$  as the share of the physical capital services-labor bundle in the production function of the sector  $i$ .  $KS_i$  and  $L_i$ , are respectively the quantity of physical capital services and labor used in the production of the good  $i$ . We suppose that physical capital services and labor are linked together through a Cobb Douglas specification,  $k$  being the share of physical capital services in the Cobb Douglas function. We define  $ME_i$  as the quantity of the materials-energy bundle used in the production of the good  $i$ . Finally  $\sigma_Y$  is the elasticity of substitution between the physical capital services-labor bundle and the materials-energy bundle.

We suppose the sum of the shares of inputs to production to be equal to one in order to render constant returns to scale.

In this general equilibrium model, producers maximize their profits subject to the production function, thus they determine their demands for each intermediate input.

The program of a producer of the good  $i$  is the following :

$$\left\{ \begin{array}{l} \text{Max}_{y_1, \dots, y_n, E_i, M_i, K S_i, L_i} p_i y_i - TC \\ \text{s.t. } y_i = \left( \alpha_{ME,i} ME_i^{1-\frac{1}{\sigma_Y}} + (1 - \alpha_{ME,i}) (K S_i^{k_i} L_i^{1-k_i})^{1-\frac{1}{\sigma_Y}} \right)^{\frac{1}{1-\frac{1}{\sigma_Y}}} \end{array} \right.$$

We define  $p_i$  as the price of the output  $i$ , and  $TC$ , the total cost of the inputs to production. Through this maximization program, each producer seeks to determine the quantity of inputs of material goods, energy goods, physical capital services and labor that allow for profit maximization.

### A2 - The Materials-Energy Bundle

With  $\alpha_{E,i}$  and  $\alpha_{M,i}$  respectively the share of energy and materials in the materials-energy bundle, we define the  $ME_i$  as following, with  $\sigma_{ME}$  the elasticity of substitution between the materials bundle and the energy bundle :

$$\left\{ \begin{array}{l} ME_i = \left( \alpha_{M,i} M_i^{\left(1-\frac{1}{\sigma_{ME}}\right)} + \alpha_{E,i} E_i^{\left(1-\frac{1}{\sigma_{ME}}\right)} \right)^{\left(\frac{1}{1-\frac{1}{\sigma_{ME}}}\right)} \\ \alpha_{M,i} + \alpha_{E,i} = 1 \end{array} \right.$$

In order to render constant returns to scale we specify that the sum of the shares of materials and energy are equal to one. In this specification,  $M_i$  and  $E_i$  are the materials and energy bundles.

### A3 - The Energy Bundle

There are four sectors in the economy that we define as the energy sectors. They are namely the coal, oil, gas and electricity sectors. Within the energy sectors, we distinguish between the fossil fuel energies (coal, oil and gas) and the non fossil fuel energies (electricity sector ). In this model, we therefore create an aggregate energy good  $E_i$ , which is a CES function of an aggregate fossil fuel good (a composite of coal, oil and gas) and the electricity good. This energy good, which is a function of all four energy goods, is introduced in the production functions of the all production sectors, with a price  $p_{E,i}$ , the price of this energy bundle per sector. In order to render more realistic results, the price of energy varies according to the sector in which it is used as an input.



We define  $E_i$  as the quantity of energy used in sector  $i$ , and, determined as a nested CES function of the fossil fuel good and electricity good :

$$E_i = \left( \eta_{F,i} F_i^{1-\frac{1}{\sigma_E}} + \eta_{EL,i} El_i^{1-\frac{1}{\sigma_E}} \right)^{\frac{1}{1-\frac{1}{\sigma_E}}}$$

In this specification, the elasticity of substitution between  $F_i$ , fossil fuel energies, and electricity is defined as  $\sigma_E$ . We suppose that  $\sigma_E = 0.7$ . In order for the specification to render constant returns to scale, we also need to introduce the constraint such that the sum of the shares of fossil fuel energies and of the electricity good, within the energy bundle used in sector  $i$ , is equal to unity.

$$\eta_{F,i} + \eta_{EL,i} = 1$$

The fossil fuel energy bundle  $F_i$ , is a function of all fossil fuels within the economy, i.e. coal, oil and gas. Consistent with the EPPA model specification, we suppose that the elasticity of substitution between fossil fuel goods is equal to one, that is,  $F_i$  is a simple Cobb Douglas function of all fossil fuel energies. The following equation determines the relationship between fossil fuels within the fossil fuel bundle.

$$F_i = C o_i^{\rho_{Co,i}} G_i^{\rho_{G,i}} O_i^{\rho_{O,i}}$$

In this specification,  $C o_i$ ,  $G_i$ , and  $O_i$  represent the quantity respectively of coal, gas and oil used in the  $i$  sector. The powers to these quantities are the shares of each fossil fuel in the fossil fuel bundle, and their sum equals to unity. Here,  $\rho_{Co,i}$ ,  $\rho_{G,i}$ , and  $\rho_{O,i}$  are respectively the shares of coal, gas and oil, in the fossil fuel bundle in sector  $i$ .

## A4 - The Materials Bundle

The materials bundle  $M_i$  is in fact a CES function of all materials armington goods  $a_j$ , and that are linked together with an elasticity of substitution of  $\sigma_M$ . We determine

the materials bundle as following :

$$M_i = \left( \sum_{j=armi}^{armf} \gamma_{m,j} a_j^{1-\frac{1}{\sigma_M}} \right)^{\frac{1}{1-\frac{1}{\sigma_M}}}$$

## A5 - An Armington Good Specification

In this model, France is considered as a small open economy, therefore, part of the goods produced is sold to the domestic market, and the remaining, to the rest of the world. As a small open economy, France cannot influence international prices that are taken as given reference prices.

In order to allow for consumers to demand domestically produced and imported goods, we define an Armington good, which is a bundle of these domestically produced and imported goods (see Armington (1969)). Moreover, producers demand Armington goods as inputs to production, as previously specified in the production functions of all sectors of the economy. The Armington good is specified as a CES function, and is defined as followed :

$$a_i = \left( \beta_i y_i^{1-\frac{1}{\sigma_A}} + (1 - \beta_i) m_i^{1-\frac{1}{\sigma_A}} \right)^{\frac{1}{1-\frac{1}{\sigma_A}}}$$

In this specification,  $a_i$  is the Armington good, which is a bundle of the domestically produced good  $y_i$  and the imported good  $m_i$ . The elasticity of substitution of the bundle, is  $\sigma_A$  with  $\sigma_A < 1$ . Moreover,  $\beta_i$  is the share of domestically produced goods in the Armington specification. This specification allows for a more realistic determination of the demand for goods, prices are therefore not the only basis for decision. Note that all inputs in the production function are Armington goods. For example, the amount of oil used for the production of good  $i$  is in fact a CES function of the oil produced domestically and imported from the rest of the world.

## A6 - The Labor Inputs

Labor in this model is differentiated according to its qualification. Therefore, industries demand a bundle of qualified and non qualified labor as inputs to production.

We consider qualified and non qualified labor to have an elasticity of substitution equal to one, therefore the relationship between these two qualifications is that of a Cobb Douglas function.

$$L_i = Q_i^{q_i} * NQ_i^{nq_i}$$

With  $q_i$  and  $nq_i$  respectively the shares of qualified labor ( $Q_i$ ) and non qualified labor ( $NQ_i$ ) in the labor bundle in the sector  $i$ , the sum of which is equal to one.

## A7 - The Government

In our specification, the government is a tax collector, who collects the revenues of all taxes on the economy, and uses these revenues to demand part of the consumption goods.

## ANNEXE B : Description of the Dynamic Model

In this annex, we describe the dynamic framework of the model. We create a recursive dynamic framework such that the model is solved as a sequence of static one period equilibria for future time periods. Each step  $t$ , represents one year starting in 1995, which is the baseline year the model is calibrated on, and we solve the model until 2012. In the recursive dynamic framework, the driving forces of the economy are increases in the endowment of labor and physical capital services. The endowment of labor increases according to an estimated active population growth coefficient. The capital stock increases due to investments in physical capital.

### B1 - Labor Supply

The active population is the quantity of labor in the economy, that, in each period  $t$ , is allocated to the production sectors. We exogenously increase the quantity of both skilled and unskilled active population according to an estimation<sup>49</sup> of the active population growth over the years. We therefore obtain the following equation.

$$\bar{L}_{t+1} = \bar{L}_t * (1 + g_{active\_pop})$$

In this equation, the endowment of active population in the period  $(t + 1)$ ,  $\bar{L}_{(t+1)}$ , is equal to the amount of active population in period  $t$ , increased by an estimated rate of growth of the active population  $g_{active\_pop}$ . We postulate this rate of growth to be 0.139% according to Amar M. Topiol A. (2001).

### B2 - Capital Supply

Physical capital increase in the economy according to the accumulation of investment, i.e., the investment in the period  $t$ , increases the stock of physical capital in  $t + 1$ . Therefore, the stock of physical capital grows according to this equation :

$$K_{t+1} = (1 - \delta_K) * K_t + I_t$$

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<sup>49</sup>We derive the estimation of the growth of France's active population over time from Amar et Topiol (2001).

The stock of capital in year  $t + 1$ ,  $K_{t+1}$ , equals the sum of the depreciated stock of capital  $(1 - \delta_K) K_t$  in the year  $t$ , and investment  $I_t$  in year  $t$ . We account for the yearly depreciation of capital defined in this equation as  $\delta_K$ .

Physical capital services derive from the stock of physical capital according to the following equation (see Paltsev (2004) and Rutherford et al. (2002)).

$$KS_t = (r + \delta_k)K_t$$

With  $KS_t$  the total value of capital services or the total capital returns for a given period, used each year as inputs into production, and  $r$  the interest rate of the economy.

### B3 - An Autonomous Energy Efficiency Parameter

In our paper, technological change is specifically modeled through an inverse autonomous energy efficiency parameter (AEEI), whereby each year more energy is produced with less inputs. This is equivalent to modeling an AEEI. Indeed, the definition of technological change is the process by which less inputs may produce the same quantities of outputs, or the same quantities of inputs may produce a higher amount of outputs (this is what we model here). We therefore suppose that the efficiency of coal, oil, gas, electricity increases over time. We choose the AEEI to be 0.075%.

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## **Chapitre 3**

# **The Effect of an Energy Constraint on the Direction of Technological Change : The Study of a Partial Theoretical Model**

### 3.1 Introduction

L'objectif de ce chapitre est d'étudier l'impact d'une contrainte environnementale sur la direction du progrès technique. Pour ce faire, nous cherchons à déterminer, dans un modèle théorique simple à trois facteurs de production, si et comment l'introduction d'une contrainte d'émission va influencer la direction du progrès technique. En effet, dans le premier chapitre de cette thèse nous avons montré que modéliser le progrès technique comme étant un facteur exogène tendait à sous-estimer la réaction d'une économie face à une politique environnementale. Dans le chapitre 2, nous avons ensuite montré à travers un modèle d'équilibre général dynamique représentant l'économie française, comment une contrainte environnementale peut affecter l'économie. Dans ce contexte, le progrès technique étant modélisé comme exogène, les secteurs contraints par la politique n'avaient d'autre choix de réaction que d'effectuer des substitutions entre ses facteurs de production. Or, l'intuition économique et la littérature que nous avons détaillée dans le premier chapitre suggère que la direction du progrès technique peut être influencée par une contrainte environnementale, ce que le modèle du chapitre 2 ne pouvait pas mettre en évidence.

Pour étudier cette question de plus près nous proposons ici l'étude d'une fonction de production à trois facteurs, le capital, l'énergie (tous deux liés par une fonction Cobb Douglas) et le travail, dans laquelle il est possible que le progrès technique repose soit sur le travail, soit sur l'agrégat capital-énergie, soit sur le travail et l'agrégat en même temps. Nous cherchons à déterminer la direction optimale du progrès technique sur le sentier de croissance optimale tout d'abord dans le cas simple de la fonction de production non contrainte. Nous introduisons ensuite une contrainte d'émissions et étudions comment elle influence la direction du progrès technique.

Dans le domaine de l'endogénéisation de la direction du progrès technique, les travaux déjà anciens de Kennedy (1964) et de Nordhaus (1968) demeurent encore la

référence. En transposant le concept de frontière des possibilités de production, à celui de "frontières de possibilités d'innovations", ces auteurs ont exposé clairement les choix qui s'offraient à tout moment au planificateur d'une économie ou à un entrepreneur représentatif, entre le progrès technique qui augmente l'efficacité du travail et le progrès technique qui augmente l'efficacité du capital, dans le cas où il n'existe que ces deux facteurs de production.

Partant du modèle formalisé de Nordhaus (1968), nous étendons la fonction de production à un facteur énergie. Nous introduisons ensuite dans le modèle une contrainte environnementale libellée sous la forme d'une consommation maximale d'énergie par tête. L'objectif de ce papier est d'évaluer la manière dont une contrainte énergétique pourrait modifier le résultat canonique de Nordhaus, à savoir que le progrès technique s'applique seulement au facteur non reproductible, le travail (progrès technique neutre au sens de Harrod).

Pour étudier ce problème, nous traitons ici essentiellement du modèle centralisé c'est à dire de l'optimisation intertemporelle d'une fonction d'utilité par un planificateur. À partir de conditions d'optimalité nous caractérisons quelques propriétés des sentiers de long terme, afin d'en déduire les nouvelles formes que peuvent revêtir le progrès technique dans le cas où le planificateur est soumis à une contrainte énergétique.

Dans le but d'étudier l'effet sur la direction du progrès technique dans le cas de l'introduction du facteur énergie dans la fonction de production, nous envisageons successivement le cas simple où il n'existe pas de contrainte sur ce facteur, et ensuite le cas où le planificateur doit prendre en compte une contrainte sur les émissions.

## 3.2 Le Cas d'une Technologie CES à Trois Facteurs Sans Contrainte Énergétique : Confirmation du Résultat de Nordhaus

Nous présentons ici tout d'abord le problème d'optimisation, puis les conditions nécessaires d'optimalité, et enfin discutons les propriétés du sentier de long terme.

### 3.2.1 Présentation de la Fonction de Production

La fonction de production adoptée dans ce papier est de type  $KLE$ , avec une technologie à trois facteurs de production, le capital, l'énergie et le travail. Nous adoptons les notations de Nordhaus de façon à préserver l'homogénéité du travail. Dans ce contexte, on suppose que l'énergie est un facteur reproductible et qu'il est produit comme tous les autres biens<sup>1</sup> et, à chaque période, entièrement utilisé dans le processus de production. L'énergie ne s'accumule pas, c'est une variable décisionnelle du planificateur. Ceci le différencie du facteur capital, qui est accumulable dans le temps. Enfin, on considère que le travail est un facteur non reproductible, qui évolue au taux de croissance de la population constant.

La fonction reliant ces trois facteurs de production est de type Constant Elasticity of Substitution (CES) emboîtée à deux niveaux : le regroupement adopté combine tout d'abord l'énergie et le capital en un facteur composite, qui est à son tour combiné au travail. Ce regroupement permet en effet de préserver la spécificité du facteur travail (facteur non reproductible).

$$Y = CES(\lambda; CD(K, E); \mu; L)$$

Dans la fonction 3.2, Le capital  $K$  et l'énergie  $E$  sont reliés par une fonction Cobb Douglas (CD). L'agrégat capital-énergie est relié au travail  $L$  par une fonction CES.

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<sup>1</sup>L'énergie peut être considérée comme un bien produit, de la même manière que l'électricité ou encore le pétrole après raffinage.

On note  $\lambda$ , le progrès technique accroissant l'efficacité de l'agrégat capital-énergie, et  $\mu$  le progrès technique accroissant l'efficacité du travail uniquement.  $Y$  est la production.

On peut réécrire  $Y$  comme suit :

$$Y = F(\lambda(K, E), \mu L) \quad (3.1)$$

$F$  est la fonction de production.  $F$  satisfait les conditions d'Inada habituelles, c'est une fonction croissante et concave, deux fois différentiable avec  $F' > 0$  et  $F'' < 0$ .  $F$  est homogène de degré 1.

Plus précisément nous utilisons une fonction de type Cobb Douglas  $CD$  pour relier le facteur composite capital-énergie, combiné au travail par une fonction à élasticité de substitution constante (CES). Il en découle que la fonction de production est de la forme suivante :

$$Y = \left( b [\lambda K^\alpha E^{1-\alpha}]^{1-\frac{1}{\sigma}} + (1-b)(\mu L)^{1-\frac{1}{\sigma}} \right)^{\frac{1}{1-\frac{1}{\sigma}}} \quad (3.2)$$

Comme le capital  $K$  et l'énergie  $E$  sont reliés par une fonction Cobb Douglas l'élasticité de substitution entre le capital et l'énergie est égale à 1, et on note  $\alpha$  la part du capital dans l'agrégat capital-énergie<sup>2</sup>. L'agrégat capital-énergie est relié au travail  $L$  par une fonction CES. On note  $\sigma$  l'élasticité de substitution entre l'agrégat capital-énergie et le travail et  $b$  la part de l'agrégat capital-énergie dans la production.

### 3.2.2 La Technologie de Production et d'Innovation

Le choix, par le planificateur, de la direction du progrès technique s'effectuera dans notre cas sur la frontière des possibilités d'innovations (F.P.I.) comme introduit par Kennedy (1964) (voir le graphique 3.1). En abscisse nous inscrivons le taux de croissance de progrès technique qui augmente l'efficacité du travail  $\frac{\dot{\mu}}{\mu}$ , et en ordonnée celui de l'efficacité du facteur composite capital-énergie,  $\frac{\dot{\lambda}}{\lambda}$ .

---

<sup>2</sup>La valeur de  $\alpha$  se révélera très importante dans les conclusions de notre modèle sur la direction du progrès technique dans le cas d'une limitation de l'utilisation d'énergie.



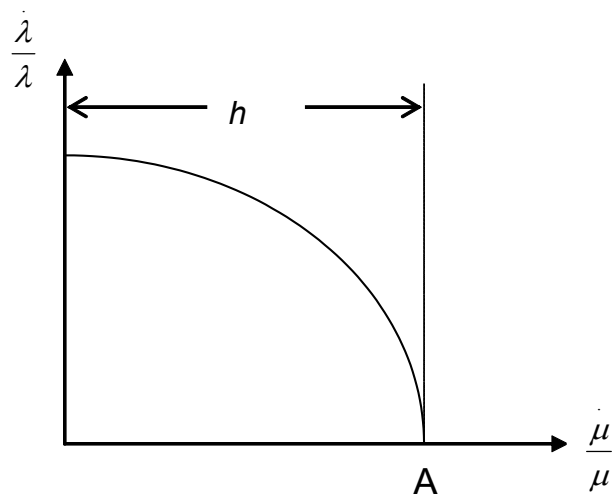


FIG. 3.1 – Frontière des possibilités d'innovation

Du coup, sur la frontière des possibilités d'innovation, le progrès technique reposant sur l'agrégat capital-énergie est une fonction du progrès technique reposant sur le travail. On aura :

$$\frac{\dot{\lambda}}{\lambda} = g\left(\frac{\dot{\mu}}{\mu}\right) \quad (3.3)$$

Il en suit que nécessairement :

$$\begin{aligned} \frac{\dot{\lambda}}{\lambda} &= g(\beta) \\ \frac{\dot{\mu}}{\mu} &= \beta \end{aligned}$$

Avec  $g$  une fonction décroissante deux fois différentiable telle que  $g' < 0$  et  $g'' < 0$ .

Dans ce cadre, une valeur jouera un rôle important, c'est l'abscisse du point A, qui indique le taux maximum de progrès technique neutre au sens de Harrod. A l'abscisse du point A, le progrès technique repose uniquement sur le travail, et pas sur l'agrégat capital-énergie. C'est en effet un repère absolu puisqu'il porte sur la croissance d'un facteur non reproductible, le travail. En ce sens il va jouer un rôle important dans la composition du taux de croissance et on le retrouvera dans les formules de convergence. Notons qu'en particulier le taux de préférence pour le présent  $\rho$  de la fonction d'utilité,

sera postulée supérieure à ce taux pour satisfaire les formules de convergence.

### 3.2.3 La Dynamique du Modèle

Le capital croît dans le temps et s'accumule selon la fonction 3.4 :

$$\dot{K} = I - \delta K \quad (3.4)$$

avec  $I$  l'investissement en capital physique et  $\delta$  le taux de dépréciation du capital.

Dans notre cadre, tout ce qui est produit, est soit consommé  $C$ , soit investit en capital  $I$  ou soit utilisé comme énergie  $E$ .

$$Y = C + I + E$$

Il en suit nécessairement que l'investissement est la résultante de l'équation suivante 3.5.

$$I = Y - C - E \quad (3.5)$$

Pour simplifier la présentation du problème, on peut réécrire la fonction 3.1 en valeurs intensives, c'est à dire en divisant chaque terme de la fonction de production par  $\mu L$ , le travail intensif. On obtient ainsi :

$$\begin{aligned} \frac{Y}{\mu L} &= F\left(\frac{\lambda(K,E)}{\mu L}, 1\right) \\ \Leftrightarrow y &= \mu f(x) \end{aligned} \quad (3.6)$$

Avec  $y = \frac{Y}{\mu L}$  et  $x = \frac{\lambda(K,E)}{\mu L}$ . Plus précisément, la valeur de  $x$  peut aussi être réécrite sous la forme  $x = \frac{\lambda k^\alpha e^{1-\alpha}}{\mu}$  avec  $k = \frac{K}{L}$  et  $e = \frac{E}{L}$ .

De la même manière on écrit la croissance du capital, équation 3.4, en valeurs intensives. Nous supposons que le travail croît de manière exogène, au taux  $n$ , taux de croissance fixe de la population, c'est à dire que  $L = L_0 e^{nt}$ . On obtient donc :

$$\begin{aligned} \dot{k} &= \frac{\dot{K}}{L} - \frac{\dot{L}}{L^2} K \\ \Leftrightarrow \dot{k} &= \frac{I - \delta K}{L} - \frac{K}{L} n \\ \Leftrightarrow \dot{k} &= i - (\delta + n)k \end{aligned}$$

Avec  $i = \frac{I}{L}$  c'est à dire l'investissement par tête.

### 3.2.4 Le Programme du Planificateur : Détermination du Hamiltonien

En accord avec les programmes d'optimisation économiques et notant  $\rho$  le taux de préférence pour le présent de la fonction d'utilité, le programme du planificateur est simplement la maximisation de la consommation totale par tête, sur la période de  $t : 0 \rightarrow +\infty$  (voir équation 3.7).

$$\text{Max} \int_0^{+\infty} \frac{C}{L} \exp^{-\rho t} dt = \int_0^{+\infty} \exp^{-\rho t} (\mu f(x_t) - i_t - e_t) dt \quad (3.7)$$

Dans le programme de maximisation, il existe trois variables d'état qui sont  $\lambda$ ,  $\mu$ , et  $k$  et qui croissent comme précisé dans la section précédente, selon les fonctions suivantes :

$$\left| \begin{array}{l} \dot{\lambda} = g(\beta) \\ \dot{\mu} = \beta \\ \dot{k} = i - (\delta + n)k \end{array} \right.$$

De plus, il existe trois variables de contrôle, qui sont des variables de décision du planificateur, qui sont  $\beta$ ,  $e$  et  $i$ .

En accord avec les règles d'optimisation, ceci revient à maximiser l'Hamiltonien suivant :

$$H = \exp^{-\rho t} \{ (\mu f(x_t) - i_t - e_t) + p_1 (i_t - (\delta + n)k_t) + p_2 \exp^{ht} \lambda_t g(\beta) + p_3 \mu_t \beta \}$$

sous les contraintes :

$$\left| \begin{array}{l} \mu f(x_t) \geq i_t + e_t + c_t \\ c_t \geq 0 \\ e_t \geq 0 \\ i_t \geq 0 \end{array} \right.$$

On note  $p_1$  la variable adjointe associé à la croissance du capital,  $p_2 \exp^{ht}$  la variable adjointe associée au progrès technique portant sur l'agrégat  $(K, E)$ , et enfin  $p_3$ , la variable adjointe associée au progrès technique portant sur le travail.

### 3.2.5 Détermination du Sentier de Croissance de Long Terme Dérivées Par Rapport aux Variables d'Etat $k$ , $\lambda$ et $\mu$

Pour ne pas allourdir l'écriture des équations, nous retirons ici les indices temporelles dans le reste de la section. Sur le sentier de croissance de long terme, les prix implicites sont nécessairement constants. Ainsi, on aura  $\dot{p}_1 = \dot{p}_2 = \dot{p}_3 = 0$ .

Dérivée du Hamiltonien par rapport à  $k$  :

$$\begin{aligned}\frac{\delta H}{\delta k} &= \lambda \alpha k^{\alpha-1} e^{1-\alpha} f'(x) - p_1(\delta + n) \\ &= -\dot{p}_1 + \rho p_1\end{aligned}$$

Avec  $\dot{p}_1 = 0$  sur le sentier de croissance de long terme :

$$\lambda \alpha k^{\alpha-1} e^{1-\alpha} f'(x) = p_1(\rho + \delta + n) \quad (3.8)$$

Dérivée du Hamiltonien par rapport à  $\lambda$  :

$$\begin{aligned}\frac{\delta H}{\delta \lambda} &= k^\alpha e^{1-\alpha} f'(x) + p_2 \exp^{ht} g(\beta) \\ &= -\dot{p}_2 \exp^{ht} - h p_2 \exp^{ht} + \rho p_2\end{aligned}$$

Avec  $\dot{p}_2 = 0$  sur le sentier de croissance de long terme :

$$k^\alpha e^{1-\alpha} f'(x) = p_2 \exp^{ht} (\rho - h - g(\beta)) \quad (3.9)$$

Dérivée du Hamiltonien par rapport à  $\mu$  :

$$\begin{aligned}\frac{\delta H}{\delta \mu} &= f(x) - f'(x) \frac{\lambda}{\mu} k^\alpha e^{1-\alpha} + p_3 \beta \\ &= -\dot{p}_3 + \rho p_3\end{aligned}$$

Avec  $\dot{p}_3 = 0$  sur le sentier de croissance de long terme :

$$(f(x) - x f'(x)) = p_3(\rho - \beta) \quad (3.10)$$

**Dérivées du Hamiltonien Par Rapport aux Variables de Contrôle  $\beta, i, e$** 

Les conditions nécessaires d'optimalité du programme supposent que les dérivées du Hamiltonien par rapport aux variables de contrôle s'annulent.

Sur le domaine de commande, on dérive le Hamiltonien par rapport à  $\beta$  :

$$\frac{\delta H}{\delta \beta} = p_2 \exp^{ht} g'(\beta) \lambda + p_3 \mu = 0 \quad (3.11)$$

De même, on dérive le Hamiltonien par rapport à  $e$  :

$$\begin{aligned} \frac{\delta H}{\delta e} &= -1 + (1 - \alpha) \lambda k^\alpha e^{-\alpha} f'(x) = 0 & (3.12) \\ \Leftrightarrow \left(\frac{k}{e}\right)^\alpha (1 - \alpha) \lambda f'(x) &= 1 \\ \Leftrightarrow k^\alpha e^{-\alpha} (1 - \alpha) \lambda f'(x) &= 1 \end{aligned}$$

Il est en revanche impossible de procéder à la dérivée du Hamiltonien par rapport à  $i$  car  $H$  est linéaire en  $i$ . Si  $p_1 > 1$  alors dans ce cas, cela conduirait à maximiser  $i$ , et donc à minimiser  $e$  (la consommation d'énergie par tête) et à minimiser  $c$  (la consommation par tête), ce qui est en contradiction avec le programme de maximisation du planificateur. Si  $p_1 < 1$  alors, dans ce cas, l'investissement est nul  $i = 0$  et le capital devra décroître nécessairement au taux  $(\delta + n)$ , ceci est aussi un cas impossible économiquement. On peut donc en conclure que nécessairement  $p_1 = 1$ .

Enfin, pour résoudre ce programme à l'optimum, il est nécessaire que le programme satisfasse les conditions initiales :

$$\left| \begin{array}{l} \lambda_0 = \lambda(0) \\ \mu_0 = \mu(0) \\ k_0 = k(0) \end{array} \right.$$

Les conditions de transversalité doivent de plus vérifier l'égalité suivante :

$$\lim_{t \rightarrow +\infty} p_2 \exp^{ht} \exp^{-\rho t} = \lim_{t \rightarrow +\infty} p_1 \exp^{-\rho t} = \lim_{t \rightarrow +\infty} p_3 \exp^{-\rho t} = 0$$

### 3.2.6 Détermination du Taux de Progrès Technique sur le Sentier de Croissance de Long Terme

#### Détermination de $x$ sur le Sentier de Croissance de Long Terme

Pour déterminer la valeur de  $x$  sur le sentier de croissance de long terme, faisons le rapport entre l'équation 3.9 et 3.10. On obtient ainsi l'équation suivante :

$$\frac{(\rho - g(\beta)) p_2 \exp^{ht}}{\rho - \beta} = \frac{f'(x) \frac{\mu}{\lambda} x}{f(x) - x f'(x)} \quad (3.13)$$

Or, en introduisant l'équation 3.11 ci dessous dans l'équation 3.13,

$$\frac{p_2 \exp^{ht}}{p_3} = -\frac{\mu}{\lambda} \frac{1}{g'(\beta)}$$

On obtient :

$$-\frac{(\rho - g(\beta))}{\rho - \beta} \frac{1}{g'(\beta)} = \frac{x f'(x)}{f(x) - x f'(x)} \quad (3.14)$$

D'après l'équation 3.14 on en conclut que  $x$  est constant sur le sentier de croissance de long terme.

#### Détermination de $\frac{e}{k}$ sur le Sentier de Croissance de Long Terme

Pour déterminer le rapport  $\frac{e}{k}$  sur le sentier de croissance de long terme, faisons le rapport entre l'équation 3.12 et l'équation 3.8. On obtient :

$$\frac{1 - \alpha k}{\alpha e} = \frac{1}{\rho + \delta + n} \quad (3.15)$$

Comme  $\rho$ ,  $\delta$ ,  $\alpha$  et  $n$  sont des constantes, il est suit que sur le sentier de croissance de long terme  $\frac{k}{e}$  est une constante et donc que  $\dot{\frac{k}{e}} = 0$ . Ceci signifie que le capital par tête et l'énergie par tête croissent au même taux sur le sentier de croissance de long terme.

#### Confirmation du Résultat Canonique de Nordhaus

D'après notre définition, nous savons que  $x = \frac{\lambda k^\alpha e^{1-\alpha}}{\mu}$ . Or nous avons montré que sur le sentier de croissance de long terme,  $x$  est nécessairement constant. Il en suit que

le taux de croissance de  $x$  est nul sur le sentier de croissance de long terme. Du coup :

$$\frac{\dot{x}}{x} = \frac{\dot{\lambda}}{\lambda} - \frac{\dot{\mu}}{\mu} + \alpha \frac{\dot{k}}{k} + (1 - \alpha) \frac{\dot{e}}{e} = 0$$

Cette équation peut être réécrite comme suit :

$$g(\beta) - \beta + \alpha \frac{\dot{k}}{k} + (1 - \alpha) \frac{\dot{e}}{e} = 0$$

Or d'après l'équation 3.15, on sait que l'énergie par tête et le capital par tête est constant sur le sentier de croissance de long terme. Du coup on a nécessairement :

$$\frac{\dot{e}}{e} = \frac{\dot{k}}{k}.$$

Il en suit que sur le sentier de croissance de long terme :

$$\beta - g(\beta) = \frac{\dot{e}}{e} = \frac{\dot{k}}{k}. \quad (3.16)$$

Reprenons l'équation 3.12 :

$$k^\alpha e^{-\alpha} (1 - \alpha) \lambda f'(x) = 1$$

Comme nous avons montré que sur le sentier de croissance de long terme,  $x$  est constant,  $\lambda$  croît au taux  $g(\beta)$  et  $\frac{k}{e}$  est une constante,  $\alpha$  est une constante et  $f'(x)$  est une constante, il en suit nécessairement que sur le sentier de croissance de long terme on a la relation suivante :

$$g(\beta) = 0 \quad (3.17)$$

Ceci implique que sur ce sentier de croissance de long terme, le progrès technique est nécessairement neutre au sens de Harrod, c'est à dire qu'il n'y a aucun progrès technique qui repose sur l'agrégat capital-énergie. Reprenons l'équation 3.9 :

$$\left(\frac{k}{e}\right)^\alpha e f'(x) = p_2 \exp^{ht} (\rho - h - g(\beta))$$

Sur le sentier de croissance de long terme,  $\frac{\dot{k}}{e}$  est nul,  $e$  croît au taux  $\beta$  (voir equation 3.16),  $\dot{p}_2$  est nul,  $\rho$  et  $h$  sont des constantes donc leurs taux de croissance sont nuls, et

$g(\beta)$  est nul donc son taux de croissance est nul. Il en suit que nécessairement on a la relation suivante :

$$\beta = h \quad (3.18)$$

Nous retrouvons ici le résultat canonique de Nordhaus, qui dans un modèle avec deux facteurs de production, le capital et le travail, soutient que le progrès technique accroît l'efficacité du facteur non reproductible, le travail.

**Proposition 3** *Dans le cas d'une fonction CES à trois facteurs où le capital et l'énergie sont reliés par une Cobb Douglas, le progrès technique est neutre au sens de Harrod sur le sentier de croissance de long terme.*

### 3.2.7 Caractérisation Complète de l'Etat Stationnaire

Sur le sentier de croissance de long terme, toutes les variables par tête ( $k, e, c, i, y$ ) croissent au taux de croissance du progrès technique neutre au sens de Harrod, c'est à dire croissent au taux  $h$ .

On aura ainsi sur le sentier de croissance de long terme :

$$\left\{ \begin{array}{l} \beta = h \\ g(\beta) = 0 \\ \frac{\dot{c}}{c} = \frac{\dot{k}}{k} = \frac{\dot{e}}{e} = \frac{\dot{i}}{i} = \frac{\dot{y}}{y} = h \\ \frac{e}{k} = \frac{1-\alpha}{\alpha}(n + \delta + \rho) \\ \frac{i}{k} = h + n + \delta \\ -\frac{\rho}{\rho-h} \frac{1}{g'(h)} = \frac{f'(x)x}{f(x)-xf'(x)} \end{array} \right.$$

Il s'agit donc d'une économie qui croît de façon homothétique au taux  $h$  ce qui du point de vu des émissions liées à la consommation d'énergie risque de poser un problème. Les émissions provenant de l'utilisation de l'énergie vont aussi croître au taux  $h$  si aucune contrainte n'est imposée. En effet, dans le cas où il n'existe pas de contrainte sur l'utilisation d'énergie, le progrès technique n'augmente pas la productivité du facteur composite capital-énergie, mais repose uniquement sur le facteur non reproductible, le travail. Il n'y a donc aucune possibilité d'augmenter l'efficacité du facteur composite capital-énergie.



**Proposition 4** *Sur le sentier de croissance de long terme, l'économie croît au taux de progrès technique, et les émissions liées à l'énergie croissent de même.*

### 3.2.8 Les Conditions Necessaires de l'Optimum sont Suffisantes si $\sigma < 1$

Les conditions de transversalités déterminées plus haut ne sont vérifiées que pour  $h < \rho$ . Or les conditions de transversalités sont nécessaires et non suffisantes pour soutenir que l'équilibre est optimal. La question à laquelle il est donc nécessaire de répondre est celle de l'optimalité de ce sentier de croissance de long terme en fonction des valeurs de l'élasticité de substitution  $\sigma$  entre l'agrégat capital-énergie et le travail. Dans notre définition de la fonction de production, la valeur de l'élasticité de substitution n'a en effet pas été fixée.

Nous nous intéressons donc au cas où l'économie se trouve initialement sur un sentier de croissance de long terme, où le progrès technique est neutre au sens de Harrod. Nous allons montrer dans cette section, que dans le cas où  $\sigma < 1$ , la fonction de préférence du planificateur est maximisée, tandis que dans le cas où  $\sigma > 1$ , le progrès technique neutre au sens de Harrod ne sera pas un sentier optimal car la fonction de préférence du planificateur est minimisée en un point. Dans ce cas seulement, le progrès technique neutre au sens de Harrod n'est plus optimal.

Dans cette section, nous cherchons à prouver que les conditions nécessaires de l'optimum sont suffisantes et maximisent le programme du planificateur dans le cas où  $\sigma < 1$ .

Pour ce faire, comme nous engageons notre analyse dans le cas où nous nous trouvons déjà sur le sentier de croissance de long terme, linéarisons  $g(\beta)$  en  $\beta = h$ . Nous savons en effet que  $\frac{\dot{\lambda}}{\lambda} = g(\beta)$ . La linéarisation en ce point nous donne l'équation suivante :

$$\frac{\dot{\lambda}}{\lambda} = -hg'(h) + \beta g'(h) \quad (3.19)$$

En posant  $A = -g'(h)$  l'équation 3.19 se réécrit :

$$\frac{\dot{\lambda}}{\lambda} = hA - \beta A$$

De même que Nordhaus, nous posons comme hypothèse que  $\mu = 1$  et  $\lambda = 1$  à l'optimum. Ceci ne contraindra en rien notre discussion par rapport à la valeur de l'élasticité de substitution  $\sigma$ , mais permet de rendre les résultats plus lisibles. Par ailleurs on définit  $B$  tel que :

$$B(t) = \int_0^t \beta(v)dv - ht$$

Toutes les autres équations du modèle restent inchangées. Définissons ainsi  $\lambda$  et  $\mu$  tels que :

$$\begin{aligned} \int_0^t \frac{\dot{\lambda}}{\lambda} dv &= \int_0^t (Ah - A\beta(v))dv = Aht - A \int_0^t \beta(v)dv = -AB \\ \int_0^t \frac{\dot{\lambda}}{\lambda} dv &= -AB \\ \ln \lambda_t - \ln \lambda_0 &= -AB \end{aligned} \quad (3.20)$$

Or comme  $\lambda = 1$  on obtient :

$$\lambda_t = \exp^{-AB}$$

De la même façon on peut obtenir  $\mu_t$  :

$$\begin{aligned} \int_0^t \frac{\dot{\mu}}{\mu} dv &= \int_0^t \beta(v)dv = B + ht \\ \ln \mu_t - \ln \mu_0 &= B + ht \end{aligned}$$

Or comme  $\mu = 1$  on obtient :

$$\mu_t = \exp^{ht} \exp^B \quad (3.21)$$

On considère maintenant un sentier optimal dans ce système linéarisé dont les variables de contrôle sont  $B(t), s(t), e(t)$ . On définit le Hamiltonien du système qui est tel que :

$$H = \exp^{-\rho t} \{ (1-s) \exp^{ht} \exp^B f(x) - e + q[s \exp^{ht} \exp^B f(x) - (\delta + n)k] \}$$

Ici, le Hamiltonien est légèrement modifié par rapport à la section précédente. En effet, nous avons comme contrainte initiale  $y = c + i + e$ . Ici nous posons comme hypothèse que  $i = sy$ . C'est à dire que la valeur de l'investissement dépend du taux d'épargne  $s$ . Du coup notre contrainte se réécrit :

$$y = sy + c + e$$

Le taux d'épargne  $s$  de l'économie est une variable contrôlée par le planificateur et appartient à  $]0; 1[$ . Ainsi comme le planificateur maximise la consommation par tête, il maximise  $(1 - s)$ . La définition du problème est ici légèrement modifiée, mais ceci ne contraint en rien notre discussion. Dans le problème précédent, le planificateur contrôlait l'investissement par tête  $i$ , ici, il contrôle simplement le taux d'épargne  $s$ .

Dans cette équation on note  $q$  le prix implicite.

Avec les nouvelles notations définies dans les équations 3.20 et 3.21, on définira la valeur de  $x$  comme suit :

$$\begin{aligned} x &= \frac{\lambda(K,E)}{\mu L} = \frac{\exp^{-AB}}{\exp^{ht} \exp^B} (k^\alpha e^{1-\alpha}) \\ \Leftrightarrow x &= \exp^{-B(A+1)-ht} (k^\alpha e^{1-\alpha}) \end{aligned} \quad (3.22)$$

### Dérivée du Hamiltonien Par Rapport à la Variable d'Etat $k$

La dérivée du Hamiltonien par rapport à la variable d'état  $k$  nous donne l'équation suivante :

$$\begin{aligned} \frac{\delta H}{\delta k} &= -q(\delta + n) + \gamma \exp^{-BA} a k^{\alpha-1} e^{1-\alpha} f'(x) \\ &= -\dot{q} + \rho q \end{aligned} \quad (3.23)$$

Avec

$$\gamma = (1 + sq - s)$$

Ce qui nous donne :

$$\dot{q} = q(\delta + n + \rho) + \gamma \exp^{-BA} a k^{\alpha-1} e^{1-\alpha} f'(x)$$

Par ailleurs on a :

$$\dot{k} = s \exp^{ht} \exp^B f(x) - (d + n)k$$

On définit la condition de transversalité qui est telle que :

$$\lim_{t \rightarrow \infty} \exp^{-\rho t} q(t) = 0$$

### Dérivée du Hamiltonien Par Rapport aux Variables de Contrôle $B, s, e$

Dérivée du Hamiltonien par rapport au taux d'épargne  $s$  :

$$\frac{\delta H}{\delta s} = 0 \Rightarrow q = 1 \quad (3.24)$$

Dérivée du Hamiltonien par rapport à l'énergie  $e$  :

$$\frac{\delta H}{\delta e} = 0 \Rightarrow \gamma \exp^{-AB} (1 - \alpha) k^\alpha e^{-\alpha} f'(x) = 0 \quad (3.25)$$

Avec  $A = -g'(h)$  et  $x = \exp^{-B(A+1)-ht} (k^\alpha e^{1-\alpha})$  on obtient la dérivée du Hamiltonien par rapport à  $B$ . Nous obtenons ainsi la relation suivante :

$$\begin{aligned} \frac{\delta H}{\delta B} &= \gamma \exp^{-\rho t} \exp^{ht} \exp^B [f(x) - (A+1)x f'(x)] \\ \Leftrightarrow \frac{\delta H}{\delta B} &= f(x) \gamma \exp^{(h-\rho)t+B} (A+1) \left[ \frac{1}{A+1} - \frac{x f'(x)}{f(x)} \right] \end{aligned} \quad (3.26)$$

Or on sait que la part de l'agregat capital-énergie dans la fonction de production est

$$\varepsilon(x) = \frac{x f'(x)}{f(x)}$$

$$\frac{\delta H}{\delta B} = f(x) \gamma \exp^{(h-\rho)t+B} (A+1) \left[ \frac{1}{A+1} - \varepsilon(x) \right]$$

Nous cherchons maintenant à déterminer quelles sont les conditions qui permettent la concavité du Hamiltonien  $H$  en  $B$ . En effet, il est important de connaître les conditions sous lesquelles,  $B$  maximise  $H$ . Car dans le cas où  $H$  n'est pas concave en  $B$  alors, la consommation par tête n'est plus maximisée. Pour ce faire calculons le signe de la

dérivée seconde de  $H$  en  $B$  dans le but de déterminer ces conditions. Nous calculons la dérivée seconde de l'équation 3.26 dans le but de déterminer son signe.

$$\frac{\delta^2 H}{\delta B^2} = \gamma \exp^{(h-\rho)t+B}(A+1) \left\{ f' \left[ \frac{1}{A+1} - \varepsilon \right] x' + f \left[ \frac{1}{A+1} - \varepsilon \right] - f \varepsilon' x' \right\} \quad (3.27)$$

Or on déduit de l'équation 3.22 la dérivée de  $x$  qui est :  $x' = -(A+1)x$ . On obtient donc :

$$\begin{aligned} \frac{\delta^2 H}{\delta B^2} &= \gamma \exp^{(h-\rho)t+B}(A+1) \left\{ -f' \left[ \frac{1}{A+1} - \varepsilon \right] x(A+1) + f \left[ \frac{1}{A+1} - \varepsilon \right] + (A+1) f \varepsilon' x \right\} \\ \Leftrightarrow \frac{\delta^2 H}{\delta B^2} &= \gamma \exp^{(h-\rho)t+B}(A+1) \left\{ \left[ \frac{1}{A+1} - \varepsilon \right] (-f' x(A+1) + f) + (A+1) f \varepsilon' x \right\} \end{aligned}$$

Il est donc nécessaire de déterminer la valeur de  $\varepsilon'$  pour connaître le signe de l'équation 3.27.

On sait que l'élasticité de substitution entre l'agrégat capital-énergie et le travail se définit comme :

$$\sigma = -f'(x) \frac{f(x) - x f'(x)}{x f(x) f''(x)}$$

Avec

$$\varepsilon(x) = \frac{x f'(x)}{f(x)}$$

La dérivée de  $\varepsilon(x)$  est donnée par la relation suivante :

$$\begin{aligned} \varepsilon' &= \frac{f'}{f} + \frac{f''}{f} x - \frac{f' x}{f^2} f' \\ &= \frac{1}{f^2} (f f' + x f f'' - x f'^2) \end{aligned}$$

Du coup, on peut réécrire  $\sigma^3$ :

$$\begin{aligned} 1 - \sigma &= 1 + \frac{f'}{x f f''} (f - x f') \\ &= \frac{f f' + x f f'' + -x f'^2}{x f f''} \\ &= \frac{f^2}{x f f''} \varepsilon' \end{aligned}$$

On en déduit la valeur de  $\varepsilon'$ .

$$\varepsilon' = (1 - \sigma) \frac{x f''}{f}$$

---

<sup>3</sup>En retirant les  $(x)$  pour simplifier l'écriture.

Nous savons que  $x$  est positif,  $f$  l'est aussi et  $f'$  est négatif.

Donc si  $(1 - \sigma) > 0$  alors  $\varepsilon'$  est négatif nécessairement et  $\frac{\delta^2 H}{\delta B^2} < 0$ .

Mais si  $(1 - \sigma) < 0$  alors  $\varepsilon'$  est positif nécessairement et  $\frac{\delta^2 H}{\delta B^2} > 0$ .

On voit ici que la valeur de  $\sigma$  sera essentielle dans l'analyse, pour déterminer si  $H$ , le Hamiltonien est concave en  $B$ .

En réintroduisant la valeur de  $\varepsilon'$  dans l'équation 3.27 :

$$\frac{\delta^2 H}{\delta B^2} = \gamma \exp^{(h-\rho)t+B} (A+1) f \left\{ \left[ \frac{1}{A+1} - \varepsilon \right] (-\varepsilon(x)(A+1) + 1) + (A+1)(1-\sigma) \frac{x f''}{f} x \right\}$$

Nous obtenons, avec  $\varepsilon(x) = \frac{1}{A+1}$  :

$$\frac{\delta^2 H}{\delta B^2} = \gamma \exp^{(h-\rho)t+B} (A+1)^2 f (1-\sigma) \frac{x^2 f''}{f} \quad (3.28)$$

### Discussion Par Rapport aux Valeurs de Sigma

Il est évident d'après cette équation que le signe de 3.28 dépend de la valeur de  $\sigma$  par rapport à 1. En effet, toutes les valeurs dans cette équation sont positives sauf  $f'' < 0$ . On peut définir trois cas :

- Si  $\sigma < 1 \Rightarrow \frac{\delta^2 H}{\delta B^2} < 0$  ce qui nous permet de conclure que  $B$  est concave en  $H$  c'est à dire que  $B$  maximise  $H$  en tous points.
- Si  $\sigma > 1 \Rightarrow \frac{\delta^2 H}{\delta B^2} > 0$  ce qui nous permet de conclure que  $B$  est convexe en  $H$  c'est à dire que  $B$  minimise  $H$  en tous points
- Si  $\sigma = 1 \Rightarrow \frac{\delta^2 H}{\delta B^2} = 0$  on ne peut rien conclure sur la convexité ou la concavité de  $B$  en  $H$ .

On se restreindra aux deux premiers cas :  $\sigma < 1$  et  $\sigma > 1$ .

Nous avons linéarisé le système au point  $\beta = h$  ce qui est la direction optimale maximale du progrès technique neutre au sens de Harrod dans le modèle original. Nous nous

se situons initialement au point  $z^* = (x^*, \lambda^*, \mu^*, k^*, \beta^*, e^*, s^*)$  que l'on définit comme le système sur le sentier de long terme dont les valeurs ont été déterminées dans l'exercice précédent. Nous allons démontrer que dans le cas où l'économie est initialement en  $z^*$  alors, si  $\sigma < 1$  il est optimal de rester sur ce sentier de long terme, tandis que si  $\sigma > 1$ , il n'est pas optimal de rester sur ce sentier.

L'économie est donc initialement en  $z^*$  avec  $z^* = (x^*, \lambda^*, \mu^*, k^*, \beta^*, e^*, s^*)$  et  $\sigma < 1$ . Ceci a pour conséquence que  $q_t = 1$ ,  $B(t) = 0$ , et  $s(t) = s^*$  (le taux d'épargne qui est déterminable sur le sentier de long terme). Dans ce cas, toutes les dérivées premières du modèles s'annulent et conduisent à un maximum. En effet,  $H$  est concave en  $k$ , en  $e$ , mais aussi en  $B$  ( $\frac{\delta^2 H}{\delta B^2} < 0$ ). On en conclut que dans le système linéarisé, quand  $\sigma < 1$  alors  $z^*$  est le sentier optimal. Mais il est nécessaire de montrer que si  $z^*$  est le sentier optimal dans le système linéarisé alors, il l'est aussi dans le système original.

Dans le problème original on cherchait à résoudre :

$$\max_{e, s, \beta} \int_0^{+\infty} \Psi(e, s, \beta, t) dt$$

Sous les contraintes :

$$\begin{cases} \dot{\lambda} = g(\beta) \\ \dot{\mu} = \beta \\ \dot{k} = s\mu f(x_t) - (\delta + \eta)k_t \end{cases}$$

Or à l'optimum on a  $\beta = h$  donc on sait que l'on peut écrire la relation suivante :

$$\max_{e, s, \beta} \int_0^{+\infty} \Psi(e, s, \beta, t) dt = \max_{s, e} \int_0^{+\infty} \Psi(e, s, h, t) dt$$

Sous les mêmes contraintes notées ci dessus.

Dans le problème linéarisé, on cherchait à résoudre :

$$\max_{e, s, B} \int_0^{+\infty} \Psi(e, s, B, t) dt$$

Sous des contraintes légèrement différentes :

$$\left\{ \begin{array}{l} \frac{\dot{\lambda}}{\lambda} = \tilde{g}(\beta) \\ \frac{\dot{\mu}}{\mu} = \beta \\ \dot{k} = s\mu f(x_t) - (\delta + \eta)k_t \end{array} \right.$$

Avec  $\tilde{g}(\beta)$ , l'équation linéarisée de  $g(\beta)$  en  $h$ .

De même, sur le sentier de long terme, on peut écrire la relation suivante sous les contraintes modifiées ci-dessus :

$$\max_{e,s,B} \int_0^{+\infty} \Psi(e, s, B, t) dt = \max_s \int_0^{+\infty} \Psi(e, s, h, t) dt$$

Or nous avons linéarisé  $g(\beta)$  au point  $\beta = h$  ce qui nous permet d'écrire que  $\tilde{g}(\beta) = g(\beta)$  en ce point. On peut donc conclure que le sentier optimal dans le système modifié est le même dans le problème original.

Dans le cas où  $\sigma < 1$ , alors si on est initialement au point  $z^* = (x^*, \lambda^*, \mu^*, k^*, \beta^*, e^*, s^*)$ , il est optimal de rester à cet équilibre. Ceci implique que dans le cas où l'élasticité de substitution entre le travail et l'agrégat capital-énergie est faible, c'est le taux de croissance du travail qui contraint la croissance. Il est donc optimal de faire du progrès technique uniquement sur le travail afin de relâcher le plus cette contrainte.

Dans le cas où  $\sigma > 1$  nous voyons que  $H$  est convexe en  $B$ . Ceci nous conduit à noter que l'équilibre  $z^* = (x^*, \lambda^*, \mu^*, k^*, \beta^*, e^*, s^*)$  est un minimum par rapport à  $B$  dans le système modifié. On peut montrer de la même manière que précédemment que si  $H$  est un minimum en  $B$  dans le système modifié, alors il l'est également dans le système original. Nous pouvons en déduire que dans le cas où  $\sigma > 1$  il existe un autre sentier qui domine celui de  $z^*$ . Si  $\sigma > 1$  alors l'agrégat capital-énergie est très substituable au travail, on peut donc en déduire que si l'on met en oeuvre du progrès technique portant uniquement sur l'agrégat alors la consommation et la production



ne seront plus contraints. L'intuition économique est telle qu'il est optimal de faire reposer tout le progrès technique sur l'agrégat capital-énergie, car il permettra une très forte croissance. Comme la substitution est forte ( $\sigma > 1$ ) les entreprises auront intérêt à utiliser plus d'agrégat que de travail, et de faire reposer le progrès technique sur l'agrégat de façon à ce que la croissance soit sans limite.

**Proposition 5** *Sur le sentier de croissance de long terme, le progrès technique neutre au sens de Harrod est un sentier optimal dans le cas seulement où l'élasticité de substitution entre le travail et l'agrégat est faible ( $\sigma < 1$ ). Dans la cas contraire, il est optimal que le progrès technique devienne neutre au sens de Hicks.*

### 3.3 Cas d'une Politique de Limitation des Emissions : Quelques Conjectures sur les Formes du Progrès Technique

Nous nous posons dans cette section la question de l'impact sur la direction du progrès technique d'une politique de contrainte des émissions. Nous avons montré dans la section précédente que toutes les variables croissaient sur le sentier de croissance de long terme, au taux  $h$ , le taux de progrès technique neutre Harrodien. Or l'énergie, qui est un facteur de production dans notre fonction, croît aussi à ce taux, ce qui de point de vue des émissions est nocif pour l'environnement. De plus, cette économie ne représente pas les contraintes de la société qui cherche des méthodes pour réduire ses émissions sans que la production ne doive être contrainte. En effet, nous avons vu dans la revue de la littérature, sur les méthodes de modélisation du progrès technique dans les modèles économie-énergie, qu'il est possible de réduire les émissions de gaz à effet de serre, sans avoir à contraindre la production, et ceci grâce au progrès technique qui permet un découplage entre production et émissions. Cherchons à voir dans ce petit modèle théorique, si la direction du progrès technique sera modifiée de façon à contrebalancer les contraintes énergétiques.

La politique de limitation des émissions de  $CO_2$  va être appréhendée sous la forme d'une contrainte imposée par le planificateur : les émissions par tête, c'est à dire en fait dans ce modèle macroéconomique, la consommation par tête en énergie  $e^4$ , devra être inférieure à un certain niveau  $\bar{e}$  (taux maximum d'énergie par tête). En effet, dans le cas précédent nous avons montré que la consommation d'énergie par tête croissait au taux  $h$ , taux maximum du progrès technique neutre Harrodien.

Imposer une telle contrainte va nécessairement influencer le sentier de long terme. La prise en compte d'un niveau d'émissions maximum va modifier le programme en ajoutant dans le domaine de commande une limitation de l'utilisation d'énergie. On aura ainsi, pour tout temps  $t$  :

$$\bar{e} - e_t \geq 0$$

Réécrivons le Hamiltonien dans le cas de cette contrainte sur l'utilisation d'énergie :

$$H = \exp^{-\rho t} \{ (\mu f(x_t) - \dot{i}_t - e_t) + p_1(\dot{i}_t - (\delta + n)k_t) + p_2 \exp^{ht} g(\beta)\lambda + p_3 \mu \beta + p_e(\bar{e} - e_t) \}$$

On désigne par  $p_e$  la variable duale associée à la contrainte de limitation des énergie. Elle représente en fait le coût associé à cette contrainte pour la fonction objectif et donc elle peut être assimilée à un prix. Dans un système décentralisé, ce prix implicite permet de calculer la taxe optimale pour atteindre les objectifs environnementaux.

### 3.3.1 Les Conditions d'Optimalité

Les conditions d'optimalité du Hamiltonien sont identiques au cas original précédent. Une seule condition d'optimalité est modifiée, c'est celle associée aux émissions par tête. Réécrivons la dérivée du Hamiltonien par rapport à  $e$ .

$$\begin{aligned} \frac{\delta H}{\delta e} &= -(1 + p_e) + (1 - \alpha)\lambda\left(\frac{k}{e}\right)^\alpha f'(x) \\ \Leftrightarrow \lambda(1 - \alpha)\left(\frac{k}{e}\right)^\alpha f'(x) &= 1 + p_e \end{aligned} \quad (3.29)$$

---

<sup>4</sup>On suppose dans ce modèle que les émissions sont reliées à la consommation d'énergie, par une fonction linéaire.

Cette équation exprime qu'à tout moment la productivité marginale de l'énergie est égale à son coût social  $(1 + p_e)$ , dans un univers décentralisé  $p_e$  serait le taux de taxe sur l'énergie.

### 3.3.2 Caractérisation de l'Etat Stable et du Progrès Technique Associé

L'état stable est ici différent du cas précédent dans la mesure où la consommation d'énergie est nécessairement bridée dans la plupart des solutions, du moins à long terme.

Recherchons une solution où  $\dot{p}_1 = 0$  sur le sentier de croissance de long terme. Reprenons l'équation 3.8 :

$$\frac{p_1(\rho + \delta + n)}{\alpha} = \lambda_t k_t^{\alpha-1} e_t^{1-\alpha} f'(x_t)$$

En différentiant cette relation par rapport au temps et en notant  $r_t = k_t^{\alpha-1} e_t^{1-\alpha}$ , on obtient l'égalité suivante :

$$\begin{aligned} & \dot{\lambda} r_t f'(x_t) + \dot{x} f''(x_t) \lambda_t r_t + \dot{r}_t \lambda_t f'(x_t) = 0 \\ \Leftrightarrow & \lambda r_t \frac{\dot{x}}{x} \frac{f''(x_t) x f(x)}{f'(x_t) [f(x) - x f'(x)]} \frac{[f(x) - x f'(x)]}{f(x)} + [\dot{\lambda} r_t + \dot{r}_t \lambda_t] = 0 \\ \Leftrightarrow & -r_t \frac{\dot{x}}{x} \left( \frac{1-\varepsilon(x)}{\sigma} \right) + \frac{\dot{\lambda}}{\lambda} r_t + \dot{r}_t = 0 \\ \Leftrightarrow & r_t \left[ \frac{\dot{\lambda}}{\lambda} - \frac{1-\varepsilon(x)}{\sigma} \frac{\dot{x}}{x} \right] + \dot{r}_t = 0 \\ \Leftrightarrow & [g(\beta) - \frac{1-\varepsilon(x)}{\sigma} \frac{\dot{x}}{x}] e_t^{1-\alpha} k_t^{\alpha-1} + (1-\alpha) \dot{e}_t e_t^{-\alpha} k_t^{\alpha-1} + (\alpha-1) e_t^{1-\alpha} k_t^{\alpha-2} \dot{k}_t = 0 \\ \Leftrightarrow & g(\beta) - \frac{1-\varepsilon(x)}{\sigma} \frac{\dot{x}}{x} = \frac{(1-\alpha) \frac{\dot{e}}{e} e_t^{1-\alpha} k_t^{\alpha-1} + (\alpha-1) \frac{\dot{k}}{k} k_t^{\alpha-1} e_t^{1-\alpha}}{e_t^{1-\alpha} k_t^{\alpha-1}} \\ \Leftrightarrow & \frac{\dot{x}}{x} = \left( (1-\alpha) \frac{\dot{e}}{e} + (\alpha-1) \frac{\dot{k}}{k} + g(\beta) \right) \frac{\sigma}{1-\varepsilon(x)} \end{aligned}$$

avec  $\sigma = \frac{-f'(x)[f(x) - x f'(x)]}{x f(x) f''(x)}$  qui est l'élasticité de substitution entre l'agrégat  $(k, e)$  et le travail, et  $\varepsilon(x) = \frac{f'(x)x}{f(x)}$ , qui est la part de l'agrégat  $(k, e)$  dans la production.

Nous avons donc la relation 3.30 :

$$\frac{\dot{x}}{x} = (1-\alpha) \left( \frac{\dot{e}}{e} - \frac{\dot{k}}{k} \right) + g(\beta) \frac{\sigma}{1-\varepsilon(x)} \quad (3.30)$$

Quand la contrainte sur les émissions est saturée, alors  $e = \bar{e}$ , ce qui implique que à terme,  $\frac{\dot{e}}{e} = 0$ . Ceci signifie qu'à long terme, l'économie utilisera la quantité d'énergie maximale qu'elle est autorisée à utiliser. On peut vraisemblablement croire dans la réalité, qu'à terme, la demande d'énergie ne croîtra plus sur le sentier de long terme<sup>5</sup>. Ainsi, si  $\frac{\dot{e}}{e} = 0$  on peut réécrire l'équation 3.30 de la façon suivante :

$$\frac{\dot{x}}{x} = (\alpha - 1)\frac{\dot{k}}{k} + g(\beta)\frac{\sigma}{1 - \varepsilon(x)} \quad (3.31)$$

Recherchons le sentier de long terme tel que  $\frac{\dot{k}}{k} = cste$ , c'est à dire que  $\frac{\dot{x}}{x} = cste$ . Pour ce faire, posons  $g(\beta) = 0$ . L'objectif est de montrer que dans le cas où il existe une contrainte sur l'énergie, le progrès technique ne pourra plus être neutre au sens de Harrod. Nous allons donc chercher à montrer que dans le cas d'une contrainte sur l'utilisation d'énergie, sur le sentier de croissance de long terme  $g(\beta) \neq 0$  nécessairement.

Nous ferons un raisonnement par l'absurde, pour montrer que nécessairement  $g(\beta) \neq 0$ . Nous savons que  $x$  est alors défini de la façon suivante, et en posant que  $g(\beta) = 0$ , on obtient :

$$\frac{\dot{x}}{x} = (\alpha - 1)\frac{\dot{k}}{k} \quad (3.32)$$

Avec :

$$x = \frac{\lambda k^\alpha e^{1-\alpha}}{\mu} \quad (3.33)$$

Nous étudierons trois cas :

- Cas A :  $\frac{\dot{k}}{k} > 0$  alors, d'après l'équation 3.32 ceci conduit à  $\frac{\dot{x}}{x} < 0$ . Admettons donc que  $\frac{\dot{x}}{x} < 0$  et que l'on se situe dans le cas où  $\sigma < 1$  (nous avons démontré dans le cas précédent que dans le cas où  $\sigma < 1$  il y a un équilibre stationnaire unique satisfaisant les conditions nécessaires du Hamiltonien). Nous avons déterminé  $x$  comme dans l'équation 3.33 et  $f(x)$  sera de la forme :

$$f(x) = (bx^{1-\frac{1}{\sigma}} + (1-b))^{\frac{1}{1-\sigma}}$$

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<sup>5</sup>Cette hypothèse est tout à fait plausible. En Allemagne, la demande d'énergie baisse de manière relativement stable. Ceci est dû notamment à des mesures d'efficacité énergétique imposées politiquement.

Or, comme  $\sigma < 1$  alors  $1 - \frac{1}{\sigma} < 0$ .

Ceci signifie que, si  $\frac{\dot{x}}{x} < 0$ , alors à l'infini  $x$  tendra nécessairement vers 0,

$$t \rightarrow +\infty \text{ alors } x \rightarrow 0$$

Il en suit que :

$$bx^{1-\frac{1}{\sigma}} \rightarrow -\infty$$

Par ailleurs,  $(1 - b)$  est négligeable devant  $-\infty$ , donc au voisinage de 0,  $f(x)$  se comportera comme  $x$ . C'est à dire :

$$f(x) \sim x \text{ quand } x \rightarrow 0$$

On en déduit que la dérivée première de  $x$  quand  $x \rightarrow 0$  est égale à l'unité, c'est à dire que :

$$f'(x) = 1 \tag{3.34}$$

Reprenons l'équation donnée par la dérivée du Hamiltonien par rapport au capital  $k$  3.8 :

$$\lambda \alpha \left(\frac{e}{k}\right)^{1-\alpha} f'(x) = (\delta + n + \rho)$$

Ainsi, si  $\frac{\dot{k}}{k} = cste$  et  $f'(x) = 1$ , alors il y a une incompatibilité car le membre de gauche décroîtrait au taux  $(\alpha - 1)\left(\frac{\dot{k}}{k}\right)$  et le membre de droite est constant. Nous avons donc démontré par un raisonnement par l'absurde que l'on ne peut pas avoir simultanément  $g(\beta) = 0$  et  $\frac{\dot{x}}{x} < 0$ .

– Cas B :  $\frac{\dot{k}}{k} < 0$  ce qui implique  $\frac{\dot{x}}{x} > 0$  nécessairement. Or nous savons que  $\frac{\dot{x}}{x} = \frac{\lambda G(k,e)}{\mu}$ . Pour que cette fraction croisse à un taux positif, sachant que le capital décroît et que l'énergie par tête est constante, il est nécessaire que  $\frac{\dot{\lambda}}{\lambda} > \frac{\dot{\mu}}{\mu}$ . Ceci signifie que sur ce sentier de croissance de long terme, le progrès technique portant sur l'agrégat capital-énergie est supérieur à celui portant sur le travail. Ce qui

est impossible car nous avons posé comme hypothèse de base que  $g(\beta) = \frac{\dot{\lambda}}{\lambda} = 0$  ce qui est en contradiction avec  $\frac{\dot{\lambda}}{\lambda} > \frac{\dot{\mu}}{\mu}$ , car le taux de croissance du progrès technique reposant sur le travail ne peut pas être négatif, cela n'a aucun sens économique. Le cas B est donc impossible.

- Cas C :  $\frac{\dot{k}}{k} = 0$  ceci implique que, d'après l'équation 3.32 :

$$\frac{\dot{x}}{x} = 0$$

Or, d'après l'équation 3.33 pour que le taux de croissance de  $x$  soit nul, avec  $\frac{\dot{k}}{k} = 0$  et  $\frac{\dot{e}}{e} = 0$  il faut nécessairement que  $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{\mu}}{\mu}$  ce qui est un cas possible. Or il faut que  $g(\beta) = 0$  nécessairement du coup, il faut que  $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{\mu}}{\mu} = 0$  et ceci est impossible par rapport aux frontières des possibilités d'innovation.

### Dans le Cas d'une Contrainte sur l'Energie $g(\beta) \neq 0$ , Nécessairement

Nous avons donc montré que sur le sentier de long terme, et quand  $g(\beta) = 0$ , alors

- Cas A est impossible :  $x$  ne peut pas décroître à un taux constant
- Cas B est impossible :  $x$  ne peut pas croître de manière constante
- Cas C est impossible :  $x$  ne peut pas être constant

Nous venons d'écarter la solution  $g(\beta) = 0$  sur le sentier de croissance de long terme dans le cas où il existe une contrainte sur l'utilisation d'énergie. Ainsi, sur le sentier de long terme, on aura nécessairement  $g(\beta) > 0$ .

**Proposition 6** *Dans le cas où à long terme, les émissions par tête sont contraintes, le progrès technique ne peut plus être neutre au sens de Harrod.*

### Caractérisation du Progrès Technique Dans le Cas d'une Contrainte Energétique

Sur le sentier d'état stable, nous savons que la croissance de  $x$  est nécessairement nulle. C'est à dire :

$$\frac{\dot{x}}{x} = 0$$

Nous allons donc continuer notre discussion dans le cas où  $g(\beta) > 0$  et  $\frac{\dot{x}}{x} = 0$  sur le sentier de long terme.

On rappelle l'équation 3.29

$$\lambda(1 - \alpha)\left(\frac{k}{e}\right)^\alpha f'(x) = 1 + p_e$$

Sur le sentier de croissance de long terme, on aura donc la relation suivante :

$$g(\beta) + \alpha\tau = \frac{\dot{p}_e}{1 + p_e} \quad (3.35)$$

De plus on rappelle l'équation 3.33 :

$$x = \frac{\lambda k^\alpha e^{1-\alpha}}{\mu}$$

La direction du progrès technique  $\beta^*$  est donnée par la résolution suivante, avec  $\tau$  le taux de croissance du capital sur le sentier de croissance à long terme et  $\frac{\dot{e}}{e} = 0$  :

$$\lambda_0 \exp^{g(\beta)t} \exp^{\alpha\tau} = \mu_0 \exp^{\beta t} + const \quad (3.36)$$

Avec *const* une constante.

Du coup d'après l'équation 3.36, la condition nécessaire pour que  $\frac{\dot{x}}{x} = 0$  est que :

$$g(\beta) + \alpha\tau = \beta \quad (3.37)$$

Ainsi, avec l'équation 3.29 et l'équation 3.37, on a la relation suivante entre le taux de taxe  $p_e$  nécessaire pour que les émissions par tête soient nulles sur le sentier de croissance de long terme et le progrès technique qui repose sur le travail  $\beta$  :

$$\beta = \frac{\dot{p}_e}{1 + p_e}$$

Comme  $\beta$  est nécessairement positif, ceci signifie que sur le sentier de croissance de long terme, le taux de taxe croit de façon à ce que la contrainte sur les émissions soit saturée.

Or, d'après l'équation 3.8, on sait que :

$$\lambda\alpha\left(\frac{e}{k}\right)^{1-\alpha}f'(x) = (\delta + n + \rho)$$

On déduit que :

$$\begin{aligned} g(\beta) &= (1 - \alpha)\frac{\dot{k}}{k} \\ &= (1 - \alpha)\tau \end{aligned}$$

Par conséquent le nouveau sentier de long terme est caractérisé par la relation suivante :

$$\tau = \frac{g(\beta)}{1 - \alpha}$$

Or en tenant compte de l'équation 3.37 on peut réintroduire la valeur de  $\tau$  :

$$g(\beta) + \alpha\frac{g(\beta)}{1 - \alpha} = \beta$$

D'où :

$$g(\beta) = (1 - \alpha)\beta \tag{3.38}$$

Graphiquement, on peut représenter ce résultat sur la frontière des possibilités d'innovation dans le graphique 3.2 :

Le graphique nous donne une relation entre le taux de croissance du progrès technique portant sur le facteur composite capital-énergie  $g(\beta)$ , et le taux de croissance du progrès technique portant sur le travail  $\beta$ .

On voit donc que le progrès technique est d'autant moins neutre Harrodien que la part du capital dans l'agrégat capital-énergie est élevée. Si la part du capital dans cet agrégat tend vers l'unité, c'est à dire qu'il n'y a pratiquement pas d'énergie utilisée dans la fonction de production, alors le progrès technique tendra vers la neutralité au sens de Harrod. En effet, on se retrouve *presque* dans le cas canonique de Nordhaus (cas de deux facteurs de production, le capital et le travail) et la contrainte qui existe sur l'énergie n'affecte pratiquement plus la fonction de production<sup>6</sup>.

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<sup>6</sup>Mais on ne retrouvera jamais les résultats canoniques de Nordhaus, car nous avons montré que  $g(\beta) \neq 0$  nécessairement.



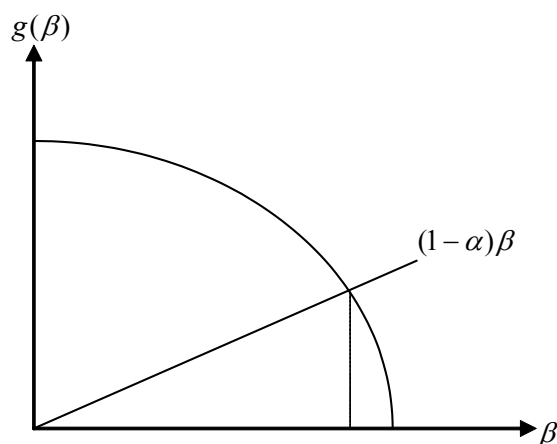


FIG. 3.2 – Taux de croissance du progrès technique sur le sentier de croissance de long terme en fonction de la part du capital dans l'agrégat capital-énergie.

En revanche, dans le cas où la part du capital dans l'agrégat capital-énergie est faible ou tend vers 0, dans ce cas le progrès technique tendra vers la neutralité au sens de Hicks. En effet, dans ce cas, le capital accumulable ne peut plus compenser la contrainte qui repose sur l'énergie, et le modèle est contraint par la non-reproductibilité du travail ainsi que par la contrainte énergétique. Le progrès technique tendra donc vers la neutralité au sens de Hicks. Notons tout de même ici, que si l'on se trouve dans le cas où on prend en compte les trois facteurs de production, ( $\alpha \in ]0, 1[$ ) le progrès technique ne sera ni neutre au sens de Harrod ou ni neutre au sens de Hicks. Ces neutralités ne seront atteintes que dans le cas où la part du capital est égale à 1, c'est à dire qu'il n'y a pas d'énergie dans la fonction de production, ou la part du capital tend vers 0 c'est à dire qu'il n'y a pas de capital dans la fonction de production.

Remarquons, que la contrainte de non reproductibilité du travail est prépondérante, dans le sens où, au maximum, le progrès technique *tendra* vers la neutralité au sens de Hicks (mais ne l'atteindra pas), et ne sera jamais plus forte en faveur de l'agrégat, et ce, quel que soit le degré de la contrainte énergétique<sup>7</sup>. Le progrès technique portant

<sup>7</sup>Nous n'avions pas donné de valeur à la contrainte énergétique.

sur le travail sera toujours plus fort que celui portant sur l'agrégat capital-énergie, si  $\alpha \in ]0, 1[$ .

De plus, il est important de noter que dans l'équation 3.38 la valeur de la contrainte énergétique  $\bar{e}$  n'apparaît pas. La direction du progrès technique ne dépend pas de la valeur de la contrainte énergétique.

**Proposition 7** *La direction du progrès technique n'est pas dirigée par la valeur de la contrainte énergétique mais seulement par la part du capital dans l'agrégat capital-énergie.*

**Proposition 8** *Sur le sentier de croissance de long terme, dans le cas où il existe une contrainte sur l'énergie, le progrès technique ne peut plus être neutre au sens de Harrod. Il repose d'autant plus sur l'agrégat capital-énergie que la part du capital dans cet agrégat est grande dans la fonction de production. Dans le cas où cette part est très proche de l'unité, le taux de progrès technique tend vers la neutralité au sens de Hicks.*

**Proposition 9** *Sur le sentier de croissance de long terme, quelle que soit la valeur de la contrainte sur l'utilisation d'énergie, le progrès technique sera toujours plus fort sur le facteur non reproductible que sur l'agrégat capital-énergie.*

### 3.4 Conclusion

Nous avons, dans ce chapitre cherché à étendre le modèle de Nordhaus, pour prendre en compte dans un premier temps un troisième facteur de production, l'énergie. Nous montrons que dans le cas où il n'existe pas de contrainte sur l'utilisation d'énergie, l'économie croît sur le sentier de croissance de long terme au taux de croissance  $h$ , qui est le taux de croissance du progrès technique. De plus le progrès technique repose uniquement sur le facteur non reproductible, le travail. Ainsi, nous confirmons le résultat canonique de Nordhaus dans le cas d'une fonction de production à trois

facteurs incluant l'énergie. Nous montrons de plus, que dans le cas, où l'élasticité de substitution entre l'agrégat capital-travail et le travail est inférieure à 1, il existe un unique équilibre stationnaire qui satisfait les conditions nécessaires d'optimisation.

Nous cherchons ensuite à déterminer comment la direction du progrès technique peut être affectée dans le cas où il existe une contrainte sur l'énergie. Nous introduisons, dans le modèle de référence, une contrainte sur l'utilisation d'énergie et montrons que dans ce cas, le progrès technique ne peut plus être neutre au sens de Harrod, mais il dépend de la part du capital dans l'agrégat capital-énergie de la fonction de production. Plus cette part tend vers l'unité, c'est à dire, plus le capital dans l'agrégat capital-énergie est fortement utilisé dans la production, plus le progrès technique tend vers la neutralité au sens de Harrod. En effet, nous retrouvons les résultats du modèle canonique de Nordhaus et le travail, non reproductible, contraint l'économie. Dans le cas où  $\alpha$  tend vers 0, c'est à dire que le capital n'est pratiquement pas utilisé dans la fonction de production, alors le progrès technique tendra vers la neutralité au sens de Hicks. En effet, le capital accumulable ne pourra compenser que de manière minimale les contraintes reposant sur l'énergie, et la fonction de production est donc contrainte par le travail et l'énergie. Nous montrons de plus que la valeur de la contrainte énergétique ne joue aucun rôle sur la direction du progrès technique. Enfin, nous montrons que le progrès technique sera toujours plus fort sur le travail que sur l'agrégat quelle que soit la valeur de la contrainte énergétique.

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## Chapitre 4

# A Forward Looking CGE Model for the French Economy with Endogenous Technological Change

## 4.1 Introduction

In the first three chapters of this thesis, we discussed the effects of including technological change in energy-economy models. In the first chapter, we made an overview of the different methods for modeling technological change in energy-economy models, noting that technological change can be modeled as an exogenous or an endogenous process. In the second chapter, we constructed a CGE model for the French economy, where technological change is modeled as an exogenous process and we introduced an environmental constraint, the French National Allocation Plan. We showed that in this framework firms may react to energy constraints through input substitutions only, and we detailed these substitution effects. In the third chapter, we showed, however, through a simple theoretical model that it is incorrect to assume that an environmental constraint has no impact on technological change.

Technological change can be defined as the process through which a same quantity of inputs in a production function, can yield an increased quantity of output. Similarly, technological change allows a level of output to be unchanged following a reduction in the use of inputs. "Induced" technological change, is the process by which technological change responds to a constraint in the model, i.e. it is therefore "induced" or determined by the constraint, and not exogenously determined.

Our goal in this chapter is to describe a method by which we model induced technological change, in a forward looking general equilibrium framework, where technological change can be a process influenced by an energy constraint. We base this last chapter on the conclusions of the three previous chapters. We take note of the shortcomings of modeling technological change as an exogenous process and we allow the firms to react to emission constraints through the process of technological change (which was not possible in the model of the second chapter)<sup>1</sup>. We show how taking ITC into account

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<sup>1</sup>We do not specifically assess the direction of technical change in this framework. Indeed, in this

in projections, influences the model's results.

Introducing endogenous technological change in GEMs has been the aim of many previous papers (see for example Goulder and Mathai (2000), Goulder and Schneider (1999), Nordhaus (2002), Sue Wing (2001), Fougereyrollas et al (2001) and for an overview on the different modeling methods of technological change in different model types see Löschel (2001). The first to model induced technological change through the stock of knowledge approach, were Goulder and Schneider (1999). In their specification, knowledge as well as knowledge services are firm specific.

In this chapter, we modify some of Goulder and Schneider's fundamental hypotheses and we introduce induced technological change as the consequence of the accumulation of a "generic" knowledge factor, accessible to the economy as a whole, not firm specific, the services of which will be demanded by firms, in the same way that they do for any input to production. The main innovation here therefore lies in the fact that we describe a method to calibrate a forward looking model on a modified SAM where Research and Development (R&D) is explicitly described in the demand matrix, and Human Capital is accumulated each year due to R&D efforts (see Sue Wing (2001)) the services of which are detailed in the factor matrix<sup>2</sup>. We follow the theory of endogenous growth and build a forward looking CGE model, where two stocks of capital (human capital and physical capital) grow over time on the balanced growth path at the rate of growth of the economy  $\gamma^3$ . Indeed, we suppose that the French economy is on a Balanced Growth Path (BGP) since 1995, all quantities in the economy therefore growing at the same growth rate.

In the following section we define the theoretical mechanisms of the "stock of knowl-

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chapter, we suppose that technical change is Hicks neutral, in the sense that it affects the productivity of all factors in the same way. We show however, that the intensity or rate of technical change depends on the value of the emission constraint.

<sup>2</sup>This information is not found in a normal SAM.

<sup>3</sup>We suppose that the growth rate of the French economy, in both versions of the model, with and without ITC, is 1% per year.



edge approach", and the specifications of a model on a BGP. We then define a Social Accounting Matrix and its construction, as well as the necessary changes one needs to implement in order to induce technological change in the model. We then describe the data and methods we used for the extraction of an estimation of human capital from the SAM, as well as how we allowed the model for France to grow on a balanced growth path. Finally, we implement the National Allocation Plan, and study the impacts of this constraint on the model with Induced Technological Change.

## 4.2 Technological Change in Energy-Economy Models

As our paper seeks to define the method we used for inducing technological change in a CGE framework, we will note briefly once more the different methods of modeling technological change in this framework alone. Indeed, there are different methods for modeling technological change in applied models and we give an overview of these different techniques whether exogenous or endogenous, and for all types of models in the first chapter of this thesis.

As seen in chapter 1, according to the modeler's choice, technological change can be modeled as "exogenous", or "endogenous". Modeling technological improvement as an "exogenous" process, suggests that technological change does not respond to any price changes, or any constraints, whether economic, or environmental, and is not affected in any way by any sort of policy. It in fact simply leads the industries, sectors, and the economy to follow a prespecified (constant or sometimes linear time) trend, where inputs to production can become more and more efficient over time.

On the contrary, technological change can be affected by policy constraints, or may react to price changes, when it is modeled as an "endogenous" process. Its rate and direction, however, depend on the way it has been modeled, and is often linked to

the decision of firms to invest in research and development (R&D) in response to new constraints.

The methods we cite briefly here fall into one or the other of these two categories.

The most common method to modeling technological change as an exogenous process, is through the use of an "Autonomous Energy Efficiency Improvement" parameter (AEEI). Backstop technologies, however, are also widely used, but more often in partial equilibrium models. Modeling technological change as an exogenous process supposes that it is not responsive to any policy or price constraints, and just kicks in, at a predetermined time.

Technological change may also be modeled as an endogenous process, through "learning by doing", or the "stock of knowledge approach", both of which we have had a close look at, in the first chapter of our thesis. In this case, endogenous technological change will allow the model to react to an environmental or economic constraint, with a goal to lessen the constraint's grip, and reduce the costs of compliance to an emission constraint. The stock of knowledge approach allows for technological change to be induced following the introduction of an emission constraint.

It is often expected, that when technological change is modeled as an induced process, then an environmental constraint in itself is the solution to the negative economic effects it might bring. In this paper, we will seek to show that such a statement is not necessarily true.

## 4.3 Induced Technological Change and the Stock of Knowledge Approach

### 4.3.1 The Inducement Process : a Description of the Dynamics of the Stock of Knowledge Approach in our Framework

To model the process of induced technological change in a CGE model, we modify a version of a CGE model for France, calibrated on the year 1995 the description of which is found in the second chapter of this thesis<sup>4</sup>. We create a forward looking version of this model, with two stocks of capital, human capital and physical capital that grow on a balanced growth path at the rate of growth of the whole economy  $\gamma$  (see Barro et Sala-i-Martin (1995) for the basics of endogenous growth theory).

To our knowledge, Goulder and Schneider (1999) is the first published work where induced technological change is modeled in a CGE model, using this concept of a stock of knowledge approach. In their paper, two sorts of knowledge are specified. One is appropriable knowledge, that is to say, each firm owns their own stock of knowledge, that is increased by investments in research and development. The other one, is spillover knowledge, which is the result on the stock of knowledge of other firms, of the investment in R&D of one specific firm. In this specification firms can react to a new environmental constraint by increasing their investments in R&D, leading to an increase in their stock of knowledge the following year, the services of which they allocate so as to minimize their net present cost of production. Therefore, the way in which firms allocate their knowledge services depends on the different price variations deriving from the constraints, and therefore leads to sectoral productivity differentials.

While detaching our work from Goulder and Schneider (1999), we propose a new

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<sup>4</sup>As a means of simplicity, and in order to not create interferences in the model's results we here do not address the question unemployment, and suppose that the labor market is at the equilibrium.

method to account for the inducement mechanism of technological change, considering an approach where human capital is a general economy-wide stock from which flow knowledge services that are allocated over firms according to their demand for it, and according to its price.

In the induced technological change version of our model for the French economy, we suppose that, similarly to the generalized stock of physical capital, the economy also possesses a generalized stock of knowledge or human capital, which, as opposed to Goulder and Schneider's model, is not firm specific. Our model therefore has two stocks of capital, physical capital and knowledge capital, that grow over time with investments. Investments in physical capital, increase the stock of physical capital, while the stock of knowledge is increased by investments in research and development. These two stocks of capital, are both subject to depreciation rates,  $\delta_h$  for human capital and  $\delta_k$  for physical capital. In the same way that capital services flow from the stock of physical capital according to a rate of return, knowledge services flow from the total stock of knowledge, and are allocated to the different sectors according to the market clearance condition. These knowledge services and capital services enter the production function of the different sectors as inputs, in the same way that the other tangible inputs do.

Therefore, when firms are confronted with an economic or environmental constraint, technological change in our specification will be induced. Technological progress derives from the knowledge services or human capital services  $HS_t$ , that flow from the accumulated stock of knowledge in the economy  $H_t$ , in the same way that capital services flow from a generalized stock of capital. These services are used as inputs in the production function of all sectors. Knowledge services may simply be seen as an "intangible" asset that enters the production function, in the same way that "tangible" inputs such as capital, labor, materials or energy do. In this case, the intangible knowledge services will increase the efficiency of the tangible inputs, as the increase in the use of knowl-

edge services leads to an increase in total output, while total tangible inputs remain unchanged. This is precisely the definition of technological change.

Indeed, on the demand side of the economy, firms facing an environmental constraint will react through two different channels. They can choose either to engage in a substitution process between different tangible inputs of production (capital, labor, materials and energy), or choose to "innovate". The process of innovation (or process of technological change) is simply determined by an increase in firms' demand for knowledge services (the intangible input) relative to the demand for all the usual tangible inputs such as labor, capital, materials and energy, thus leading to a reallocation of the tangible inputs to production and affecting the total output. These knowledge services, that firms compete for as inputs to their production, derive from the stock of human capital which is increased each year through investments in research and development. Usually, however, firms will choose to engage simultaneously in both types of substitutions<sup>5</sup>.

Within the realms of our fully dynamic model, we show how Hicks' (1932) innovation theory whereby changes in the relative prices of factors, will lead to innovations, functions when technological change is modeled through the stock of knowledge approach.

### 4.3.2 A Dynamic CGE Model for the French Economy

In this section, we define the key equations of the model, such that human capital services, as inputs to production, and investments in R&D are accounted for.

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<sup>5</sup>As these two types of types of substitutions are the fundamental mechanisms of the model, modeling the French economy with technical change defined as an exogenous process allowed us to pinpoint the specific mechanisms that determine the substitution process between the tangible inputs. In this chapter, we will now focus on the induced technical change process, namely the substitution process that takes place between tangible goods and the intangible good (knowledge services) in the face of an environmental constraint.

### The Production Function

As defined earlier, technological change in this model, is based on the notion of substitution between tangible inputs and the intangible input. Formally, the intangible knowledge services may enter the production function as a substitute to the tangible inputs (see equation 4.1). Human capital services are introduced into the firm  $i$ 's production function as inputs related to all other tangible inputs through a Constant Elasticity of Substitution relation. In our specification, in order to account for the two possible reactions of firms to an economic or environmental constraint, namely substitutions between tangible inputs or innovation (substitution of human capital services to tangible inputs) we determine the production function similarly to Goulder and Schneider (1999) as follows with  $i = (1 \dots n)$  and at a time  $t$  :

$$\left\{ \begin{array}{l} y_i = \left( \alpha_{KLEM,i} KLEM_i^{1-\frac{1}{\sigma_Y}} + \alpha_{HS,i} HS_i^{1-\frac{1}{\sigma_Y}} \right)^{\frac{1}{1-\frac{1}{\sigma_Y}}} \\ \alpha_{KLEM,i} + \alpha_{HS,i} = 1 \end{array} \right. \quad (4.1)$$

$HS_i$  is defined as the inputs of human capital services that are related to the capital-labor-energy-materials bundle through a constant elasticity of substitution  $\sigma_Y$ <sup>6</sup>. In this case, when human capital services increase over time, all else being equal, then the production of good  $i$  will increase. Such an increase can be assimilated to a Hicks-neutral technological progress simply because the efficiency of all tangible factors increase over time, through the increase of human capital services - the intangible input.  $KLEM$  is a CES function of the bundle of tangible inputs namely capital services, labor, energy and materials. This specification is defined in more detail in the second chapter of this thesis. Formally, one can define :

$$\left\{ \begin{array}{l} KLEM_i = \left( \alpha_{ME,i} ME_i^{1-\frac{1}{\sigma_{klem}}} + \alpha_{KL,i} (KS_i^k L_i^{1-k})^{1-\frac{1}{\sigma_{klem}}} \right)^{\frac{1}{1-\frac{1}{\sigma_{klem}}}} \\ \alpha_{ME,i} + \alpha_{KL,i} = 1 \end{array} \right. \quad (4.2)$$

We here note  $y_i$  as the production of the good  $i$ . In the  $KLEM$  bundle, we define  $a_{ME,i}$

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<sup>6</sup>The elasticity of substitution between tangible inputs and the intangible input, is the same for all sector  $i$ .

as the share of  $ME_i$  (the materials-energy bundle), and  $\alpha_{kl,i}$  as the share of the capital-labor bundle in the production function of the  $i$  sector.  $KS_i$  and  $L_i$ , are respectively the quantity of capital services and labor used in the production of the good  $i$ . We suppose that capital services and labor are linked together through a Cobb Douglas specification,  $k$  being the share of capital services in the Cobb Douglas function. We define  $ME_i$  as the quantity of the materials-energy bundle used in the production of the good  $i$ . In our specification the materials bundle  $M_i$  is a bundle of the output of all goods produced by all the firms of the economy and by the rest of the world. Indeed, we suppose that firms use the production of other firms as inputs to their production. Finally  $\sigma_{klem}$  is the elasticity of substitution between the capital services-labor bundle and the energy-materials bundle<sup>7</sup>.

We suppose the sum of the shares of inputs to production to be equal to one in order to render constant returns to scale.

In this general equilibrium model, producers maximize their profits subject to the production function, and therefore determine their demands for each intermediate input. The program of a producer of the good  $i$  is the following :

$$\left\{ \begin{array}{l} \text{Max}_{y_1, \dots, y_n, E_i, M_i, KS_i, L_i, HS_i} (p_i y_i - TC) \\ \text{s.t. } y_i = \left( \alpha_{KLEM,i} KLEM_i^{1-\frac{1}{\sigma_Y}} + \alpha_{HS,i} HS^{1-\frac{1}{\sigma_Y}} \right)^{\frac{1}{1-\frac{1}{\sigma_Y}}} \end{array} \right. \quad (4.3)$$

We define  $p_i$  as the price of the output  $i$ , and  $TC$ , the total cost of the inputs to production. Through this maximization program, each producer seeks to determine the quantity of inputs of material goods, energy goods, capital services, labor and human capital services that allow for profit maximization. There should be exact equivalence between supply and demand on the market for each good. This allows for the necessary market clearance fundamental to all general equilibrium models.

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<sup>7</sup>The values of the elasticities of substitution are found in the Annex A of this chapter.

### A Dynamic Model on a Balanced Growth Path

Fully-dynamic models are particularly useful in order to assess the dynamics of policy reforms, and in our case of an emission constraint. In order to be able to calibrate the dynamic model, we suppose that the French economy, is on a balanced growth path since 1995<sup>8</sup>, where all activities and assets increase at the rate of growth  $\gamma$  (Barro and Sala-i-Martin 1995), which is the rate of growth of the economy. Specifically, both stocks of capital increase at the same rate of growth  $\gamma$  on the balanced growth path. We can therefore derive the following equations 4.4 :

$$\begin{aligned} K_{t+1} &= (1 + \gamma) K_t \\ H_{t+1} &= (1 + \gamma) H_t \end{aligned} \tag{4.4}$$

With  $K_t$  the stock of physical capital and  $H_t$  the stock of human capital in the economy.

$$\begin{aligned} K_{t+1} &= I_t + (1 - \delta_k) K_t \\ H_{t+1} &= R_t + (1 - \delta_h) H_t \end{aligned} \tag{4.5}$$

The stock of physical capital  $K_t$  grows each year with investment in physical capital  $I_t$ , and is discounted by the physical capital's rate of depreciation,  $\delta_k$ . Similarly, the stock of human capital  $H_t$  grows each year with investments in research and development  $R_t$ , and is discounted by the human capital's rate of depreciation<sup>9</sup>,  $\delta_h$ <sup>10</sup>. Taking

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<sup>8</sup>1995, is the year on which the model is calibrated.

<sup>9</sup>Although the stock of knowledge cannot "vanish" in the same way as physical capital can (through the process of "wear and tear" or the simple obsolescence of older physical capital due to the introduction of new and more efficient capital), human capital stocks also depreciates over time. It can be the result of the further introduction of new and more accurate knowledge, such that the older knowledge becomes obsolete, or, when no new human capital is introduced, a continuous alteration of the productive environment can be the cause of a lesser need of the older knowledge.

More precisely, in the case of patents, the depreciation rate of human capital can be the consequence of the firms' continuous efforts in terms of R&D and therefore the introduction of new patents will make a previous patent obsolete. Another justification lies in the forced closure of a patent after some years, when it must be open to the public knowledge.

Postulating a depreciation rate for human capital, is contrary to what Goulder and Schneider pose as a hypothesis. Indeed, they suppose that human capital does not depreciate over time, but note that this hypothesis is an arbitrary decision of theirs.

<sup>10</sup>There is no theoretical reason why the two depreciation rates of physical capital and human capital



into account the two equations 4.4 and 4.5, we determine the investment in physical capital at time  $t$ ,  $I_t$ , and the investment in research and development at time  $t$ ,  $R_t$ , on the balanced growth path as growing according to the following equations :

$$\begin{aligned} I_t &= (\gamma + \delta_k) K_t \\ R_t &= (\gamma + \delta_h) H_t \end{aligned} \quad (4.6)$$

Moreover, the production of each sector in our model, also grows on the steady-state at the rate of growth  $\gamma$ . Formally,

$$Y_{t+1} = Y_t(1 + \gamma)$$

**Physical Capital Services or Returns to Capital** The physical capital stock can therefore be rewritten from equation 4.6 as follows :

$$K_t = \frac{I_t}{(\gamma + \delta_k)} \quad (4.7)$$

According to OECD Statistics Working Paper 2003/6, as physical capital is an asset of an economy, the cumulative stock of all the past investments in physical capital, will generate a flow of productive services, which are called "capital services". In our case investments  $I_t$  increase the stock of physical capital  $K_t$ , from which flow "physical capital services". These capital services, are considered the only measurable capital input to production and productivity analysis, and derive from the stock of physical capital. They are the value that we find in a Social Accounting Matrix. The OECD Statistics Working Paper 2003/6 provide a good explanation of what capital services are :

"Take the example of an office building. Service flows of an office building are the protection against rain, the comfort and storage services that the building provides to personnel during a given period" (OECD Statistics Working Paper 2003/6).

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should be the same. Therefore, we assume their values to be different.

As we are initially on a steady-state, it is important to note that there are *two* prices for capital as capital may be bought or rented. There is a purchase price of capital at a time  $t$ ,  $p_t^K$ , which is the price at which new capital is bought, and a rental price of capital  $r_t^K$ . Indeed the capital stock in an economy is determined by the total value of the capital services (or total capital returns) and the rental rate (or rate of return) of capital stocks, which is the sum of the interest rate of the economy and the rate of depreciation of the capital stock (for a detailed discussion of the definition and determination of the rate of return of capital, see Paltsev (2004) and Rutherford et al. (2002)<sup>11</sup>). With  $KS_t$  the total value of capital services or the total capital returns for a given period used each year as inputs into production, one can derive the following equation, with  $r_k$  the interest rate :

$$KS_t = r_t^K K_t = (r_k + \delta_k)K_t \quad (4.8)$$

Equalizing the equations 4.7 and 4.8 allows us to derive the value of the interest rate  $r_k$  necessary for capital to grow on a balanced growth path :

$$\frac{KS_t}{(r_k + \delta_k)} = \frac{I_t}{(\gamma + \delta_k)} \quad (4.9)$$

and

$$r_k = (\gamma + \delta_k) * \left( \frac{KS_t}{I_t} \right) - \delta_k \quad (4.10)$$

The interest rate  $r_k$  necessary to allow physical capital to grow on the balanced growth path, is therefore a function of the growth rate of the economy  $\gamma$ , the depreciation rate of physical capital  $\delta_k$ , the physical capital services  $KS_t$  and of the investment in physical capital  $I_t$ .

**Knowledge Services** Similarly, one can derive from equation 4.6 that human capital in time  $t$  can be rewritten :

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<sup>11</sup>As this equality has already been determined in Paltsev (2004) and Rutherford (2002) we do not derive the equations once more.

$$H_t = \frac{R_t}{(\gamma + \delta_h)} \quad (4.11)$$

Similarly to physical capital services, human capital services  $HS_t$  flow from a stock of general knowledge  $H_t$ , and are introduced in the production functions as inputs to production. We note here again, the rate of return of human capital  $r_t^H$ , as the sum of the human capital depreciation rate  $\delta_h$  and the interest rate  $r_h$  :

$$HS_t = r_t^H H_t = (r_h + \delta_h)H_t \quad (4.12)$$

Equalizing equations 4.11 and 4.12 allows us to derive the value of the interest rate  $r_h$  necessary for human capital to grow on a balanced growth path :

$$\frac{HS_t}{(r_h + \delta_h)} = \frac{R_t}{(\gamma + \delta_h)} \quad (4.13)$$

and

$$r_h = (\gamma + \delta_h) * \left( \frac{HS_t}{R_t} \right) - \delta_h \quad (4.14)$$

The interest rate necessary to allow human capital to be on the balanced growth path, is therefore a function of the growth rate of the economy  $\gamma$ , the depreciation rate of human capital  $\delta_h$ , the human capital services  $HS_t$ , and the investment in R&D  $R_t$ .

**The Interest Rate** The key-point of this issue is that we must suppose the uniqueness of the interest rate,  $r$  for the economy to be on a balanced growth path. Assuming this uniqueness of interest rate, all the future prices of the model, in terms of present value, are discounted by the interest rate and are given by the equation 4.15<sup>12</sup> :

$$p(t) = p_0 \left( \frac{1}{1+r} \right)^t \quad (4.15)$$

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<sup>12</sup>On the balanced growth path, the discounted value of all future prices fall at the rate of the interest rate if this rate is constant. On the steady state growth path, all quantities (capital, labor, human capital, materials, output, etc...) grow at the rate of growth of the economy.

However, we have just determined the values of  $r_k$  and  $r_h$  allowing for physical capital and human capital to grow on the balanced growth path. Nothing ensures equality of these two interest rates. And, quite the contrary so, given the lack of accurateness of data, and in particular the different values of the depreciation rates. Therefore, for the economy to be on a balanced growth path (where physical capital and human capital increase at the same rate  $\gamma$ ), one must assure the following equality to ensure the uniqueness of the interest rate.

$$(\gamma + \delta_h) * \left( \frac{HS_t}{R_t} \right) - \delta_h = r = (\gamma + \delta_k) * \left( \frac{KS_t}{I_t} \right) - \delta_k$$

**Approximating an Infinite Horizon** Finally, in order to approximate an infinite horizon in our model, we follow the method proposed by Lau et al (2002) and followed specifically by Rutherford et al (2002). We first choose a final period that we note  $T+1$ , where we suppose that the value of physical capital and human capital assets satisfy the balanced growth constraints. With such a specification, the model is therefore decomposed into two periods, the first one going from  $t : 0 \rightarrow T$  and the next period going from  $t : T + 1 \rightarrow +\infty$ . In the second period we suggest that the economy is necessarily on a balanced growth path. Therefore, to solve the model in  $T + 1$  we assume that the increase in the investment in the terminal period in both human capital and physical capital is equal to the increase in production :

$$\frac{I_T}{I_{T-1}} = \frac{R_T}{R_{T-1}} = \frac{Y_T}{Y_{T-1}} = (1 + \gamma)$$

This equation is the called the *primal termination condition*.

In the following section we define what a social accounting matrix is and the methods we used to create a model for the French economy, on a balanced growth path, with two stocks of capital. Then, we define how we allowed for the uniqueness of the interest rate, through the modifying of the SAM, and the method of extraction of human capital considering the constraint of uniqueness of interest rate.

## 4.4 A Social Accounting Matrix

The model being a Computable General Equilibrium Model, it is calibrated on a Social Accounting Matrix (SAM). In order to present the changes we have undertaken, we here introduce the reader to a simplified SAM, and our naming of its different components. The specificities of a SAM rely in the fact that it is a snapshot of the economy in its balanced state. That is to say, for one given year, there is a "sink" for all "source", there is a demand for all supply. Formally this can be summed up in the very well known aggregate income accounting definition which follows :

$$Y = C + I + G + X - M$$

Where  $Y$  is the total production of the economy,  $C$  the final private demand,  $I$  investments in physical capital,  $G$  final public demand,  $X$  exports and  $M$  imports. Graphically, a very simplified SAM is represented as in table 4.1.

The first matrix, (upper left) is the "intermediary consumption matrix". We shall call this matrix  $\bar{X}$ . In this matrix we find the different values of all the goods that have been exchanged between industries during one given year. The intermediate consumption matrix is square, because we suppose that each industry (of which there are  $n$ ) produces one unique good  $j$  and uses, as inputs to its production, a share of all other produced goods  $i = 1..j...n$  (of which there are  $n$ ). Each small square  $\bar{x}_{ij}$  in this matrix therefore represents the value of interindustry transactions, i.e. the value of the goods produced by industry  $i$ , and sold to industry  $j$  as an input to  $j$ 's production. Since, the SAM is balanced, the sum over  $j$  of all the values in the row  $i$ , equals the sum over  $i$  of all the values in industry  $j$  (when  $j$  equals  $i$ ), that is to say, all that is produced by the industry  $i$  (column  $i$ ) will necessarily be used in the other sectors as intermediate inputs (row  $i$ ).

The second matrix, (upper right), is the "final consumption matrix". We shall call this matrix  $\bar{G}$ . This matrix represents the demand sectors of the economy. In

		J=1...n commodities				C I	
i:1...n							
		-	-	-	-	$\bar{X}_{ij}$	
Production factors	K					$\bar{V}_{Kj}$	
	L					$\bar{V}_{Lj}$	

TAB. 4.1 – A simple Social Accounting Matrix

this simplified SAM, all goods that are produced are either consumed (column C), or invested (column I)<sup>13</sup>. SAMs may differ in their precision, and some have more or less columns and/or rows according to the chosen disaggregation in the demand matrix. For example, instead of having one unique column  $C$ , for total consumption in the economy, some may have two columns : private consumption and public consumption. In this SAM,  $\bar{g}_{Ci}$  and  $\bar{g}_{Ii}$  are the value of the good  $i$  respectively consumed and invested during one given year.

The third and last matrix (lower left), is the "factor matrix". We shall call it  $\bar{V}$ . In this simplified SAM, there are only two factors of production, which are capital and labor. This matrix shows in what proportions the production factors are used in the economy, for the production of each industry. Therefore,  $\bar{v}_{kj}$  and  $\bar{v}_{lj}$  are the value of respectively capital and labor each industry  $j$  uses during a given year as inputs to production.

## 4.5 Extracting Human Capital Services and R&D from the SAM

### 4.5.1 The Extraction

In order to determine the effects of introducing technological change through the stock of knowledge approach in our CGE model for the French economy, we must determine the values of human capital services that are used in a given year, as inputs into the production of each sector  $i$ . Such values are not in fact found in a SAM, nor easily found in country statistics, as human capital services are indeed an intangible input. Direct measures of human capital services are available for very few countries, and there are many different methods to account for it in an economy. The measurement of human capital services is thus a complex task. Taking this into account, we determine

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<sup>13</sup>In this matrix you would also find the Export and Import columns.

an estimation of the value of human capital services from the SAM by using relevant information concerning investments in research and development and patent data for each sector. We then extract this estimated value of human capital services, that is embodied in the different cells of the interindustry transaction matrix, and thus modify the SAM.

### **Extracting Human Capital Services from the Interindustry Transaction Matrix**

In this section, we choose to consider initially the matrix of interindustry transactions,  $\bar{X}$ . We base our work on the assumption that, part of the value of any given interindustry transaction, is in fact the value of embodied R&D. Indeed, according to the United Nations' System of National Accounts (UN (1993)), research and development is defined as an expense or a current cost of production, and, in any case, is treated as an *intermediate input to production*. More precisely, specific work by André van den Berg, (Berg, van den, (2000)), seeks to assess the types of activities with which knowledge tends to be associated. Therefore, in terms closer to those that we have been using in this paper, van den Berg, identifies which cells in  $\bar{X}_{ij}$ , R&D is some share of.

Following these views our primary goal resides in defining what portions  $w_{ij}$  of the cells in  $\bar{X}$ , could represent human capital. With  $R$ , total known R&D expenditures in the economy, we therefore seek to determine  $w_{ij}$  such that :

$$R = w_{ij} * \bar{X}_{ij} \quad (4.16)$$

Let us consider a good  $\bar{x}_{i,j}$  that is sold from industry  $i$  to industry  $j$ . We simply derive the value of the good  $\bar{x}_{i,j}$  from the SAM. In our specification we assume that some share of the value of the good  $\bar{x}_{i,j}$  is in fact knowledge that is embodied in the good (see Griliches (1992) and his definition of "embodied spillovers"). We must therefore extract an estimation of the R&D embodied in this good  $\bar{x}_{i,j}$ , that is to say, we must determine the share of the value of this good that represents embodied R&D.



However, taking into account the fact that a SAM must at all times be balanced, as required by the law of supply and demand, all that is produced in the economy must be consumed / demanded, therefore the simple extraction of an estimation of R&D, must therefore be rebalanced by a reintegration of these values within the SAM through the creation of an additional column as well as an additional row (Sue Wing (2001)). Therefore, once the shares of R&D are extracted from the  $\bar{X}$  matrix, they are reintegrated in the SAM through the creation of an extra column in the  $\bar{G}$  matrix,  $\bar{g}_{Ri}$ , representing the demand for research and development in the economy, as well as through an extra row in the factor matrix,  $\bar{v}_{hi}$ , representing the value of human capital services used as inputs into the production of the different goods.

### **Extracting Human Capital Services from the Factor Matrix**

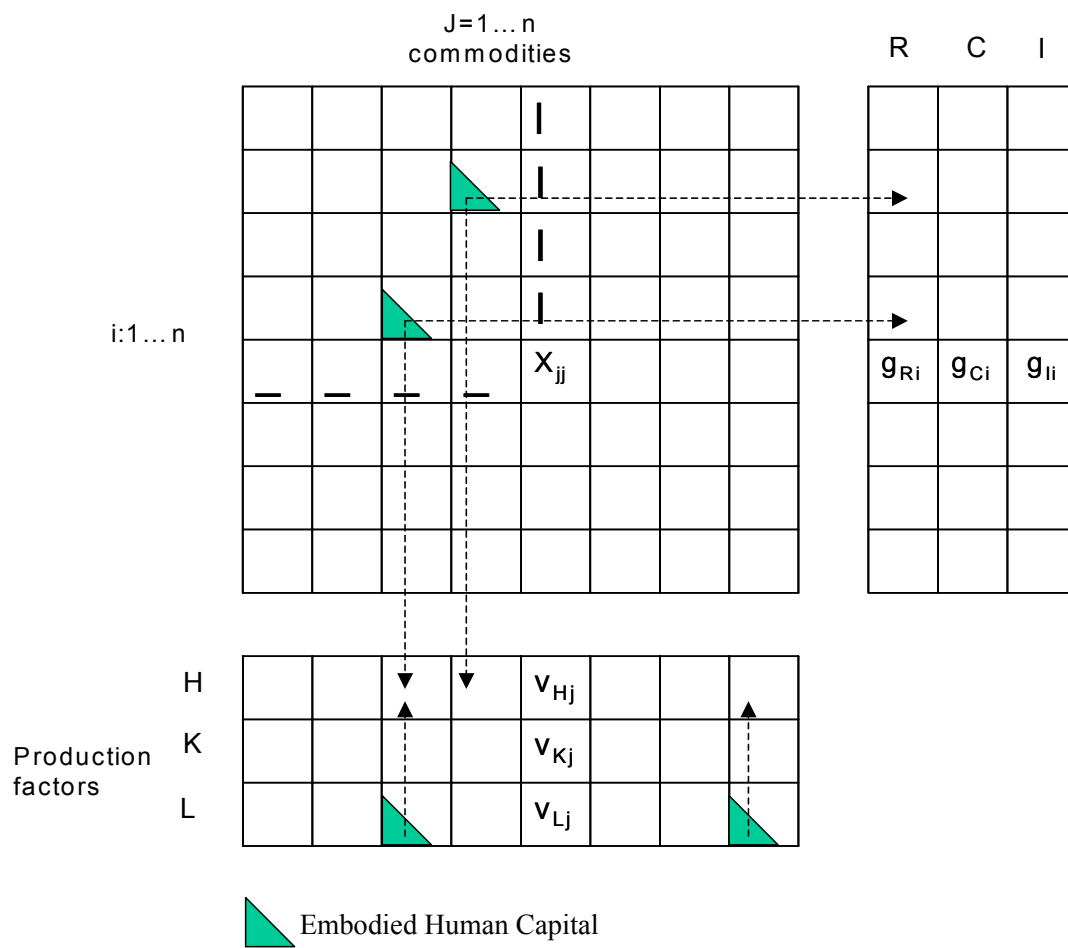
Human capital services are however not only found in the interindustry consumption matrix,  $\bar{X}$ , but can also be embodied in labor. Indeed, the SAM gives us the total value of all labor used in the french economy in 1995, with no information on the skills of the labor used. Using data on labor skills, we extract an estimation of human capital services embodied in labor, and by doing so, we will add the values of human capital services embodied in labor to the new row  $\bar{v}_{hj}$ , that has been compiled with the estimation of human capital services embodied in the interindustry transaction matrix. We therefore compile all human capital services that may be embodied in the SAM.

The new SAM once we have extracted estimates of human capital from the  $\bar{X}$  matrix and the  $\bar{V}$  matrix, would then look like the figure 4.2. Note however that the new values,  $\tilde{x}_{ij}$ , in the  $\bar{X}$  matrix are now necessarily smaller than those before extraction of R&D, and the values of  $\tilde{v}_{L,j}$  are smaller than those before the extraction<sup>14</sup>.

In this case, the aggregate income accounting definition is now modified as  $R$ , the investment in research and development, is now a demand in the final consumption

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<sup>14</sup>Note that after modifying the SAM according to this method, the sum of column  $j$  is still equal to the sum of row  $j$ , as the SAM is still balanced.



TAB. 4.2 – A Social Accounting Matrix with Extraction of Human Capital

matrix :

$$Y = C + I + R + G + X - M \quad (4.17)$$

## 4.5.2 Data and Sources for Extraction

In the previous section, we theoretically described how we meant to proceed to extract human capital services from a social accounting matrix. In this section, we describe the practical methods which we undertook in order to extract these estimated values.

First, we explain the methods of estimation and extraction of interindustry R&D spillovers embodied in the interindustry transaction matrix. Then, we determine how we approximate the value of human capital services that is embodied in labor, and extract it from the value of labor given in the factor matrix.

### Extracting Human Capital from the Interindustry Transaction Matrix

The first goal of our work was to seek to capture some mix of the two major R&D spillovers, namely "rent" and "knowledge" spillovers. Indeed, rent spillovers are directly related to economic transactions, meaning they occur when the prices of intermediate inputs do not reflect the quality improvements that follow from R&D investments. On the other hand, knowledge spillovers occur when the knowledge that is embodied in an industry's innovation contributes to other industries' innovation processes. Knowledge spillovers are not necessarily linked to interindustry transactions, as they can occur due to simple imitation (for a more detailed analysis of rent and knowledge spillovers see Van Pottelsberghe de la Potterie (1997)). However, Van Pottelsberghe de la Potterie suggests that :

"The ambiguity (in conceptually distinguishing between rent and knowledge spillovers) results from the fact that it is difficult to dissociate empirically rent spillovers from knowledge spillovers (..). First rent spillovers are

approximated through economic transactions which may also imply some transfers of knowledge. Second, the two types of R&D spillover might not be combined, but their respective profiles across industries might be similar".

These difficulties taken into account, we seek to capture a "mix" of rent spillovers (embodied in the value of the goods) and knowledge spillovers (approximated by the patent flows between industries) by following the method of P. Hanel (2000) for the creation of an interindustry technological matrix. Indeed, Hanel allocates R&D expenditures among different industries proportionally to the number of patents that an industry is granted and uses. Following his method, we build a matrix for France which is an estimation of the knowledge embodied in the  $\bar{X}$  of the SAM.

**The Patent Matrix** We base our calculations on information on international patenting and the Yale Technology Concordance made available by D. Johnson at Wellesely. We follow Hanel's method to create an estimation of an interindustry technological flows matrix. In the Johnson and Evenson Patent Set (JEPS), we use a series of matrices that determine the potential industries of manufacture (IOM) of patents, and the potential sectors of use (SOU) of these patents, for France which we aggregate<sup>15</sup>. The elements in the matrix  $P_{i,jk}$ , are the numbers of patents that were likely to be manufactured by the sector  $i$  (industry  $i$ , being the industry of manufacture), and that are likely to be used by the sector  $j$  (industry  $j$ , being the sector of use) and issued to firms from country  $k$  (in our case  $k$  is France). This matrix is in fact an estimate of the *likely* interindustry patent flows. Following Hanel's method, we compute a "patent output coefficient"  $p_{i,j,k}$  by dividing each elements of the row  $j$  of the matrix  $P_{i,jk}$  by the sum of all patents manufactured by the industry  $i$ . Mathematically, one may describe this as in equation 4.18 :

$$p_{i,j,k} = \frac{P_{i,j,k}}{\sum_j P_{i,j,k}} \quad (4.18)$$

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<sup>15</sup>Because, the dataset did not have data for 1995, we use the data available for France in this dataset, which dates back to the year 1993.

This calculation allows us to estimate in what way the R&D expenditures in the industry  $i$ , were "distributed" to the different user industries  $j$ . Indeed, the data from the French Ministry of Youth, Education and Research - 2004 (Ministere de la Jeunesse, de l'Education Nationale et de la Recherche (2004)), gives us precise estimates of the research and development expenditures per industry  $i$ , in 1995 in France, namely  $R_{i,k}$ . Thanks to this data, we estimate the way in which the research and development of one industry  $i$  "spills over" to all industries  $j$ , by simply creating a matrix of technology flows  $R_{i,j,k}$ . We define this matrix as in equation 4.19 :

$$R_{i,j,k} = R_{i,k} * p_{i,j,k} \quad (4.19)$$

This matrix is in fact the result of the "spreading" of research and development expenditures according to the patent profile for each sector<sup>16</sup>. We use this matrix to extract from the  $\bar{X}$  matrix, an estimation of the R&D that was embodied in the values of the goods transacted in France in 1995. We proceed to the extraction, using GAMS (General Algebraic Modeling System - Brooke et al (1996)). In order to complete the balancing of the SAM following the calibration, one R&D column is added to the  $\bar{G}$  matrix, and one human capital services row is added to the  $\bar{V}$  matrix. In this specification, the sum over all industries  $j$ , of human capital is necessarily equal to the sum over  $i$  of all R&D in the SAM<sup>17</sup>.

**Accounting for Negative Values in the  $\tilde{X}$  Matrix** In order for the extraction of human capital from the  $\bar{X}$  matrix to be meaningful, it is necessary that the values of research and development, given by the French research ministry, and spread over the industries through the use of the Johnson-Evenson patent data set, be in all cells

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<sup>16</sup>For the sectors of construction, transport and other market services, we had no data on the patent flows. We therefore were constrained to have to add a 1 in each of the rows of the patent matrix so as to spread the value of R&D in this sector. Without such change the model would not have calibrated, as there were values of R&D that had no patent counterpart.

<sup>17</sup>This equality follows directly from the way we just modified the SAM. Extracting values of human capital services from the interindustry transaction matrix and creating an extra column and an extra row in the SAM, does not unbalance it.

smaller than the initial values in the  $\bar{X}$  matrix. More precisely, we can only extract human capital services out of a cell where the value of the goods exchanged is greater than our estimation of the value of human capital services embodied in the cell<sup>18</sup>. If we do not account for that, the result will be the creation of a new matrix of interindustry transactions, where some cells have negative values<sup>19</sup>. In order to deal with this problem, we add a constraint in the GAMS code, that prohibits any extraction in one cell if the value of the estimated human capital for that cell is greater than the value of the interindustry transaction. The natural consequence is therefore that the summing up over  $i$  or  $j$  of the resulted matrix of human capital now differs slightly from the initial values of research and development spendings given by the French Research Ministry.

However, human capital services are not necessarily embodied only in the interindustry transactions. We suppose that it can also be embodied in the value of labor found in the SAM. Extracting human capital services from the factor matrix is indeed the second part of our work. In the following section we determine how we proceed for such an extraction.

### **Extracting Human Capital Services from the Factor Matrix**

The SAM for France in 1995, does not give any information on the decomposition of labor in the economy, i.e., does not precisely determine the amount of qualified and non qualified workers in the economy, nor the average wages of both these groups of workers. Additional statistics are therefore necessary to determine a proxy of human capital services embodied in labor<sup>20</sup>. We use data from the Ministère de la Jeunesse, de

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<sup>18</sup>This problem can occur considering the different sources of our data.

<sup>19</sup>In Social Accounting Matrices, all cells necessarily have either positive or null values. A negative value in a SAM does not have any economic signification (except for the IMPORT column, and the SUBSIDY row, which is a negative tax).

<sup>20</sup>While we are aware of the intricacies in the evaluation of human capital, we choose a relatively simple approach in measuring it, as its evaluation is not the goal of our paper. However, we do recognize that alternative measures or proxies of human capital have effects on economic growth (see Hanushek and Kimko (2000)). Further research should be undertaken concerning our measurement of

l'Education Nationale et de la Recherche (2004) to compute the number of researchers that were involved in research and development activities in 1995 in France. We multiply the number of researchers involved in R&D activities by the average wage of qualified workers<sup>21</sup>, and therefore obtain a "value of researchers" in million euros. We suppose that the value of these researchers can proxy the human capital services that are taken into account in the labor value row in the factor matrix, and we extract it from the labor row. In order to account for all human capital services in the economy, we add this estimation of human capital services to the value of human capital services that was extracted from the  $\bar{X}$  matrix<sup>22</sup>. By so doing we modify the SAM once more such that the value of labor in the economy represents only that of all workers that are not researchers engaged in research activities.

Therefore, the sum over  $j$  of all human capital services in the SAM is now not equal to the sum over  $i$  of all R&D in the economy.

### **A Necessary Rebalancing of the SAM**

Having extracted an estimation of human capital services from the interindustry transaction matrix as well as from the factor matrix, we create a new row in the factor matrix representing human capital services. We simply sum over the different sectors the values of human capital extracted from the  $\bar{X}$  matrix and the estimation of human capital extracted from the labor row. We also introduce a new column, representing investments in research and development, in the demand matrix of the SAM. These extractions and column / row creations however did not affect the balancing of the SAM, for the extracted estimated values of human capital were reentered into the

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human capital, for a more precise and justifiable approach to endogenizing technological change.

<sup>21</sup>We suppose that workers who have accumulated more human capital over their lifetime, through learning by doing, education attainment, or a higher than average number of years of school, have higher wages than those that have accumulated little human capital.

<sup>22</sup>Human capital services can also be embodied in the value of physical capital services determined in the SAM. Otto et al. (2005) for instance extract from the physical capital services row a proxy of human capital services which is the value of investment in information and communication infrastructure (ICT).

SAM to preserve the column / row balance.

However, we are seeking to develop a forward looking model for the French economy, therefore on a steady state. The model must thus be calibrated on a SAM that allows for the economy to be on a balanced growth path. A rapid computation of the interest rates that derive from the SAM's values of human capital services and physical capital services provides the economy with *two* different interest rates for both physical capital and human capital to grow on the balanced growth path. In order to solve this problem, we choose to keep the value of the interest rate that allows physical capital to be on the balanced growth path, given by the equation 4.10. We choose to do this for two reasons. First because the values in the SAM relative to physical capital services and investment in physical capital have not been modified by our extraction of human capital as they are the SAM's original ones. Second because the value of the interest rate we obtain is 6.2%, which is very close to its statistical value in 1995 (see Banque de France (1996))<sup>23</sup>. We, therefore, consider that the interest rate that is necessary for physical capital to be on the steady state is the interest rate of the whole economy.

However, we know that the interest rate necessary for human capital to grow on the balanced growth path is given by the following equation :

$$r_h = (\gamma + \delta_h) * \left( \frac{HS_t}{R_t} \right) - \delta_h$$

The investment in R&D,  $R_t$  is thus defined by the equation 4.20

$$R_t = \frac{(\gamma + \delta_h)}{(r_h + \delta_h)} HS_t \quad (4.20)$$

However, the value of investment in R&D that necessary for human capital to grow on the balanced growth path is given by the relation 4.21, where  $r_k$  is the value of the interest rate that is necessary for physical capital services to grow on the balanced

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<sup>23</sup>In our model, the interest rate is that of 6,2% per year, while it was 6,5% a year in 1995 for a 15 year loan to the government.



growth path and is determined by the equation 4.10 :

$$R'_t = \frac{(\gamma + \delta_h)}{(r_k + \delta_h)} HS_t \quad (4.21)$$

We therefore modify the new SAM, by increasing all the values of the cells in the R&D column by the ratio  $\frac{R'_t}{R_t}$ .

This ad-hoc modification of the column of research and development then leads the new SAM to be unbalanced.

To rebalance the SAM, we minimize the square of the deviation between all the cells in the initial unbalanced SAM and all the cells in the new balanced SAM<sup>24</sup>. The new SAM we obtain is now rebalanced. However, in the process of rebalancing, the values of the human capital services and physical capital services are then very slightly modified, which leads once more to a very slight difference in interest rates<sup>25</sup>. A second rebalancing of the SAM is necessary, constrained by the equations 4.22, to lay down the final balanced SAM, that allows the whole economy to grow on a balanced growth path. We use GAMS and the solver CONOPT<sup>26</sup> to rebalance the SAM, as the minimization of the square of the deviation between all the cells in the initial SAM and all the cells in the new SAM is a non linear programme.

$$\begin{aligned} r_k &= (\gamma + \delta_h) * \left( \frac{HS''_t}{R''_t} \right) - \delta_h \\ r_k &= (\gamma + \delta_k) * \left( \frac{KS''_t}{I''_t} \right) - \delta_k \end{aligned} \quad (4.22)$$

The complete model code is in the Annex E of this chapter.

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<sup>24</sup>We are seeking to have a SAM that is the closest possible to the original one.

<sup>25</sup>The difference is only noticeable at the 10e-4. However, in the creation of the forward looking model, even such a slight difference leads to computational errors.

<sup>26</sup>CONOPT is a large-scale non linear optimization (NLP) solver developed by ARKI Consulting and Development A/S.

## 4.6 Induced Technological Change and the NAP

We now have built a fully-dynamic model, with two stocks of capital, physical and human capital that grow on the balanced growth path at rate of growth of the economy. Technological change is induced by the stock of knowledge approach, whereby, industries facing an environmental constraint, may choose to demand more human capital services, which are intangible inputs, and therefore increase the efficiency of the tangible inputs (capital services, energy, labor and materials). In this section, we will seek to determine the effects of induced technological change on the results of the model we just built, in the case of the introduction of an emission constraint similar to the French National Allocation Plan.

For the sake of our analysis, we construct two forward looking models, one with Induced Technological Change and one with no ITC<sup>27</sup>. The goal of our work will be to compare the behaviors of the two models in the case where they are constrained by the same constraint. We will therefore seek to address how taking into account Induced Technological Change in a CGE framework changes the model's results.

### 4.6.1 Business as Usual

In this section we present the Business as Usual trends in emissions in the two versions of the model, one with ITC and the other without ITC. In the following graph, we see that total emissions will grow and reach in 2025, end of our simulation period, approximately 132 Mega Tons of Carbon (MtC). The model predicts business as usual emissions that are very close to those predicted by the Observatoire de l'Énergie (2004)<sup>28</sup> (see Annex A2).

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<sup>27</sup>In the forward looking version of the model without ITC, we simply do not extract any estimation of human capital services from the SAM, and we calibrate the model on the initial SAM. We suppose that the economy grows at the same rate of growth as the one chosen for the ITC version of the model.

<sup>28</sup>The Observatoire de l'Énergie (2004) predicts total emissions to reach 129 MtC in 2020, while our models predict France's total emissions to reach 126 MtC that year.

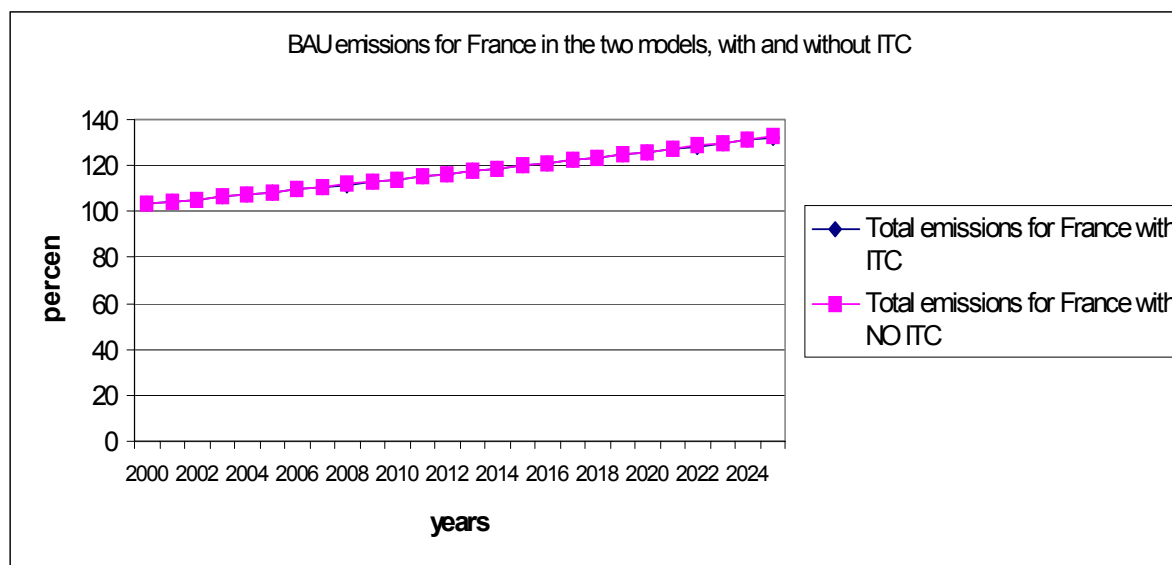


FIG. 4.1 – Business as Usual emissions for France in the case of ITC and NO ITC

In the business as usual scenario we split the seventeen sectors between covered and non covered sectors<sup>29</sup>. Within the covered sectors, we identify energy producing sectors and energy intensive sectors. The following table shows how energy producing sectors, energy intensive sectors, and non covered sectors' emissions grow on the baseline.

In the baseline scenario, the demand for human capital services grows over time, as the economy grows. In the same way, the demand for physical capital services grows over the study period. This reflects the fact that the stocks of human capital and physical capital accumulate over time and are a driving force of the economy. The two following graphs define the business as usual trends of human capital services (see figure 4.3) and physical capital services (see figure 4.4) both in the cases of NO ITC and ITC<sup>30</sup>.

Physical capital services grow according to the same trend in both models for the

<sup>29</sup>We consider covered sectors, all sectors that will be constrained by the National Allocation Plan (NAP), and non covered sectors, all sectors that will not be constrained by the NAP.

<sup>30</sup>In the case where ITC is not taken into account, the SAM is not modified such that human capital services are extracted. Therefore, we cannot present how human capital services evolve over time in the BAU case when there is NO ITC.

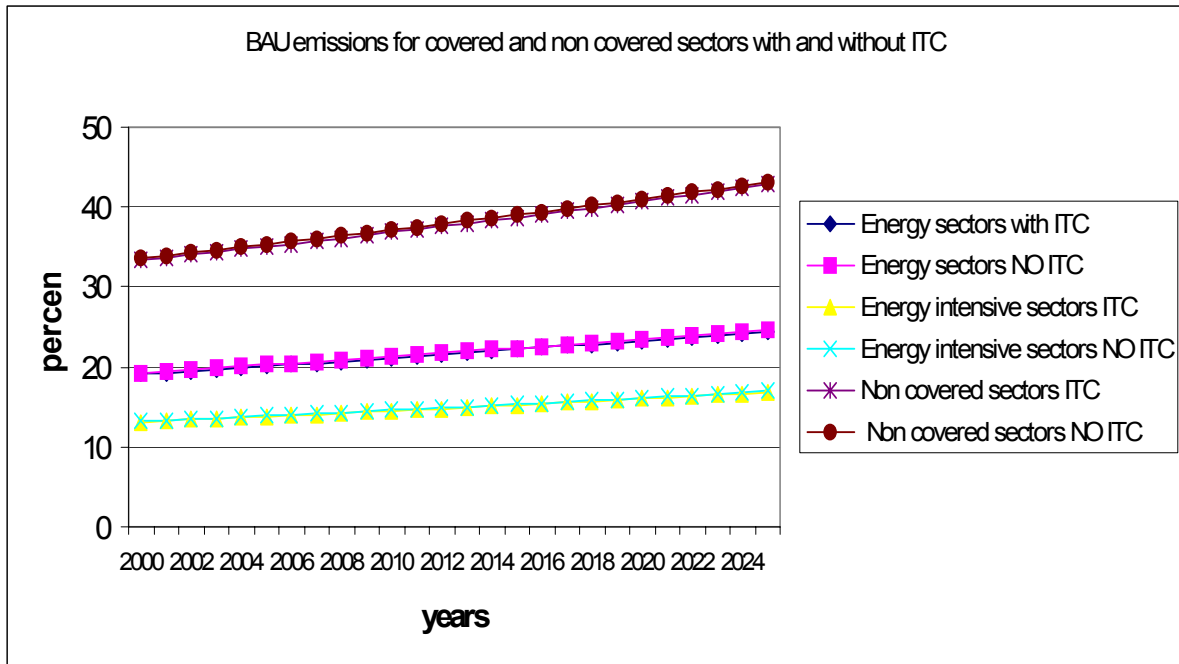


FIG. 4.2 – Business as usual emissions for covered and non covered sectors with ITC and with NO ITC

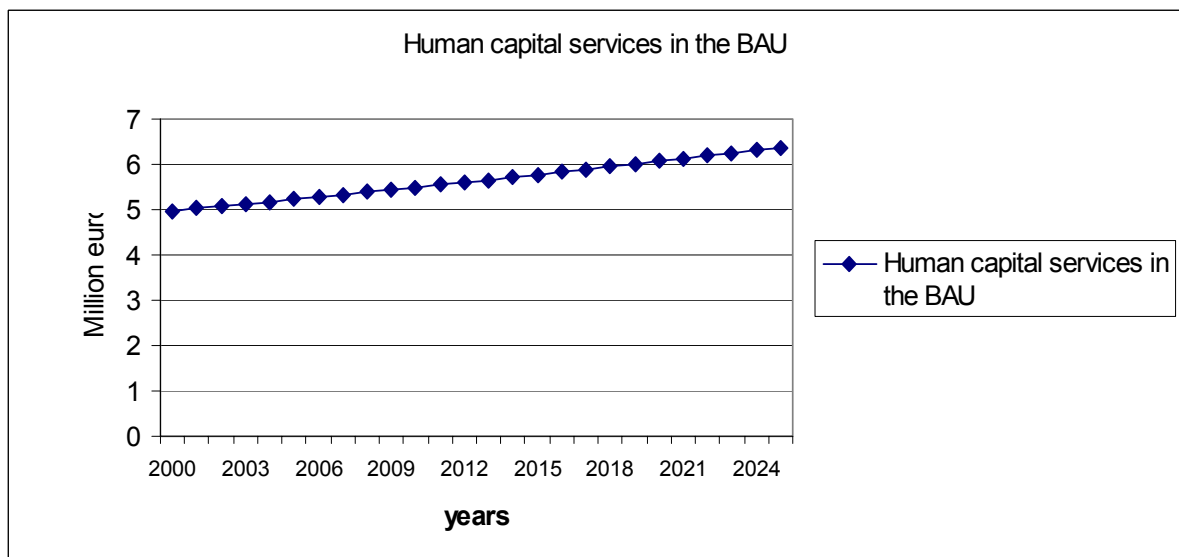


FIG. 4.3 – Business as usual human capital services

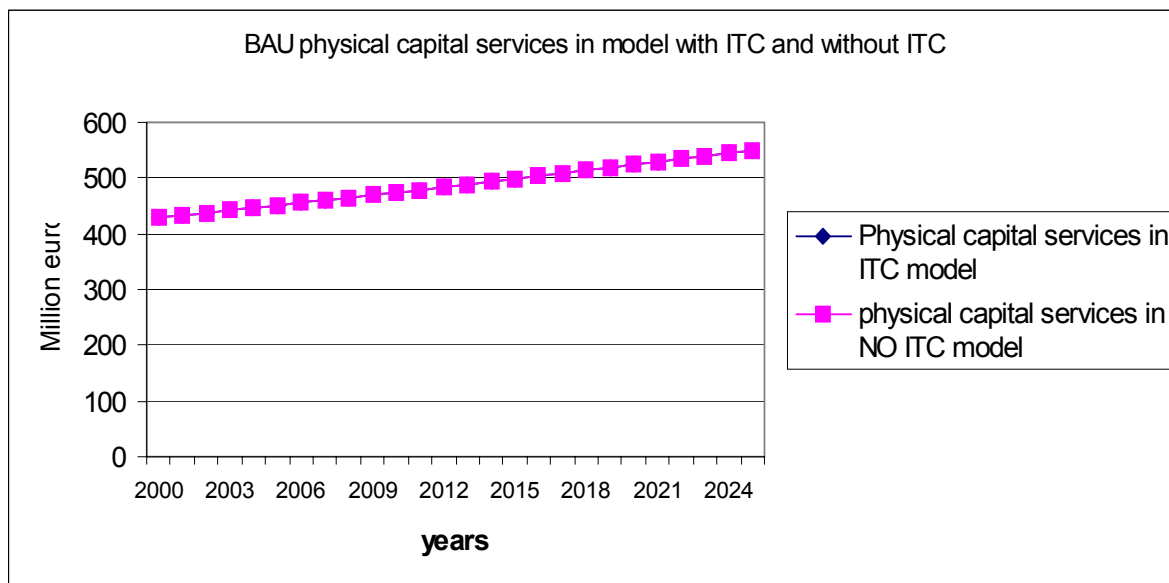


FIG. 4.4 – Business as usual physical capital services

French economy (see figure 4.4).

In the same way as physical capital services and human capital services do, total labor and materials also grow on a balanced growth path. In the following section, we choose to model the National Allocation Plan for France, in order to see how introducing induced technological change in a computable general equilibrium framework affects the model's results.

#### 4.6.2 The National Allocation Plan : A Very Small Energy Constraint

In order to understand how the model behaves when ITC is taken into account, and is constrained by energy limitations, we introduce such limitations in the two versions of the model, with ITC and without ITC. We then compare the results we obtain to identify in which way introducing induced technological change influences the results of our model. We take a close look at the mechanisms that take place in the model with ITC.

To undertake such a comparison, the energy constraint that we choose to study here consists of an emission constraint, whereby energy producing sectors and energy intensive sectors (namely "covered sectors") together may not emit more than what is legally permitted in the French National Allocation Plan, i.e. may not emit more than 33.6 MtC each year between 2005 and 2007. The non covered sectors, are all the other sectors of the economy which are not constrained by the National Allocation Plan. We extend this constraint on covered sectors, to 2012.

We allow for banking (as described in the second chapter of this thesis), first between 2005 and 2007, then between 2008 and 2012, in order to derive some first effects of these constraints on the model's behavior. As we do not know if and how, the National Allocation Plan will be further constrained between 2008 and 2012, we do not make any assumptions on the constraining of the NAP and simply constrain both versions of the model with a "NAP forever" constraint.

The goal of this process, is to initially refrain from complicating the constraints in order to shed light on the different mechanisms in the model with ITC. We compare the impacts of this emission constraint on the two versions of the same model for the French economy.

## **Emissions**

Following the introduction of the National Allocation Plan, total emissions for the French economy decrease in the first period (2005-2007) by approximately 0.75% and in the second period (2008-2012) by an average of 2.25% (see figure 4.5). In the case where ITC is modeled, total emission reductions are slightly greater than in the case where there is no ITC. Induced technological change seems to play a small role in increasing the impact of emission constraints, and leading to greater emission reductions.

A closer look at the emission reductions in the case of covered sectors and non covered sectors, shows that both covered and non covered sectors see their emission

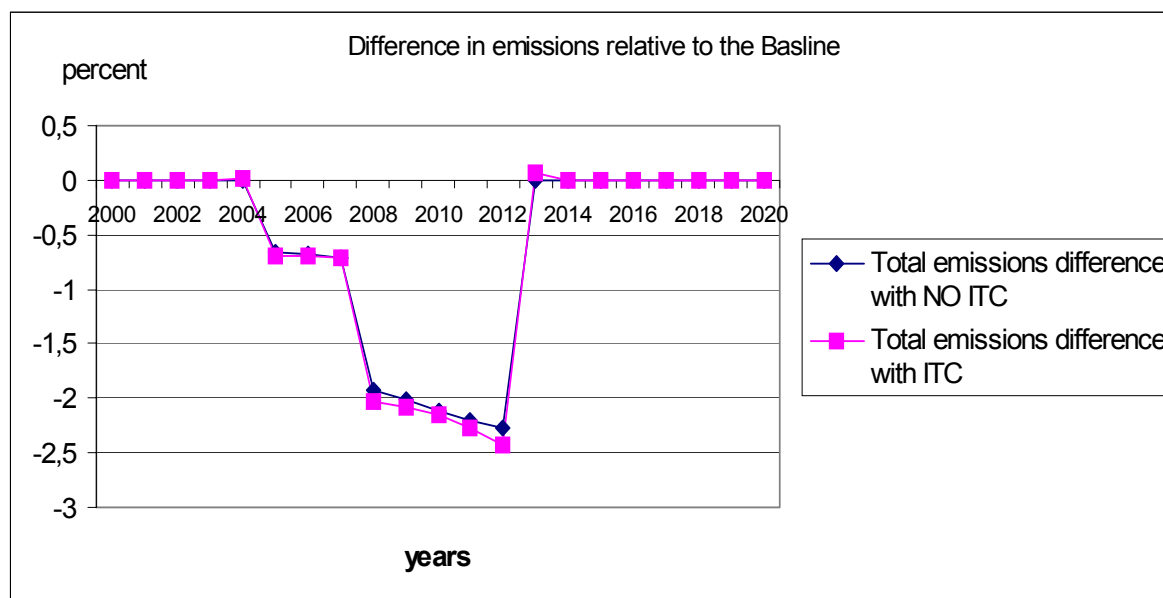


FIG. 4.5 – Emission difference relative to the BAU in the case of ITC and NO ITC

reductions further accentuated in the case where ITC is modeled in comparison to the case where there is no ITC, but these differences are particularly small in our case, as the National Allocation Plan is clearly a very loose constraint.

Of course, total emission reductions are stronger for covered sectors (both in the case of ITC and no ITC), as these sectors are constrained by the emission restrictions. Indeed, when covered sectors' emissions decline by almost 6% in the second period of the constraint, non covered sectors' emissions, who are not concerned by the emission constraint, only reduce their emissions by an average of 0.4% relative to the BAU. Finally we note that emission reductions are slightly stronger in the case of ITC for non covered sectors than for covered sectors. Indeed, we will see in the section on the demand for human capital services that this is simply due to the fact that the demand for human capital services is greater in the case of non covered sectors than in the case of covered sectors.

To understand why emissions are further reduced in the case where ITC is taken into account, we compare for all sectors, the percentage difference between the ratio of

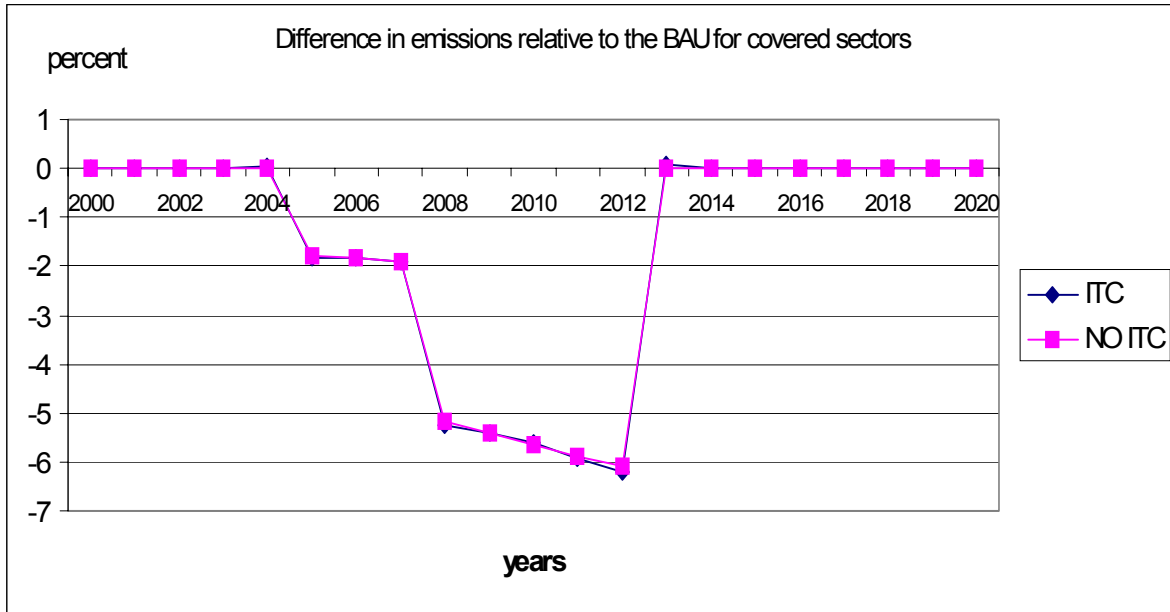


FIG. 4.6 – Covered sectors emission difference relative to the BAU

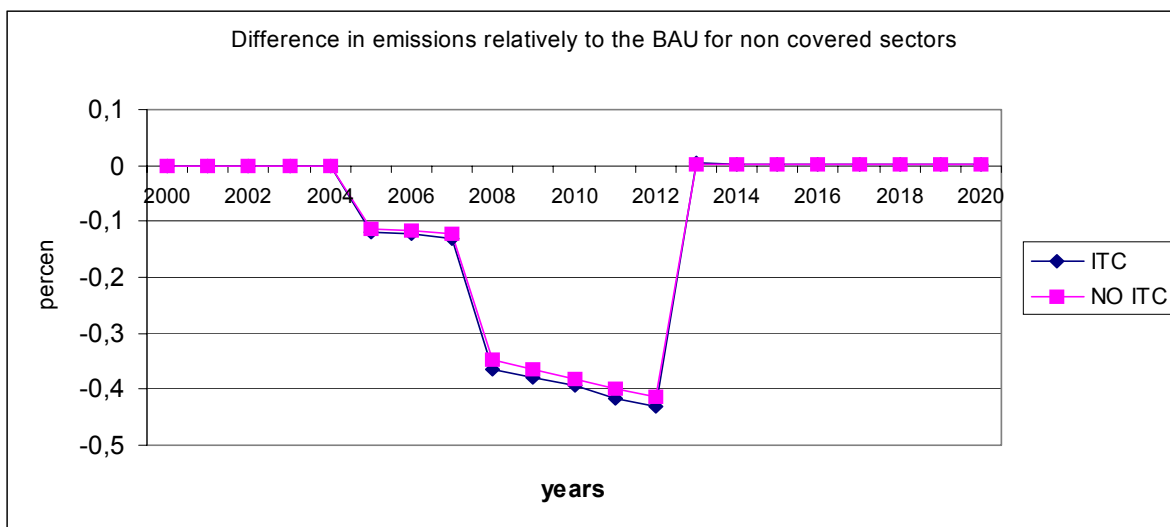


FIG. 4.7 – Non covered sectors emission difference relative to the BAU



production / tangible inputs in the case of the policy and in the case of the BAU both for the model with ITC and without ITC. It appears that the difference between the ratio of production / tangible inputs, in the case of the policy and in the case of the BAU, is greater in the case of ITC than in the case of NO ITC. Indeed, for all sectors, it appears that (see tables in Annex C) :

$$100 * \left( \frac{PROD_{pol}}{TANG_{pol}} / \frac{PROD_{bau}}{TANG_{bau}} - 1 \right)_{ITC} > 100 * \left( \frac{PROD_{pol}}{TANG_{pol}} / \frac{PROD_{bau}}{TANG_{bau}} - 1 \right)_{NOITC}$$

Such a result derives from the fact that there is a possibility to substitute between tangible inputs and the intangible input in the case where ITC is taken into account, that is inexistent when NO ITC is accounted for. Therefore, a general result appears, whereby, in the case of ITC, tangible inputs are simply less used as inputs into production than in the case of NO ITC. In other terms, tangible goods, are simply more efficient.

Therefore, this induced technological change effect, whereby the demand for tangible goods in the case of ITC is smaller than the demand for tangible goods in the case of NO ITC, also leads to the result on emissions that we are studying here. As less tangible inputs are needed due to the induced technological change effect, this mechanically decreases the total amount of emissions. For this reason it appears that in the case of ITC, emission reductions are greater than in the case of NO ITC.

## **Production**

When the National Allocation Plan is introduced, the total production of the economy is slightly reduced (see figure 4.8). These reductions are minimal due to the fact that the NAP is hardly constraining.

Indeed, both the productions of covered and non covered sectors are affected by the restriction in emissions. However, the covered and non covered sectors are not affected in the same way. It appears that the covered sectors' production is indeed constrained by the emission reduction, while the production of the non covered sectors is greater

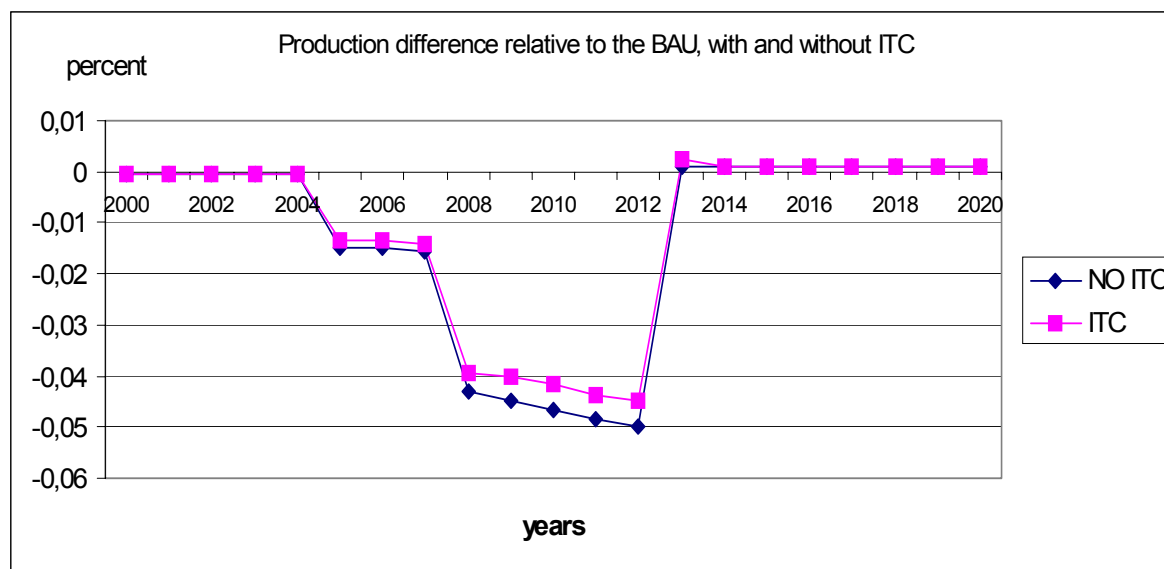


FIG. 4.8 – Production difference relative to the BAU in the case of ITC and NO ITC

than the BAU. And this is the case for both versions of the model, whether ITC and NO ITC<sup>31</sup>. The production of covered sectors, decreases between 2005 and 2007 and then further as the constraint is introduced once more in 2008 until 2012 (see figure 4.9). This is due to the fact that the demand for these goods by both non covered sectors and covered sectors is reduced<sup>32</sup> as they are associated with the constraint.

On the contrary, non covered sectors' production increases with the introduction of the NAP, relative to the baseline value (see figure 4.10).

Such an increase in the production of non covered sectors is due to the fact that, as covered sectors' production is less demanded as inputs to production, both types

<sup>31</sup>It would be difficult to clearly see on the graphs representing the production differences relatively to the baseline, how the model reacts with ITC and no ITC, for both covered and non covered sectors. Such graphs would be practically unreadable. Therefore, we choose here to simply not differentiate between the two versions, as the differences between the two versions would be almost impossible to see in any case on the chosen scale. We show in the following graphs that the differences are very small in the case where ITC and no ITC are taken into account, but are however significant.

<sup>32</sup>Both covered and non covered sectors use the goods produced by both these types of sectors as inputs to their production (see production function). If the price of goods produced by covered sectors increases, then necessarily both covered and non covered sectors reduce their demand for the goods produced by covered sectors. Therefore, because supply must equal demand in a general equilibrium framework, covered sectors' production decreases following the environmental constraint.

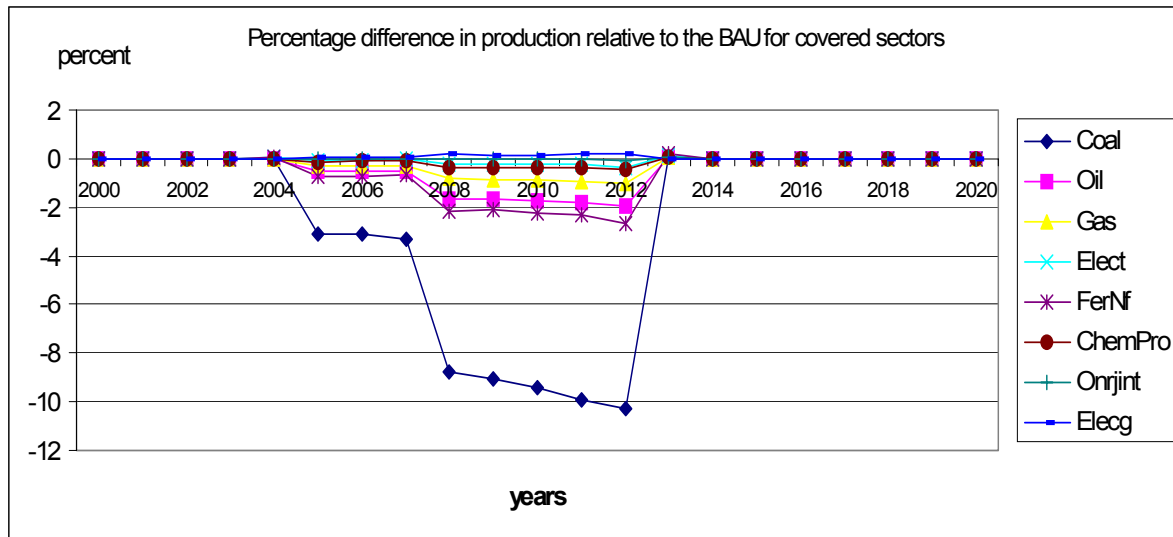


FIG. 4.9 – Covered sectors' production difference relative to the BAU

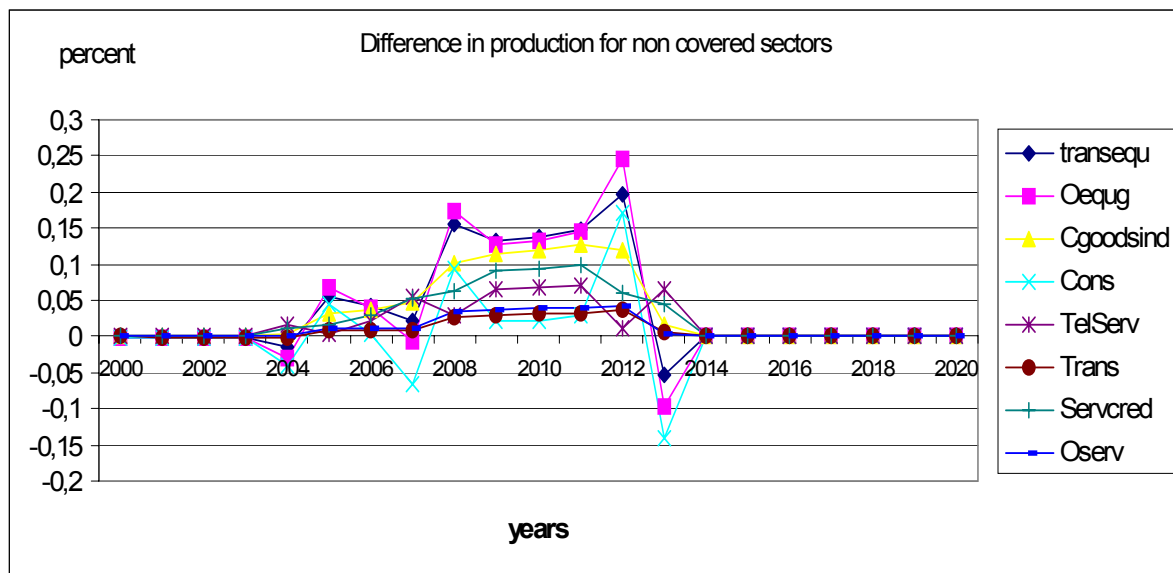


FIG. 4.10 – Non covered sectors production difference relative to the BAU

of sectors demand non covered sectors's goods as inputs to production. Indeed, non covered sectors' goods are not constrained by the policy. Therefore, as the demand for these goods increases, and as, in the general equilibrium framework supply must necessarily equal demand, the non covered sectors' production also increases.

However, an interesting result emerges as we compare the production differences both in the case of ITC and in the case where there is NO ITC. In the case of non covered sectors, it appears that when technological change is induced in the model, this *limits* their production increase following the introduction of the constraint on the covered sectors (see figure 4.11). Their production increase is smaller in the case of ITC, then in the case of NO ITC. Indeed, as both covered and non covered sectors now have made substitutions in favor of more human capital services, their demand for non covered sectors goods in the case of ITC, is not as great as their demand was for these goods in the case where there is no ITC. As we are in a general equilibrium framework, if the demand for the goods produced by non covered sectors is not as strong in the case of ITC, then the production of non covered sectors' is necessarily not as strong as in the case where technological change is impossible.

**Proposition 10** *The introduction of ITC in the model, constrains the production increase of the non covered sectors in comparison to the case of NO ITC.*

A similar result appears in the case of the covered sectors. As we compare the covered sectors' production in the case of ITC and in the case where technological change is not induced, it appears that when ITC is taken into account, the covered sectors' production is *less* reduced in the case of ITC, compared to the case of NO ITC (see figure 4.12). Induced technological change therefore reduces the negative impact it has on the production of sectors that are constrained by an environmental constraint.

Indeed, as the covered sectors are constrained in their emissions, they increase their demand for human capital services as inputs to production. They substitute

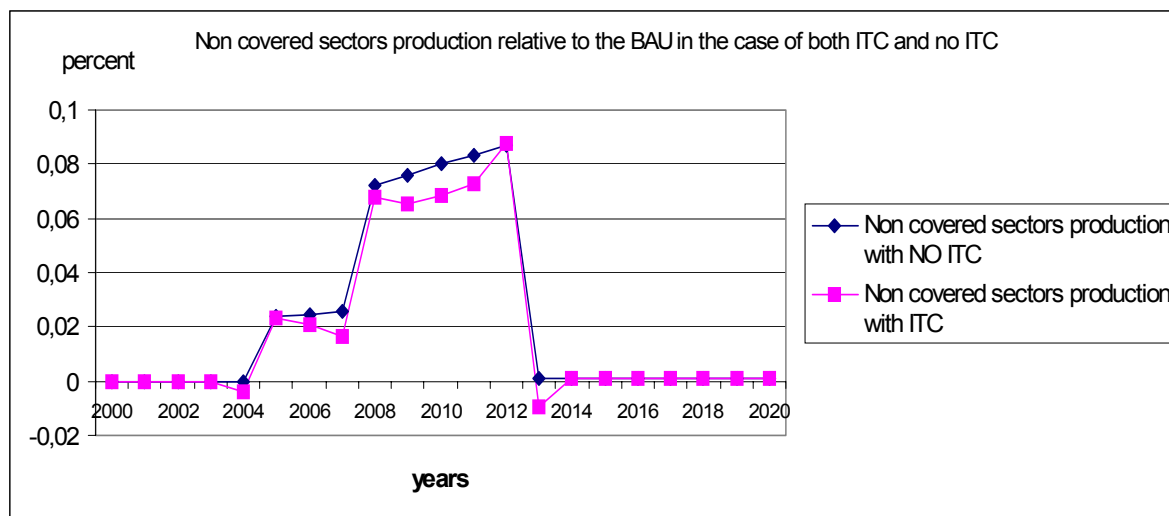


FIG. 4.11 – Non covered sectors production difference relative to the BAU in the case of ITC and NO ITC

between the tangible and intangible goods, and use less fossil fuels for their production as in the case where there is NO ITC. Therefore, the constraints that are on the covered sectors are lessened, as this additional substitution process is introduced and the covered sectors are less energy intensive, and emit less (as seen in the section on emissions). For this reason, non covered sectors, do not reduce their demand for covered sectors goods as much as in the case where technological change is induced compared to the case where there is NO ITC. Therefore, covered sectors' production is less reduced than in the case of NO ITC.

**Proposition 11** *The introduction of ITC in the model reduces the negative impact on the production of covered sectors in comparison to the case of NO ITC.*

## Capitals

Now that we have shed light on the fact that emissions are more reduced in the case where ITC is modeled, both for covered sectors and for non covered sectors, it is important to understand how the demand for human capital services and physical

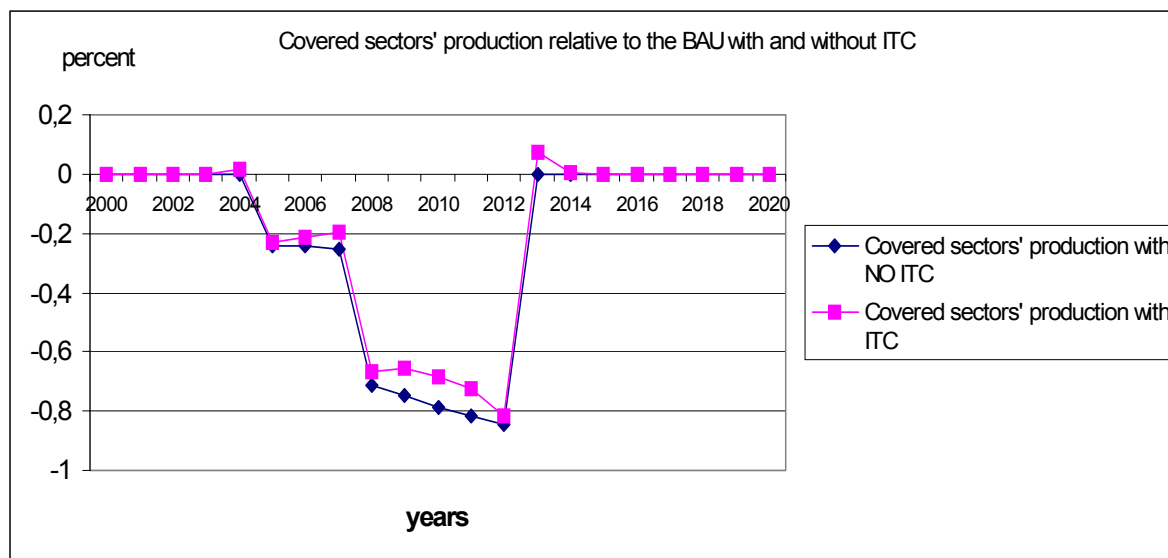


FIG. 4.12 – Covered sectors production difference relative to the BAU with ITC and NO ITC

capital services vary in both these types of sectors following the introduction of the National Allocation Plan<sup>33</sup>.

**Human Capital Services : the Basis for Induced Technological Change** In our specification, induced technological change is modeled through the "Stock of Knowledge Approach". Firms, facing an energy constraint, may choose to substitute between their tangible inputs (capital, labor, energy, materials<sup>34</sup>), and also demand an intangible input (human capital) as a substitute to all tangible ones. This second substitution process is the process of induced technological change. In this case, in order to identify how ITC functions in this model, it is important to understand the variations in the demand for human capital services following the introduction of an energy constraint. Of course, we can study these variations only with the model with ITC, and not with

<sup>33</sup>In the case where there is no ITC, the model is calibrated on a social accounting matrix where human capital services have not been extracted. Therefore, we can only show how human capital services are affected in the case of ITC, when a policy is introduced.

<sup>34</sup>The "Materials" input being a bundle of the production goods of both covered and non covered sectors as defined in the second chapter of the thesis.

the model without ITC, because in that case the human capital row is not specified, and no human capital has been extracted from the social accounting matrix.

In this general equilibrium framework with ITC, four effects will influence the demand for human capital services : a *substitution effect*, an *induced technological change effect*, a *revenue effect*, and an *investment effect*. The total impact on the demand for human capital services will be the result of the sum of all these effects.

#### **Four Effects**

##### – Substitution Effect

When facing an emission constraint, both covered and non covered sectors substitute between their tangible goods used as inputs into production (capital, labor, energy, materials). This *substitution effect* is by definition neutral on the demand for human capital services, as the demand for human capital services is not affected directly by these inter-tangible input substitutions. The covered sectors engage in substitutions because their emissions are constrained, and non covered sectors engage in substitutions because they demand less goods produced by the covered sectors the prices of which have gone up.

##### – Induced technological Change Effect

As the emission constraint is introduced, both covered and non covered sectors increase their demand for human capital services, according to the elasticity of substitution between tangible goods and the intangible good. Covered sectors increase their demand for the intangible good because of the constraint on their use of fossil fuels, and non covered sectors increase their demand for the intangible good because of the price increase of the goods produced by the tangible goods and also because their own production increases following the introduction of the constraint. This increase in the demand for human capital services is the *induced technological change* effect. However, the general equilibrium framework of our work supposes that an increase in the total

demand for human capital services in year  $t$  must be satisfied by an increase in the supply for human capital services that same year. In order for there to be an increase in the supply for human capital services in year  $t$ , there must be an increase in the investment in research and development in year  $t - 1$  that will lead to a greater than baseline level of stock of human capital in year  $t$ . An increased supply in human capital services to satisfy an increased demand in human capital services is thus necessarily linked to an increase in the investment in R&D the previous year.

$$H_{t+1} = R_t + (1 - \delta_h)H_t$$

Therefore, the induced technological change effect in year  $t$  relies on the investment effort in year  $t - 1$ .

– Revenue Effect

The *revenue effect*, is the effect that derives from the variation in the sectors' production. In the case of the covered sectors, following the introduction of an emission constraint, their production decreases as the demand for the goods that they produce, decreases. This revenue effect, has a negative impact on the covered sectors' demand for all inputs. It will therefore lead covered sectors to demand less human capital services. In the case of the non covered sectors, however, the revenue effect has a positive impact on their demand for inputs as their production increases following the introduction of the constraint on the covered sectors. The production increase that they enjoy leads them to increase their demand for human capital services as inputs to production.

– Investment effect

The investment effect is linked to the aggregate income accounting definition (see equation 4.23), and derives from the value of production relative to its baseline value.

$$Y_t = C_t + I_t + R_t + G_t + X_t - M_t \quad (4.23)$$

If in the year  $t$ , an emission constraint is introduced on the covered sectors, the total production of both covered and non covered sectors decrease that same year  $t$ . It follows,



that the investment in research and development in year  $t$  mechanically decreases (see equation 4.23). This allows for a smaller than baseline increase in the stock of human capital as seen in equation 4.24.

$$H_{t+1} = R_t + (1 - \delta_h)H_t \quad (4.24)$$

A lower than baseline level of investment in R&D in year  $t$ , following the contraction of production in year  $t$ , leads to a stock of human capital in year  $t + 1$  that will be smaller than the baseline level. However, human capital services in year  $t + 1$  derive from the stock of human capital in year  $t + 1$ . Therefore, the amount of human capital services that will be available on the market in year  $t + 1$  will be smaller than in the baseline value. If a policy is introduced in year  $t$ , then the *investment effect* in year  $t + 1$  has a negative impact on the supply for human capital services.

It follows that the investment effect in year  $t$  will be neutral on the supply for human capital services in year  $t$ . Indeed, if in year  $t$  a constraint is introduced. Then total production in year  $t - 1$  will not be reduced, as the constraint is introduced only the year after. Therefore, as the investment in R&D in year  $t - 1$  will not fall under the baseline level, then the value of the total stock of human capital will be the same as its baseline value. It follows that in year  $t$ , date of the introduction of the emission constraint, the supply for human capital services will not be affected by the investment effect. However, the investment effect will have a negative effect on the supply for human capital services in year  $t + 1$ , as total production falls in year  $t$  under the baseline level following the introduction of the constraint.

It is worthwhile noting that both the induced technological change effect and the investment effect are subject to a time lag, while the substitution effect and the revenue effect have both immediate consequences. These time differences will be clearly observable in the model results on human capital services.

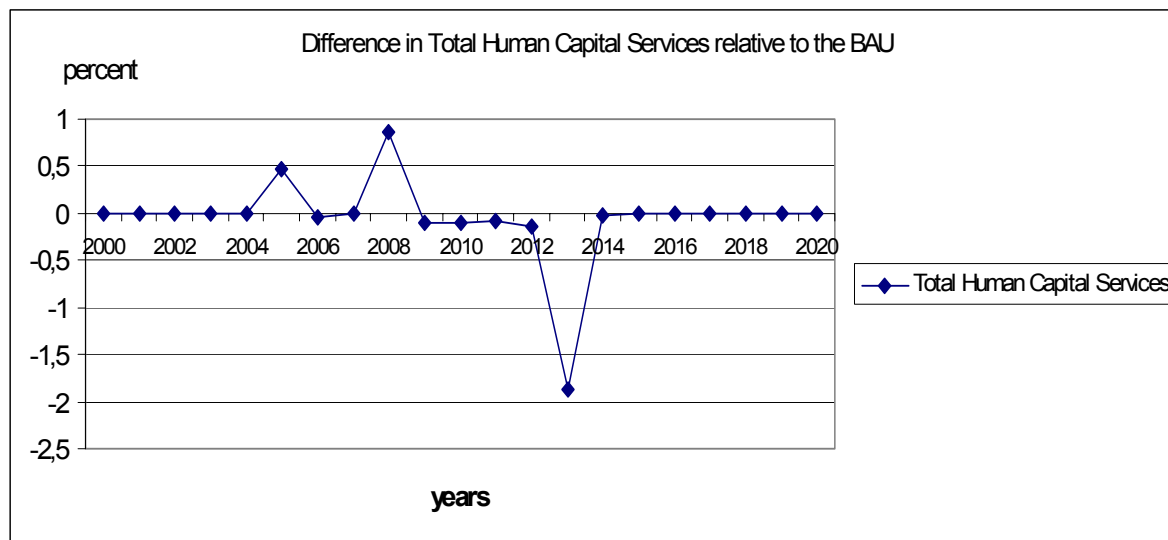


FIG. 4.13 – Difference in total human capital services relative to the BAU

#### The Case of all Sectors : Peaks of Demand for Human Capital Services

To understand how these four effects influence both covered and non covered sectors, it is necessary to first look at the total variations in the demand for human capital services. It appears, that the first years of the introduction of the NAP, both in 2005 and in 2008 (when the second banking period begins), there are peaks in the total demand for human capital services. The following years, the demand for human capital services falls back to the baseline level, although the constraint is still active. In 2013, first unconstrained date after the NAP, there is a 2% reduction in the demand for human capital services relative to the baseline scenario.

What appears here is that the industries' response in terms of technological change to the energy constraints is very rapid and disappears after the first year of the constraint. In 2005, the NAP is introduced, and banking is allowed until 2007. We here note that the first peak in the demand for human capital services is the first year of the introduction of the emission constraint. Although the constraint still remains in 2006 and 2007, the demand for human capital services returns to its value in the benchmark.

Next, between 2008 and 2012, banking is also allowed over the period. Therefore, in 2008, there is a second peak in demand for human capital services. However, between 2009 and 2012, the demand for human capital services return to its value in the baseline. Finally, while 2012 is still constrained by the NAP, 2013 is a completely unconstrained year, and the demand for human capital services therefore drops by close to 2%.

While our work is inscribed in a different setting, these findings are consistent with D. Popp (2002), who also sheds light on the existence of peaks of induced technological change, which disappear the following year. Indeed, in his paper, Popp suggests that, as his model captures diminishing returns to research, it becomes more difficult for firms who have already invested largely in R&D to produce even more new innovations, as increased R&D spending becomes necessary for these new innovations to occur. Therefore, because of diminishing returns, after the introduction of a policy, there is a burst in knowledge that will quickly disappear due to the "shifting" in research efforts towards areas that will be more productive.

In our case the reason for these peaks depend mainly on the *investment effect* described earlier, whereby investment in research and development in year  $t$ , influences the stock of human capital in year  $t+1$ , and therefore the total supply of human capital services in year  $t+1$ . The model we have built is a forward-looking model, whereby the economy knows that emission restrictions will be introduced in 2005 for a first banking period, and then again in 2008 for a second banking period, and entirely relaxed in 2013. One of the main features of forward-looking models rests in the fact that as the economy can anticipate these policies, and it may choose to modify its behavior even before the introduction of the policy. With this in mind, firms will foresee in 2004 and in 2007, that an emission constraint will be introduced in 2005 and 2008, and will know in 2012 that it will be entirely relaxed in 2013.

To understand the mechanisms that lie behind the variations in the demand for

human capital services, it is important to have a closer look at the different years.

### **Year 2005 and 2008 : First years of introduction of the constraints**

In 2005, as the covered sectors face the emission constraint, both covered and non covered sectors demand more human capital services as they engage in the induced technological change process described above. In order to be able to demand more human capital services that year, the investment in R&D in 2004 will necessarily have to increase relative to the its baseline value so as to increase the total stock of knowledge in 2005 from which knowledge services will derive<sup>35</sup>. By increasing the investment in R&D, the supply in human capital services to both covered and non covered sectors becomes much higher than in the baseline level. This satisfies the demand of both covered and non covered sectors for these services (see equations 4.25 and 4.26). This is the *induced technological change effect*. While investment in R&D is not firm-specific, the total stock of human capital is also not firm specific. The total knowledge services that will derive from the total stock of human capital services will enter the market for inputs, and will be demanded by both covered and non covered sectors. For this reason, we see the total supply of human capital services increase in 2005 (and also in 2008) relative to the baseline.

$$H_{2005} = R_{2004} + (1 - \delta_h) H_{2004} \quad (4.25)$$

$$HS_{2005} = (r_h + \delta_h) H_{2005} \quad (4.26)$$

In 2005, moreover, the investment effect is neutral on the demand for human capital services because total production in 2004 is unaffected by the constraint. On the contrary, the revenue effect has a negative impact on the demand for human capital services, as total production decreases in 2005. The substitution effect keeps a neutral role on the demand for human capital services.

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<sup>35</sup>The fact that the investment in R&D in 2004 increases relatively to the baseline level is due to the induced technical change effect, which is independant from the investment effect simple consequence of production variations.

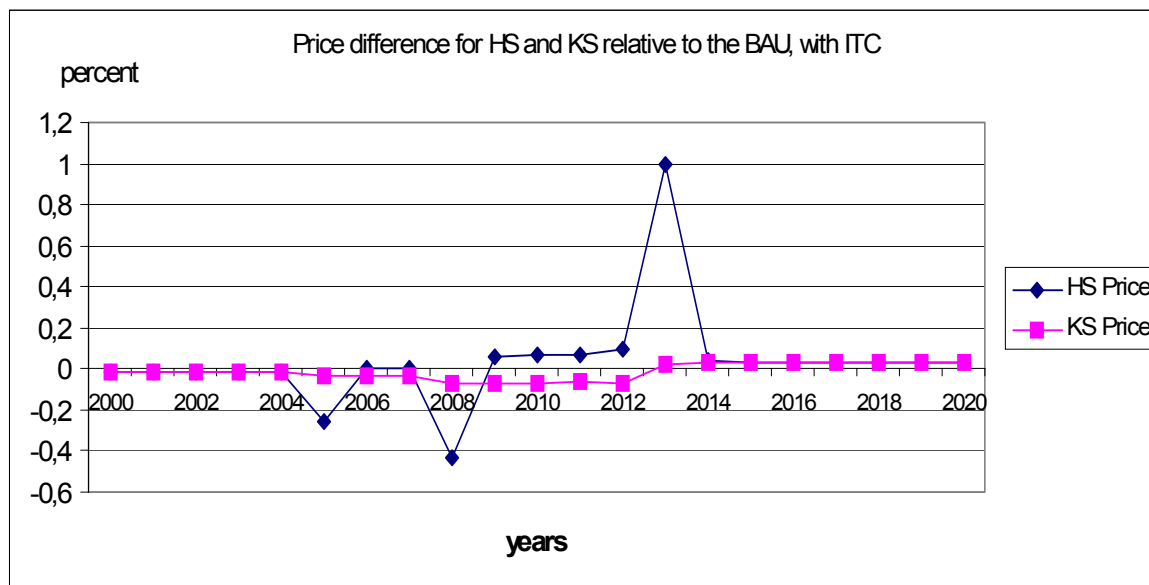


FIG. 4.14 – Price difference for human capital services and physical capital services relative to the BAU

The demand for human capital services is therefore the result of all the four effects :

- The substitution effect has a neutral impact on human capital services
- The investment effect has a neutral impact on human capital services
- The revenue effect has a negative impact on human capital services
- The induced technological change effect has a positive impact on human capital services

ital services

In 2005, the result on total human capital services suggests that the induced technological change effect is greater than the revenue effect in the year 2005, first year of the introduction of the constraint.

The immediate consequence of an increase in the total supply of human capital services in 2005, relative to the baseline is the reduction in the price of these services, as seen in the following graph whereby it appears that the price of human capital services decreases sharply in 2005 (as well as in 2008, first year of the second constraint).

**Proposition 12** *The first years of the introduction of the constraints, there are peaks in the demand for human capital services because of the induced technological change effect.*

**Year 2006 and following (except 2013) :**

In 2006, 2007, 2009, 2010, 2011 and 2012, it appears that the demand for human capital services returns to its baseline level. In 2006, as the constraint still binds the emissions of covered sectors, total production values are still under their baseline values. The revenue effect that year has a negative impact on the demand for human capital services.

The investment effect also has a negative impact on the demand for human capital services in 2006. Let's retrieve the aggregate income accounting definition :

$$Y_{2005} = C_{2005} + I_{2005} + R_{2005} + G_{2005} + X_{2005} - M_{2005}$$

In 2005, total production decreases due to the introduction of the emission constraint, and its level falls below the baseline level as seen on the graph representing production variations. This decrease in production leads to a necessary decrease in the investment in research and development in 2005,  $R_{2005}$ , the value of which also necessarily falls under the baseline level. However, while in 2005, in the policy case, the stock of human capital is greater than the stock of human capital in the baseline scenario, the stock of human capital in 2006 will necessarily fall back to the baseline level due to the underinvestment in research and development in 2005 consequence of the drop in total production. Therefore, the drop in human capital services in 2006, is due to the underinvestment in R&D in 2005, consequence of the total production drop following the introduction of the constraint. This is the investment effect. The same reasoning explains the drop in human capital services in 2009. The induced technological change effect has a positive impact on the demand for human capital services in 2006, while the substitution effect has no impact on it.

In 2006 the demand for human capital services is the result of all the four effects :

- The substitution effect has a neutral impact on human capital services
- The investment effect has a negative impact on human capital services
- The revenue effect has a negative impact on human capital services
- The induced technological change effect has a positive impact on human capital services

ital services

The only difference between 2006 and 2005, is the fact that now, the investment effect which was neutral in 2005, has a negative impact on human capital services. Total demand for human capital services in 2006 is the combination of these effects, whereby the sum of the negative impacts of the revenue and investment effects equal the positive impact of the induced technological change effect, and leads to a baseline level of demand for human capital services that year. Therefore the induced technological change effect equals the sum of the revenue and investment effect.

It is here important to note that, while the emission constraints are still active in 2006, 2007, 2009, 2010 and 2011, firms may now not have access to the Induced technological change effect because of the investment effect that simply counterbalances it. Therefore, firms may now only face the emission constraints through the substitution effect that takes place between the tangible inputs, as if ITC was now not an option anymore.

**Proposition 13** *In the years following the introduction of the emission constraint, and while the constraint is still active, firms only have the option of substituting between tangible inputs, as the induced technological change effect is simply counterbalanced by the investment effect.*

#### **Year 2013 :**

What remains to be understood, is the reason why in 2013 once the emission restrictions disappear, the demand for human capital services is lower by almost 2% than

in the baseline.

Now, as we have just seen, while the emission constraints were still constraining the covered sectors right until 2012, the demand for human capital services stays very close to its baseline level (except for the years 2005 and 2008 where there is a burst in demand for these services). Indeed, firms will therefore have to face the emission constraints by simply substituting between tangible inputs (less goods produced by covered sectors and more goods produced by non covered sectors are used as inputs to the production of all sectors).

As the emission constraint is now relaxed, the demand for the goods produced by covered sectors, will increase dramatically in comparison to when the constraint was in place, as these inputs become relatively cheaper. Similarly, the demand for goods produced by non covered sectors will decrease relative to the previous year, as the incentive to use their production as inputs vanishes with the suppression of the constraint<sup>36</sup>. In any case, the suppression of the constraint acts as a sudden burst in the supply of tangible inputs to production, as the induced technological change effect simply disappears, with the disappearing of the constraint.

In 2013, the emission constraint is inexistent. However, in 2012, covered sectors were still constrained in their emissions and total production was under the baseline level. Therefore, the investment effect has a negative impact on the demand for human capital services in 2013. As total production is below the baseline level in 2012, the investment in research and development in 2012 is lower than its baseline level. It follows that the stock of human capital in 2013 is still lower than the baseline level, even if there is no emission constraint that year. This is due to the time lags that are in the model. The supply of human capital services that will derive from this stock of

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<sup>36</sup>A quick look at the graphs representing the production for both covered and non covered sectors clearly shows that, in 2013 covered sectors' production jumps to slightly over the baseline value, and non covered sectors production also fall to slightly under the baseline value.



capital will therefore drop relative to the baseline. The investment effect will have a negative impact on the supply of human capital services in 2013.

In 2013 the demand for human capital services is the result of all four effects :

- The substitution effect has a neutral impact on human capital services
- The investment effect has a negative impact on human capital services
- The revenue effect has a neutral impact on human capital services
- The induced technological change effect has a neutral impact on human capital services

The total demand for human capital services in 2013 is the combination of these effects, whereby the only effect that impacts human capital services is the investment effect. The drop in 2013, is therefore the isolated investment effect. Due to the limited amount in human capital services that will be on the market in 2013, the price for these services will be higher that year than its baseline level, as seen on the graph representing the prices.

**The Case of Covered Sectors** In the case of the covered sectors, we see the same peaks in the demand for human capital services relative to the baseline the first years of the introduction and constraining of the emission constraint, namely in 2005 and 2008. Between 2006 and 2007, the demand for HS falls back to the baseline level, except for gas and coal, where it falls below the baseline level. Between 2009 and 2012, the demand for human capital services, falls below the baseline level in the case of coal and in the case of both gas, and ferrous and non ferrous, while for the other covered sectors, it simply returns to the baseline level.

The variations in the demand for human capital services are also the result of the four effects described earlier. The only difference is that it appears that for coal, gas, ferrous and non ferrous goods the demand for human capital services falls even below the baseline level. This is due to the revenue effect that has a negative impact on the

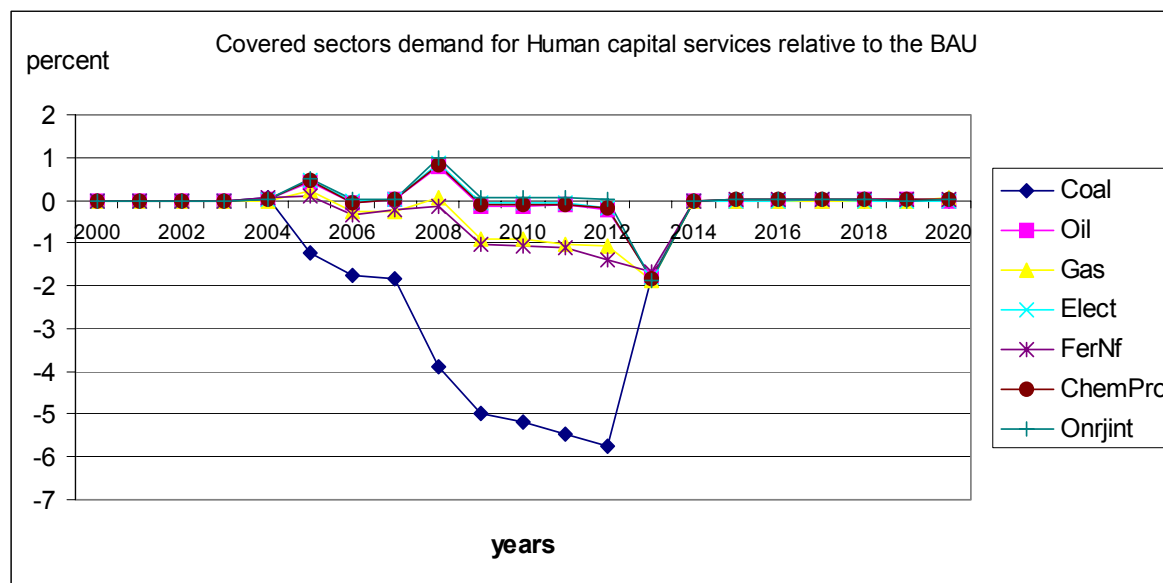


FIG. 4.15 – Covered sectors demand for human capital services relative to the BAU

demand for human capital services, as covered sectors' production decreases strongly following the introduction of the constraint<sup>37</sup>. It comes as no surprise that the revenue effect is very strong for coal, as its production decrease is remarkable following the emission constraint.

**The Case of Non Covered Sectors** In the case of non covered sectors, the pattern is very much the same as for the whole economy. While covered sectors face an emission constraint, their produced goods are less demanded by the non covered sectors, who demand more of the intangible good and more of other inputs to production. The intangible good is also a more attractive input to production as its price falls in 2005 and 2008 due to the increase in its supply to the whole economy. Moreover, non covered

<sup>37</sup>The revenue effect that covered sectors are subject to, is stronger than the total revenue effect the whole economy is subject to. In fact covered sectors' production decreases following the introduction of the constraint, while non covered sectors' production increases. Total production being the sum of the production of both covered and non covered sectors, its decrease following the introduction of the constraint is smaller than the covered sectors' production decrease. For this reason the revenue effect that covered sectors are subject to, is stronger than the total revenue effect the whole economy is subject to.

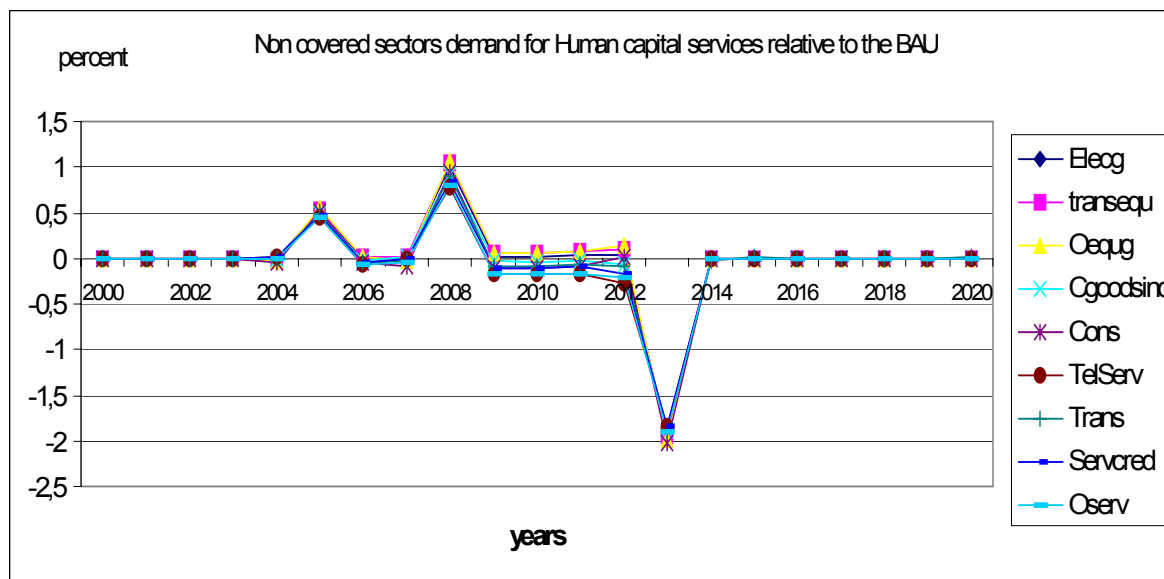


FIG. 4.16 – Non covered sectors demand for human capital services relative to the BAU

sectors also increase their demand for human capital services simply because their production increases and their need for inputs increases accordingly. For this reason we see that, while non covered sectors are not constrained in their emissions they demand human capital services.

One comment however needs to be made. The investment effect has a negative impact on the non covered sectors' demand for human capital services, while the production of non covered sectors **increases** rather than decreases following the introduction of the NAP. This can seem initially as a contradiction, as we had argued that the investment effect had a negative impact on the demand for human capital services if the production falls under the baseline level. However, it is not. The reason for the decrease in the non covered sectors' demand for human capital services lies in the specificity of our model, whereby research and development is **not firm specific** (as opposed to Goulder and Schneider (1999)), and the total stock of human capital belongs to the whole economy. The human capital services that derive from the general stock of human capital are allocated to the different sectors according to their demand for them

and its price. For this reason, the investment effect derives from the **value of total production** relative to the BAU, and not solely the value of non covered sectors' production. It is therefore possible, for non covered sectors, whose production increases following the introduction of the NAP, to be negatively affected by the investment effect.

**Conclusion** We shed light on the fact that four effects influence the final variations of human capital services following the introduction of an emission constraint. A substitution effect, a revenue effect an induced technological change effect, and an investment effect. These effects influence the demand for human capital services of both covered and non covered sectors.

Also, we show that similarly to Popp (2002), there are peaks in the demand for human capital services the initial years of the introduction of the emission constraints, which disappear the following years while the constraint is still in place. We here show that the investment effect, whereby the total production of all sectors decreases following the introduction of the emission constraint, necessarily leads to a reduction in the investment in research and development and of the use of human capital services the following year. Induced technological change, therefore, only has a very short time span for both covered and non covered sectors, as the investment effect neutralizes the induced technological change effect. The years following the introduction of the constraint, firms will necessarily then have to face the emission constraints by simple substitutions between tangible inputs. This supports Nordhaus (2002) suggestion, whereby substitutions between tangible inputs are more important than the induced technological change effect.

The variations in human capital services for covered and non covered sectors, support the initial position Goulder and Schneider (1999) and Sue Wing (2001), whereby it appears that in the case where technological change is accounted for, non covered

sectors, i.e. sectors that are not affected by the emission constraint, will increase their demand for human capital services more than covered sectors will. In fact, in the case of this emission policy, R&D is stimulated in carbon-competing industries (industries that produce low-carbon energy). Indeed, in the case of the covered sectors, the induced technological change effect is constrained by the revenue effect, as their production decreases relative to the baseline because of the emissions constraint. In the case of non covered sectors the revenue effect, on the contrary, has a positive effect on the demand for human capital services. Indeed, less tangibles, and therefore less fossil fuels are needed for production. This result also supports Otto et al. (2006) who show that technological change is directed towards non CO<sub>2</sub> intensive goods in the case of a CO<sub>2</sub> constraint.

Finally, we show how an economy wide stock of knowledge increased by non firm specific investments in R&D can limit the induced technological change effect of firms that are not subject to the emission constraint.

**Physical Capital Services** Now that we have shed light on the different effects leading to differences in the demand for human capital services relative to the baseline, it is important to have a look at the effects of an emission constraint on the demand for physical capital services as inputs into production.

**The Case of Both Sectors : The Constraint of the Aggregate Income Accounting Definition - An Eviction Effect or Crowding-Out Effect** In the following graph, we show the total demand for physical capital services both in the case of ITC and NO ITC. It appears that in the case where there is NO ITC, the effect on the demand for physical capital services is relatively smooth. An initial very minimal decrease appears in the first period and after 2008, the demand for physical capital services increases slowly. However, in the case where technological change is induced it appears that the demand for physical capital services decreases sharply in 2005 and in

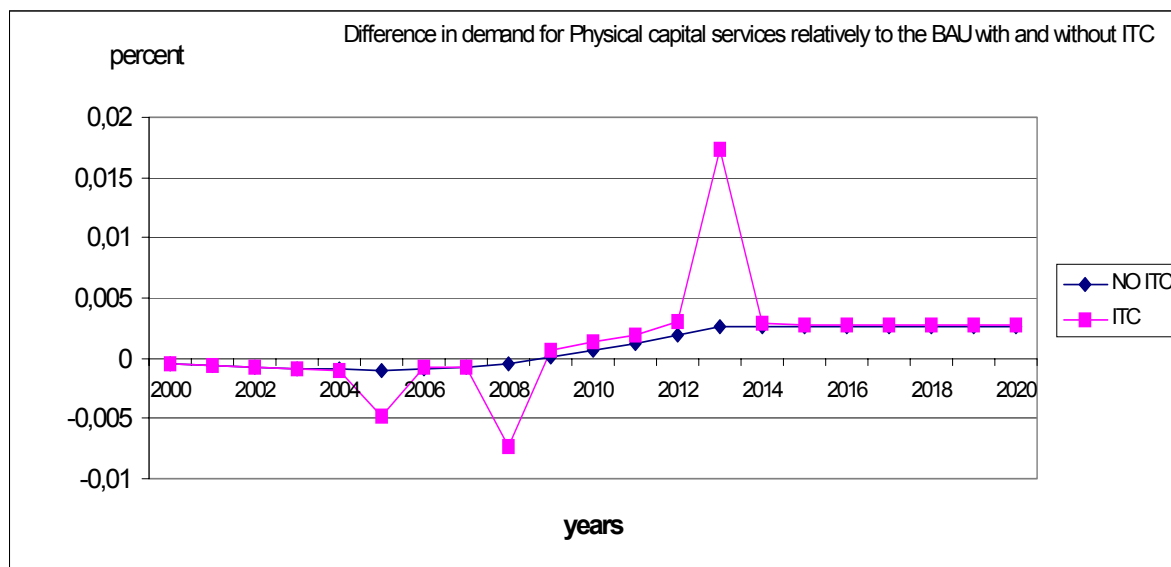


FIG. 4.17 – Difference in demand for physical capital services relative to the BAU in the case of ITC and NO ITC

2008 (in the same way that the demand for human capital services increases sharply those years). Similarly, in 2013, when the emission constraint is released, a peak of demand for physical capital services appears (in the same way that there is a sharp decrease in the demand for human capital services that same year).

It appears that the chart is exactly the opposite of the one representing total variations in human capital services. This is due to the *eviction effect* or *crowding out effect*. The eviction effect or crowding out effect is the direct consequence of the aggregate income accounting definition (see equation 4.17). It is important to recall that both the investment in physical capital and investment in research and development derive from this equation. Therefore, if in the year  $t$ , all else being equal, the investment in R&D increases to satisfy an increased demand for human capital services the following year, the investment in physical capital must necessarily be decreased in year  $t$ , as total production is fixed.

$$Y = C + I + R + G + X - M$$

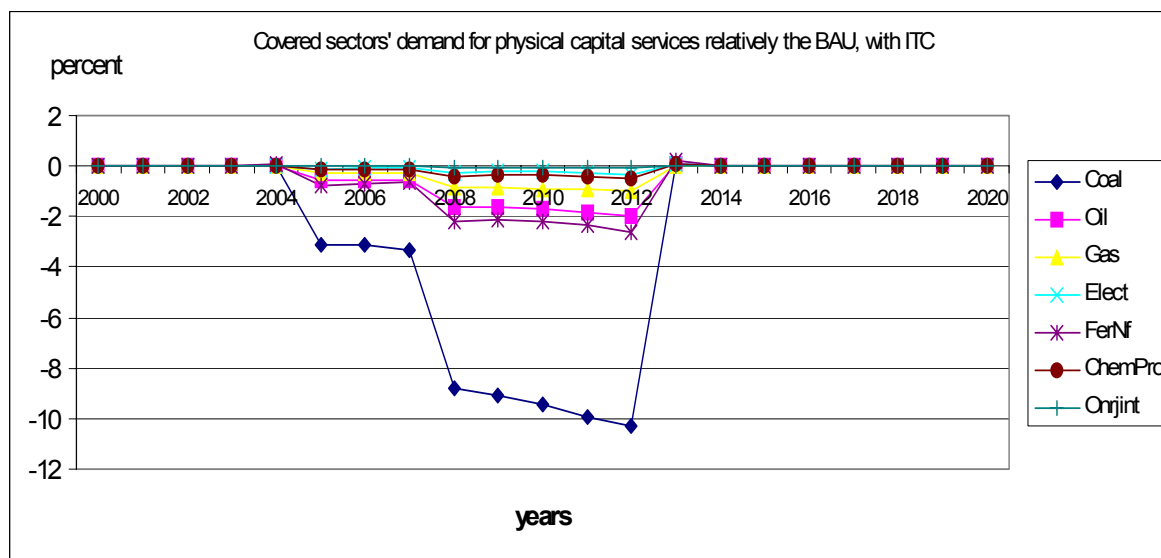


FIG. 4.18 – Covered sectors demand for physical capital services relative to the BAU with ITC

The eviction effect therefore causes the demand for physical capital services and the demand for human capital services to vary in opposite directions. According to the aggregate income accounting definition, if  $I_t$  increases,  $R_t$  must decrease, all else being equal. For this reason, the total demand for physical capital varies in the opposite direction of the total demand for human capital services.

**The Case of Covered Sectors** In the case of ITC, the demand for physical capital services varies according to the sectors. Covered sectors see their demand for physical capital services generally decrease following the introduction of the NAP.

Following the introduction of the NAP, the revenue effect due to the reduction in these sectors' production leads to a decrease in the demand for physical capital services relative to the baseline. Moreover, the induced technological change effect that takes place in favor of the demand for human capital services also has a negative impact on the demand for physical capital services. Only the substitution effect between the tangible inputs may have a positive effect on their usage, but this is unsure. The

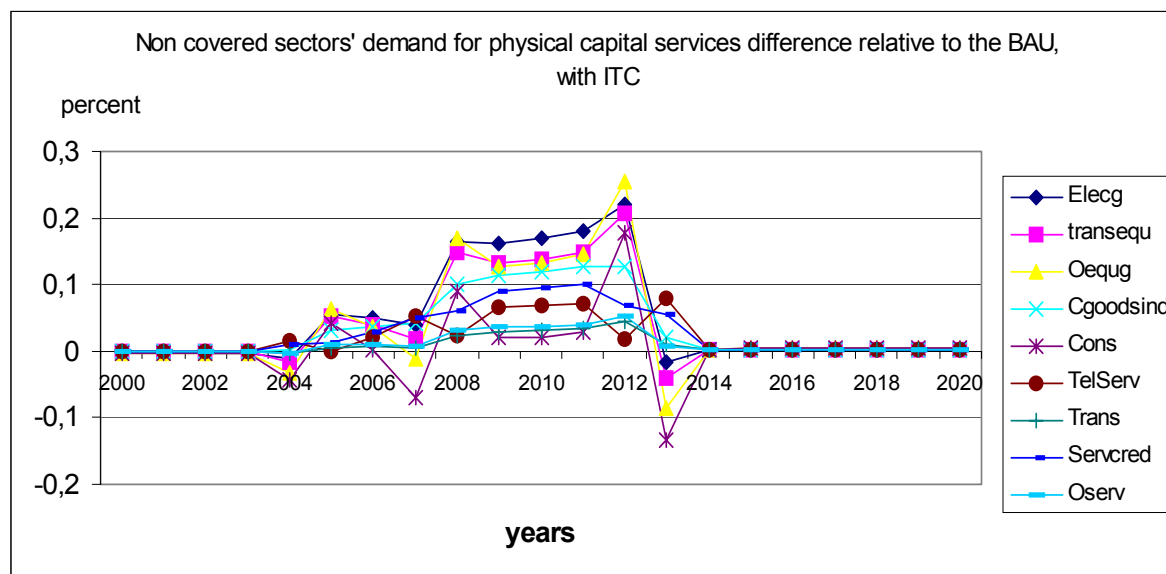


FIG. 4.19 – Non covered sectors demand for physical capital services relative to the BAU with ITC

investment effect also leads to a reduction in the demand for physical capital services. It thus comes as no surprise that the sum of the revenue effect, the induced technological change effect, and the investment effect is greater in the case of the covered sectors than the substitution effect (the impact on physical capital services, of which is uncertain). For this reason, the demand for physical capital services decreases relatively the BAU, following the introduction of the constraint.

**The Case of Non Covered Sectors** The demand for physical capital services increases quite significantly in the case of the non covered sectors.

In the case of the non covered sectors, the revenue effect has a positive impact on the demand for human capital services, as the production for non covered sectors increases. Moreover, the induced technological change effect has a negative impact on the demand for physical capital services because of the increased demand for human capital services, the intangible input. The investment effect also has a negative effect on the demand for physical capital services. Finally, the impact of the substitution effect



on the demand for physical capital services remains unsure. For non covered sectors, it appears (see graph on demand for physical capital services for non covered sectors), that the sum of the revenue effect and the substitution effect overrule the induced technological change effect and the investment effect, as the total demand for physical capital services increases similarly to the production.

The only difference between covered sectors and non covered sectors is the direction of the revenue effect. It directs the total demand for physical capital services directly.

**Conclusion** The total demand for physical capital services follows the inverse pattern of the total demand for human capital services, due to the fact that the investment in research and development and the investment in physical capital both derive from the aggregate income accounting definition. We here show that there is a crowding out effect, whereby investment in research and development reduces the possibilities to invest in physical capital. Therefore, an increase in the investment in R&D one year, will necessarily lead to a decrease in the demand for physical capital services the following year.

A close look at the demand for physical capital services both for covered and non covered sectors, shows that the only difference between the groups of sectors is the direction of the revenue effect, which clearly appears to be the main guide to the demand for physical capital services. The revenue effect is the strongest effect that plays a role in the demand for physical capital services. This is particularly clear if we compare the production variations and variations in the demand for physical capital services, in both groups of sectors after the introduction of the NAP. When the production increases, the demand for physical capital services also increases in a similar fashion, and when the production decreases the demand for physical capital services decreases in a similar fashion.

## 4.7 Conclusion

In this paper we presented a new method for modeling technological change in a CGE framework. We constructed a CGE model for France calibrated on a SAM that we modified such that a new factor of production, human capital, and a new demand, investment in research and development, may be accounted for. We then created a forward looking model with two capital stocks, physical capital and human capital, that grow with the same rate of growth  $\gamma$  which is the growth rate of the economy. We thus suppose that the French economy is on a balanced growth path since 1995.

In this setting, firms may now react to any constraint on the economy, by either substituting between tangible inputs or by substituting human capital, the intangible input, for the other tangible inputs (physical capital services, labor, energy, materials). This last substitution possibility is the induced technological change effect.

While the differences between the case with ITC and the case without ITC are indeed minimal, we show that in the case where ITC is taken into account, emissions are more reduced following the introduction of an emission constraint, comparatively to the case where there is NO ITC. Indeed, the induced technological change effect, leads to a reduced demand for tangible goods (including a reduced demand for the goods produced by all sectors, which create emissions), comparatively to the case where there is NO ITC. It follows that emissions reductions are accentuated through the induced technological change effect, as it builds on the substitution effect between the tangible goods (only possible reaction of firms in the case where there is NO ITC).

We show that in the case where ITC is taken into account, the production variations are limited both in the cases of the covered sectors and the non covered sectors, relative to the case where ITC is not taken into account. Indeed, we show that following the introduction of an emission constraint, because of the induced technological change effect, whereby firms may now demand intangible goods facing an environmental con-

straint, the stringiness of the constraint is automatically reduced, because generally less tangible goods are necessary for production (the constraint becomes therefore less restrictive). This leads to a reduced drop in the demand for the covered sectors' production. As the drop in the demand for the production of covered sectors is not so big, the increase in the demand for non covered sectors' production is also therefore limited in the case where there technological change is taken into account.

Moreover, similarly to Sue Wing (2001), we show that non covered sectors (sectors that are not constrained in any way by an emission constraint) will increase their demand for human capital services more than covered sectors will, because the revenue effect, whereby covered sectors' production decreases and non covered sectors' production increases, limits the induced technological change effect for covered sectors, and enhances it for non covered sectors.

Similarly to Popp (2002), we show that peaks in the demand for human capital services appear the first years of the introduction of the constraint, and disappear the following years, although the constraint is still active. This is due to the fact that the model contains a time-lag, whereby investment in research and development a first year influences the supply of human capital services the following year. We show that the induced technological change effect is effective only the first years of the introduction of a policy. After that the investment effect neutralizes the induced technological change effect. Such a result suggests that the induced technological change effect responds only to the strengthening of a constraint. In order for a policy to lead to durable induced technological change, it appears necessary for a policy to be constantly increased in stringency. Otherwise, firms will choose to engage in substitutions between their tangible inputs (capital, labor, energy, materials) in order to face an emission constraint, rather than increase their demand for human capital services. We hereby show that induced technological change is a very shortly lived process that can only be induced by a constant increase in a policy's stringency.

Our model suggests that the induced technological change effect is small. Similarly to Nordhaus (2002), it appears that over the time span during which the policy is implemented, the substitutions between tangible inputs play a greater role in helping the firms face the emission constraints, than the induced technological change process. Indeed, after the first year of the implementation, firms will face the environmental constraint by engaging in substitution processes between their tangible inputs, while their demand for human capital services returns to the baseline level.

We show that the total demand for physical capital services is ruled by a crowding out effect consequence of the aggregate income accounting definition. Therefore, an investment in R&D in year  $t$  necessary leads to a decrease in the supply for physical capital services in year  $t+1$ . We also show, that the major effect influencing the demand for physical capital services in the case of covered and non covered sectors, is the revenue effect, while both the induced technological change effect, and the investment effect rule the demand for human capital services.

## ANNEXE A : Rates and Elasticities

To calibrate the model, we use a number of values. We first use a SAM for France compiled by EUROSTAT and GEM-E3 researchers (see National Technical University of Athens). This SAM has 17 sectors, three of which are the fossil fuel sectors. Two factors of production are taken into account, capital and labor.

### A1 - Data for Human Capital Estimation

We need to estimate the human capital embodied in the interindustry transaction matrix and in the factor matrix, to proceed to the extraction of these values from the SAM.

In the case of the interindustry transaction matrix, we use the Yale Technology Concordance made available by D. Johnson at Wellesely, and multiply the patent matrix to the values of sectoral R&D in 1995 derived from the Centre de l'Informatique Statistique et de l'Aide à la Décision of the Ministère de l'éducation nationale, de l'enseignement supérieur et de la recherche. This gives us an estimation of a interindustry technology matrix.

To estimate human capital in the factor matrix, we determine the number of researchers that were involved in R&D activities in firms in 1995. The only values available from the same source as for the values of sectors R&D (Centre de l'Informatique Statistique et de l'Aide à la Décision of the Ministère de l'éducation nationale, de l'enseignement supérieur et de la recherche), being only for the years 1992 and 1998, we average the two values per sector to make an estimation of their number in 1995. To obtain a value of human capital, we multiply this estimate by the average wage for qualified workers, based on the article of Gubian et Ponthieux (2000).

### A2 - The Model's Rates

We construct a forward looking version of the model. Therefore, we suppose that the model is on a balanced growth path, since 1995, where all sectors grow at the

	2000	2010	2020
DGEM-OE	105,6	119	129
ITC	105,2	114	126
NO ITC	103.3	114	126

FIG. 4.20 – CO<sub>2</sub> emissions for France

growth rate of the economy. We choose  $\gamma$ , the growth rate of the economy, to be 1% per year on the balanced growth path.

Physical capital and human capital grow on the balanced growth path at the rate of growth of the economy, and their stocks depreciate each year at different depreciation rates. The depreciation rate of human capital is often considered to be approximately 15% (Bosworth D. and Jobome G., (2001)). Nadiri et al (1993) estimate that the depreciation rate for human capital in the manufacturing sector in the US is 12.9%, and the depreciation rate for physical capital is 5.9%<sup>38</sup>.

The model predicts business as usual emissions that are very close to those predicted by the French General Directorate for Energy and Raw Materials, and the Observatoire de l'Énergie (2004). In table 4.20 we display the predicted CO<sub>2</sub> emissions in the Business as Usual scenarios in Mega Tons of Carbon (MtC), for the French economy, for the DGEM-OE model, and ours with and without the Induced Technological Change specification.

### A3 - The Model's Elasticities of Substitution

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<sup>38</sup>We are well aware that we are applying these values to all sectors, and in France. However, we do not expect these values to be too different to the French values.

Elasticity of substitution between human capital services and KLEM	2
Elasticity of substitution between physical capital services-labor and materials-energy	0.7
Elasticity of substitution between materials and energy	0.75
Elasticity of substitution between capital and labor	1
Elasticity of substitution between fossil fuels and electricity	0.7
Elasticity of substitution between materials	0.6
Elasticity of substitution between fossil fuels	1
Armington Elasticity	2

FIG. 4.21 – Elasticities of substitution in the model

## ANNEXE B : The Social Accounting Matrix with Human Capital Services

We here present the new Social Accounting Matrix with human capital services as an input to production and R&D as a demand factor (Value in Million Euros).

	Agric	Coal	Oil	Gas	Elect	FerNf	ChemPro	Onrjint	Elecg	transequ	Oeug
Agric	10.034	0.007			0.002	2.52E-04	0.044	0.278			0.01
Coal		0.626			0.42	0.82	0.049	0.096			
Oil	1.853	0.03	11.404	0.007	0.073	0.37	2.453	0.919	0.425	0.442	0.458
Gas	0.065			0.033	0.08	0.218	0.604	0.855	0.067	0.178	0.053
Elect	0.294	0.079	0.252	0.027	4.135	1.369	1.274	2.158	0.314	0.768	0.435
FerNf	0.141	0.002	0.011		0.057	11.226		5.962	1.148	5.221	4.09
ChemPro	4.715	0.043	0.831		0.054	0.62	14.097	2.593	0.729	1.16	0.484
Onrjint	0.306	0.274	1.355	0.089	0.979	1.291	4.688	28.909	8.223	12.505	7.58
Elecg	0.011	0.018	0.266	0.013	0.537	0.279	0.188	1.134	6.748	6.696	3.085
transequ	0.112		0.009	0.002	0.018	0.012	0.057	0.293	0.056	20.894	0.083
Oeug	0.967	0.097	0.101	0.017	0.145	0.259	0.513	1.36	0.57	2.285	5.686
Cgoodsind	7.421	0.073	0.118		0.019	0.056	3.815	1.756	4.42	6.392	1.592
Cons	0.094	0.05	0.654	0.295	0.847	0.053	0.129	0.124	0.099	0.205	0.127
TelServ	0.012	0.011	0.061	0.046	0.222	0.198	0.567	1.071	0.502	0.486	0.69
Trans	0.459	0.059	0.767	0.269	0.333	0.908	2.697	6.402	2.112	1.477	1.319
Servcred	0.311	5.32E-04	0.155	0.004	0.124	0.225	0.626	0.728	0.505	0.663	0.535
Oserv	6.92	0.72	4.73	0.909	4.639	3.087	12.058	14.868	11.603	22.086	17.035
SUBSIDY	-3.311	-0.93	-0.003	-0.002	-0.063	-0.068	-0.207	-0.805	-0.114	-1.284	-0.86
VA_TAX	0.809	0.069	3.32	0.718	1.65	0.03	1.569	4.225	4.052	7.499	5.973
DUTIES	0.116	0.001	0.175	0.002	0.029	0.072	0.15	0.237	0.115	0.251	0.139
ID_TAX	1.142	0.121	19.282	0.233	3.183	0.653	1.652	2.732	1.615	2.302	1.546
SL	1.658	0.86	2.532	0.608	5.173	4.772	10.162	26.993	16.221	18.027	14.993
UL	2.781	0.021	0.396	0.005	0.056	0.128	1.368	0.512	1.116	1.874	0.995
Human Cap.	0.809	0.014	0.124	0.013	0.094	0.236	0.233	0.213	0.528	0.633	0.316
Physical Cap.	26.179	0.276	0.713	0.257	13.526	4.71	11.518	21.508	13.269	13.953	10.415

	Cgoodsind	Cons	TelServ	Trans	Servcred	Oserv	FCONS	INV	DSTOCK	EXPORTS	IMPORT	R&D
Agric	28.408		2.97E-04			2.808	18.75	0.499	-2.072	12.2	-7.448	0.379
Coal	2.00E-02	3.52E-04				0.003	0.51		0.689	0.035	-0.747	
Oil	2.797	1.646	0.259	4.705	0.652	11.897	17.598		-1.139	2.806	-12.678	0.275
Gas	0.38	6.00E-03	4.13E-04		0.001	0.631	4.367			0.073	-4.073	0.008
Elect	1.127	8.20E-02	8.23E-04	0.268	0.009	2.671	18.143			2.912	-0.178	0.192
FerNf	0.475	3.01		0.099		0.37	0.226		-4.314	14.462	-10.657	
ChemPro	6.652	1.166		0.041		6.982	21.385		3.403	29.1	-23.995	0.241
Onrjint	6.439	15.714	0.235	0.315	2.007	19.325	18.476	8.304	-11.524	22.302	-23.043	0.376
Elecg	0.081	4.999	0.661	0.118		7.581	10.115	14.857	20.157	18.617	-22.275	0.438
transequ	0.177	0.189	0.082	2.115		12.191	30.821	15.811	32.544	47.34	-38.453	0.358
Oeug	1.493	4.499		0.127	0.018	6.33	3.405	39.412	12.848	27.194	-30.77	0.221
Cgoodsind	32.286	6.773	0.154	0.549	0.044	15.743	117.83	2.198	-1.846	41.811	-46.278	0.226
Cons	0.136	0.064	0.045	0.118		3.976	0.103		5.624		11.388	
TelServ	0.864	0.594	2.194	0.403	3.423	11.393	10.944		0.113	0.176	-0.303	0.15
Trans	2.328	3.938	0.458	7.968	0.389	17.701	17.204		-4.722	4.975	-4.396	
Servcred	1.003	2.295		0.767	30.413	50.704	6.947		-0.71	2.026	-4.849	0.231
Oserv	35.61	32.583	1.508	8.331	34.948	113.901	645.817	22.911	-43.692	43.007	-22.486	0.12
SUBSIDY	-4.477	-0.828	-0.001	-3.748	-0.961							
VA_TAX	6.599	16.544	2.467	1.827								
DUTIES	0.425											
ID_TAX	7.687	3.321	0.459	2.08		3.822						
SL	26.458	33.089	5.749	18.38		0.423	382.43					
UL	6.005	0.083	5.161	0.566		6.899	23.544					
Human Cap.	0.259	0.355	0.22	0.099	0.333	0.247						
Physical Cap.	31.922	21.17	14.164	17.521	6.304	200.694						



## ANNEXE C : Tables of differences in the ratios Production / Tangible inputs in the policy case and in the BAU case, for both ITC and no ITC

In the first table, we present the values of  $100 * (\frac{PROD_{pol}}{TANG_{pol}} / \frac{PROD_{bau}}{TANG_{bau}} - 1)_{ITC}$  for all sectors in the case where ITC is taken into account.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
<b>Agric</b>	1,299E-05	-3,434E-06	-5,288E-06	3,739E-07	4,0617E-06	0,00574735	-0,0005978	-0,0003395	0,01031899	-0,0015933	-0,0016625	-0,0015224	-0,0019937
<b>Coal</b>	-2,33E-06	-2,307E-06	-2,284E-06	-2,262E-06	-0,0002403	0,00790085	0,00582608	0,00628985	0,02151206	0,01814322	0,01934937	0,02021099	0,02078547
<b>Oil</b>	-7,971E-06	-7,892E-06	-7,814E-06	-5,139E-06	-1,471E-05	0,00281517	0,00137401	0,00155361	0,00700775	0,00439305	0,00460227	0,00492683	0,00504324
<b>Gas</b>	0,00026849	0	0	0,00028089	-5,773E-05	0,00214902	-0,000296	-9,746E-05	0,00443093	-0,0004059	-0,0006175	-0,0002942	-0,0001738
<b>Elect</b>	5,0894E-06	7,588E-06	-1,571E-05	0	1,6244E-05	0,00151484	0,00011238	0,00019985	0,00303218	0,0038632	0,0044346	0,00051104	0,00045221
<b>FerF</b>	-2,124E-05	-2,008E-05	1,03E-05	7,628E-06	-1,872E-05	0,00363057	0,00272363	0,00312576	0,01546119	0,00349487	0,00386346	0,00352641	0,00366551
<b>ChemPro</b>	4,100E-06	5,309E-06	-7,112E-06	1,7144E-05	-2,73E-06	0,00193026	0,00025347	0,00035162	0,00410133	0,00085542	0,0003975	0,00102508	0,00036644
<b>Onjirt</b>	2,3379E-06	4,5747E-06	-7,016E-07	-3,00E-08	-5,577E-06	0,00094752	2,8467E-05	7,0883E-05	0,00183453	0,00014501	0,00015182	0,00018485	0,00014825
<b>Electg</b>	1,0688E-06	-4,332E-06	4,5642E-06	-8,42E-06	-9,147E-06	0,00360599	-0,0004074	-0,0002624	0,00624928	-0,0010875	-0,0011234	-0,0010287	-0,0012885
<b>transequ</b>	-5,547E-07	-2,831E-06	-4,626E-06	-6,462E-06	-1,001E-06	0,00259413	-0,0001861	-8,128E-05	0,00475101	-0,0004508	-0,0004736	-0,0003888	-0,0005569
<b>Chemg</b>	8,74E-07	-1,121E-06	-1,525E-05	-7,989E-06	-1,224E-05	0,00214267	-0,000141	-4,805E-05	0,00992873	-0,0003678	-0,0003816	-0,0003241	-0,0004525
<b>Qgoodsind</b>	-4,886E-06	5,3892E-07	-3,723E-06	1,2327E-06	1,9298E-07	0,00062302	-6,907E-05	-5,141E-05	0,00110506	-0,000208	-0,0002141	-0,0001938	-0,0002418
<b>Cons</b>	-3,336E-06	2,008E-06	1,8037E-06	2,398E-06	3,6032E-06	0,00123239	-0,0001297	-8,194E-05	0,00221587	-0,0003378	-0,000348	-0,0003233	-0,000406
<b>TelSav</b>	-2,571E-05	9,611E-06	1,189E-05	2,964E-05	-1,242E-05	0,00308189	-0,0005881	-0,0004547	0,00524363	-0,0016452	-0,000173	-0,0016895	-0,0019548
<b>Trans</b>	8,7518E-06	6,988E-06	5,2147E-06	1,7822E-05	-1,633E-05	0,00072671	-5,139E-05	-4,632E-05	0,00132758	-0,0001582	-0,000173	-0,0001479	-0,0001982
<b>Sarvred</b>	-1,019E-05	-1,368E-07	-3,38E-07	2,675E-07	-1,023E-05	0,00160249	-0,0002491	-0,0001828	0,0027895	-0,0006871	-0,0007173	-0,0006786	-0,0008136
<b>Osav</b>	2,1025E-07	-2,998E-07	-7,747E-07	-1,944E-07	-1,16E-06	0,00011772	-1,998E-05	-1,511E-05	0,00020127	-5,354E-05	-5,617E-05	-5,433E-05	-6,324E-05

### Case with ITC

In the second table we present the values of  $100 * (\frac{PROD_{pol}}{TANG_{pol}} / \frac{PROD_{bau}}{TANG_{bau}} - 1)_{NOITC}$  for all sectors in the case where ITC is not taken into account.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
<b>Agric</b>	2,8287E-05	1,2513E-05	1,1283E-05	1,0079E-05	8,8906E-06	-0,0087864	-0,0089046	-0,0093213	-0,0267563	-0,028032	-0,029515	-0,0307083	-0,031936
<b>Coal</b>	-5,678E-05	0,00026121	0,00025863	-0,0004214	-0,0004172	-0,8542367	-0,8538117	-0,9048065	-2,5072011	-2,6212869	-2,7511369	-2,8561183	-2,963711
<b>Oil</b>	-4,424E-05	-4,38E-05	5,9294E-05	3,9138E-05	3,8751E-05	-0,4201163	-0,4248455	-0,4455779	-1,2683175	-1,3283463	-1,3973089	-1,4531562	-1,5106696
<b>Gas</b>	0	0	0	0	0	-0,028256	-0,0289084	-0,0306424	-0,0858668	-0,0901913	-0,0949179	-0,0982682	-0,1024369
<b>Elect</b>	-3,815E-05	-6,37E-05	-2,345E-05	-7,406E-05	-0,0001488	-0,1169895	-0,118218	-0,1240141	-0,3472772	-0,3632796	-0,3816101	-0,3964282	-0,4117164
<b>FerN</b>	2,5669E-05	-2,198E-05	-1,802E-05	-4,344E-05	3,0799E-05	-0,1249614	-0,1263186	-0,1324655	-0,372088	-0,3893147	-0,4091022	-0,4250571	-0,4415066
<b>ChemPro</b>	1,2469E-05	-4,162E-06	-4,663E-08	1,7134E-05	-2,066E-06	-0,0618101	-0,0625041	-0,0655613	-0,1870117	-0,1958751	-0,2061063	-0,2143809	-0,2228871
<b>Onjint</b>	-8,571E-06	2,1396E-06	-1,546E-06	-5,884E-06	-2,824E-06	-0,0283474	-0,0286655	-0,030067	-0,0856666	-0,0896229	-0,094276	-0,0980474	-0,1019298
<b>Elecg</b>	-2,73E-05	-1,452E-05	-2,709E-05	-2,166E-06	-2,343E-06	-0,0020499	-0,0020517	-0,0021694	-0,0061884	-0,0064861	-0,0066039	-0,007083	-0,0073608
<b>transequ</b>	8,7239E-07	3,5624E-06	-8,771E-06	-9,414E-06	-1,004E-05	-0,0011118	-0,0011222	-0,0011829	-0,0033644	-0,0035401	-0,0037237	-0,0038626	-0,004027
<b>Coqg</b>	-1,102E-05	-1,325E-05	6,4645E-06	1,7197E-06	-2,932E-06	-0,0017929	-0,0018207	-0,0019028	-0,0054774	-0,0057303	-0,0060414	-0,0062846	-0,006514
<b>Ggoodsind</b>	1,8538E-06	2,1052E-06	7,1354E-06	2,5926E-06	2,8288E-06	-0,0042298	-0,0042739	-0,0044852	-0,0128115	-0,0134241	-0,0141355	-0,0147121	-0,0152949
<b>Cons</b>	-4,192E-06	-5,128E-06	6,2107E-06	-7,017E-06	3,9719E-06	-0,0033574	-0,0033931	-0,0035667	-0,0102166	-0,0107154	-0,011271	-0,0117304	-0,0121904
<b>TelSav</b>	-8,439E-05	3,1103E-05	3,2207E-06	-5,141E-05	-0,000105	-0,0077429	-0,007702	-0,0081315	-0,0231588	-0,024438	-0,0256473	-0,026589	-0,0276648
<b>Trans</b>	1,3742E-05	1,3368E-05	-1,887E-06	2,7143E-05	1,205E-05	-0,0305791	-0,0309293	-0,0324646	-0,0928671	-0,0973012	-0,1023873	-0,1065396	-0,110786
<b>Sarvred</b>	-5,599E-06	1,1567E-05	-4,086E-06	2,7577E-06	9,4668E-06	-0,0015257	-0,0015566	-0,0016135	-0,0046542	-0,0048726	-0,0051307	-0,005348	-0,0055521
<b>Osav</b>	2,6544E-06	-6,884E-07	-5,886E-07	9,5081E-07	4,8286E-06	-0,0071614	-0,0072425	-0,0075984	-0,0217373	-0,0227754	-0,0239701	-0,0249886	-0,0259331

## Case with no ITC

The values of the first table are greater than the values of the second table, which means that in the case of ITC, simply less tangible inputs are used as inputs to production than in the case where there is no ITC. This results from the fact that the demand for human capital services as an input to production leads to a lesser demand for the tangible inputs.

## ANNEXE D : The Dual Approach

In this annex we present an algebraic summary of the forward looking model. This model is formulated as a MCP or Mixed Complementary Problem.

Three classes of equations or conditions of equilibrium underlie the economic equilibrium of the model :

- Zero profit conditions which are dual to the levels of activity of each sector
- Market clearance conditions for factors of production and goods which are dual to the prices of factors and goods
- Income balance definition for the representative agent which is dual to the aggregate income level

Therefore, in the complementarity format, the series of equations of these three classes of equilibrium conditions are linked or paired to a dual variable. The symbol  $\perp$  represents the duality. All prices reported in this annex are in present values.

The economy is here modeled as a representative agent, with  $n$  industries (indexed by  $j = 1 \dots n$ ). Each industry produces one unique good (indexed by  $i = 1 \dots n$ ). There are seventeen sectors in the economy. We define *noncov*, *cov*, *ener* and *nener* as subsections of  $i$  and as following :

<i>noncov</i>	non covered sectors
<i>cov</i>	covered sectors
<i>ener</i>	energy sectors
<i>nener</i>	non energy sectors
<i>FF</i>	fossil fuel sectors

These four subsections are defined as in the following table :

Agriculture	<i>noncov</i>	<i>ne</i>	
Coal	<i>cov</i>	<i>ener</i>	<i>FF</i>
Oil	<i>cov</i>	<i>ener</i>	<i>FF</i>
Gas	<i>cov</i>	<i>ener</i>	<i>FF</i>
Electricity	<i>cov</i>	<i>ener</i>	
Ferrous and non ferrous metals	<i>cov</i>	<i>ne</i>	
Chemical Products	<i>cov</i>	<i>ne</i>	
Other Energy Intensive Goods	<i>cov</i>	<i>ne</i>	
Electric Goods	<i>noncov</i>	<i>ne</i>	
Transport Equipment	<i>noncov</i>	<i>ne</i>	
Other Equipment Goods	<i>noncov</i>	<i>ne</i>	
Consumer Goods Industries	<i>noncov</i>	<i>ne</i>	
Construction	<i>noncov</i>	<i>ne</i>	
Telecommunication Services	<i>noncov</i>	<i>ne</i>	
Transport	<i>noncov</i>	<i>ne</i>	
Service and Credit insurances	<i>noncov</i>	<i>ne</i>	
Other Services	<i>noncov</i>	<i>ne</i>	

We use the acronyms *CES* (Constant Elasticity of Substitution) and *CD* (Cobb Douglas) and *LT* (Leontieff) to indicate the functional form in some of the equations for sake of simplicity.

## D1 - Definition of Terms

Prices :

$p_{i,t}$	Price of good produced by industry $i$ at time $t$
$P_t$	Price of total consumption at time $t$
$PK_{t+1}$	Dual price of the physical capital stock in $t + 1$
$PKT$	Dual price of physical capital stock in final period
$PH_{t+1}$	Dual price of the human capital stock in $t + 1$
$PHT$	Dual price of human capital stock in final period
$RK_t$	Rental price of physical capital at time $t$
$r_{kt}$	Rental rate of physical capital at time $t$
$RH_t$	Rental price of human capital at time $t$
$r_{ht}$	Rental rate of human capital at time $t$
$w_t$	Wage rate at time $t$
$p_{ME_{i,t}}$	Price of the materials-energy bundle for sector $i$ at time $t$
$p_{M_{i,t}}$	Price of materials for sector $i$ at time $t$
$p_{E_{i,t}}$	Price of the energy bundle for sector $i$ at time $t$
$p_{FF_{i,t}}$	Price of fossil fuel bundle (ff) in sectors $i$ at time $t$
$p_{ac_{i,t}}$	Price of ff in covered sectors in sectors $i$ with carbon tax at time $t$

$p_t^{FT}$	Price of foreign exchange at time $t$
$p_{m_{i,t}}$	Price of imported good $i$ at time $t$
$p_{x_{i,t}}$	Price of exported good $i$ at time $t$
$p_{A_{i,t}}$	Price of armington good $i$ at time $t$
$p_U$	Price of utility
$p_{const}$	Price of consumption for representative agent
$ptcl_t$	Price of carbon

## Elasticities of substitution and shares

$\sigma_Y$	elasticity of substitution between tangible and intangible inputs
$\sigma_{xkl}$	elasticity of substitution between the capital-labor bundle and the materials-energy bundle
$k_i$	share of capital in the capital-labor bundle
$\sigma_I$	elasticity of substitution in intratemporal investment
$\sigma_A$	elasticity of substitution between domestic and imported goods
$\sigma_{ME}$	elasticity of substitution between materials and energy
$\sigma_{FFE}$	elasticity of substitution between fossil fuels and electricity

## Variables

$L_t$	Labor at time $t$
$I_t$	Investment in physical capital at time $t$
$\tilde{I}_{it}$	Investment in physical capital industry $i$ at time $t$
$R_t$	Investment in human capital at time $t$
$\tilde{R}_{it}$	Investment in human capital industry $i$ at time $t$
$V_{K_t}$	Value of physical capital services at time $t$
$V_{H_t}$	Value of human capital services at time $t$
$y_{i,t}$	Good produced by industry $i$ at time $t$
$x_{i,jt}$	Interindustry transaction good at time $t$
$Cons_t$	Consumption at time $t$
$m_{j,t}$	Import of good $j$ at time $t$
$ex_{j,t}$	Export of good $j$ at time $t$
$BOP_t$	Balance of Payment at time $t$
$BOP_0$	Balance of Payment in the baseline
$A_{i,t}$	Armington aggregate of good $i$ at time $t$
$EXP_t$	Export of goods at time $t$
$IMP_t$	Import of goods at time $t$
$U$	Utility of the representative agent
$W_t$	Intratemporal utility
$BUDG$	Budget of the representative agent

## Profits

$\Pi_{i,t}$	Zero profit condition for good $i$ at time $t$
$\Pi_{i,t}^I$	Zero profit condition for investment in physical capital
$\Pi_{i,t}^R$	Zero profit condition for investment in human capital
$\Pi_{i,t}^{IMP}$	Zero profit condition for imported good $i$ at time $t$
$\Pi_{i,t}^{EXP}$	Zero profit condition for exported good $i$ at time $t$
$\Pi_{i,t}^A$	Zero profit condition for armington good $i$ at time $t$
$\Pi^U$	Zero profit condition for intertemporal utility
$\Pi_t^{Cons}$	Zero profit condition for intratemporal utility at time $t$

Parameters

$\alpha_y$	Share of tangibles in the production function
$\beta$	Share of the materials-energy bundle in the tangible goods
$k$	Share of physical capital services (PCS) in the PCS-labor bundle
$\alpha_{M,i}$	Share of materials in the materials-energy bundle for sector $i$
$\alpha_{FF,i}$	Share of fossil fuels in the fossil fuel-electricity bundle for sector $i$
$b_i$	Share of domestic goods in the armington specification
$\delta_k$	Depreciation rate of physical capital
$\delta_h$	Depreciation rate of human capital
$g$	Growth rate of the economy
$\rho$	Rate of time preference
$ccoe_{FF}$	Carbon emission coefficient on each fossil fuel

## D2 - Algebraic Summary of the Model

The summary of the model is determined through the zero profit, market clearance and income balance conditions.

*In our model, there are six zero profit market conditions.*

- Zero profit condition for  $t = 1..T$  for production of goods  $\perp y_{i,t}$

$$\begin{aligned} \Pi_{i,t} &= \left( \alpha_y (\beta p_{ME_{i,t}}^{\frac{\sigma_{xkl}-1}{\sigma_{xkl}}} + (1-\beta) (RK_t^k w_t^{1-k})^{\frac{\sigma_{xkl}-1}{\sigma_{xkl}}})^{\frac{\sigma_{xkl}}{\sigma_{xkl}-1} * \frac{\sigma_Y-1}{\sigma_Y}} + (1-\alpha_y) RH_t^{\frac{\sigma_Y-1}{\sigma_Y}} \right)^{\frac{\sigma_Y}{\sigma_Y-1}} \\ -p_{i,t} &\geq 0 \end{aligned} \tag{4.27}$$

With :

$$p_{ME_{i,t}} = \left( \alpha_{M,i} p_{M_{i,t}}^{\left(1-\frac{1}{\sigma_{ME}}\right)} + (1-\alpha_{M,i}) p_{E_{i,t}}^{\left(1-\frac{1}{\sigma_{ME}}\right)} \right)^{\left(\frac{1}{1-\frac{1}{\sigma_{ME}}}\right)}$$

With

$$p_{M_{i,t}} = CES(p_{A_{ne,t}})$$

With

$$pE_{i,t} = \left( \alpha_{FF} p_{FF_{i,t}}^{(1-\frac{1}{\sigma_{FFE}})} + (1 - \alpha_{FF}) p_{A_{elect,t}}^{(1-\frac{1}{\sigma_{FFE}})} \right) \left( \frac{1}{1-\frac{1}{\sigma_{FFE}}} \right)$$

With

$$\begin{aligned} p_{FF_{i,t}} &= CD(pac_{Coal,t}; pac_{Oil,t}; pac_{Gas,t}) & \text{if } i = cov \\ p_{FF_{i,t}} &= CD(pA_{Coal,t}; pA_{Oil,t}; pA_{Gas,t}) & \text{if } i = noncov \end{aligned}$$

With

$$pac_{FF,t} = LT(p_{AFF,t}; ptcl_t; ccoef_{FF}) \quad \text{if } i = cov$$

– Zero profit condition for  $t = 1..T - 1$  for investment in physical capital  $\perp I_{i,t}$

$$\Pi_{i,t}^I = p_{A_{i,t}} - PK_{t+1} = 0 \tag{4.28}$$

– Zero profit terminal condition in the post terminal period  $T$  for investment in physical capital  $\perp I_{i,T}$

$$\Pi_{i,T}^I = p_{A_{i,T}} - PKT = 0 \tag{4.29}$$

– Zero profit condition for  $t = 1..T - 1$  for investment in human capital  $\perp R_{i,t}$

$$\Pi_{i,t}^R = p_{i,t} - PH_{t+1} = 0 \tag{4.30}$$

– Zero profit terminal condition in the post terminal period  $T$  for investment in physical capital  $\perp R_{i,T}$

$$\Pi_{i,T}^R = p_{i,T} - PHT = 0 \tag{4.31}$$

– Zero profit condition for  $t = 1..T - 1$  for physical capital accumulation.  $\perp K_{i,t}$

$$PK_t = RK_t + (1 - \delta_k)PK_{t+1} \tag{4.32}$$

– Zero profit condition in the post terminal period  $T$  for physical capital  $\perp K_{i,T}$

$$PK_T = RK_T + (1 - \delta_k)PKT$$

– Zero profit condition for  $t = 1..T - 1$  for human capital accumulation  $\perp H_{i,t}$

$$PH_t = RH_t + (1 - \delta_h)PH_{t+1} \tag{4.33}$$

- Zero profit condition in the post terminal period  $T$  for human capital  $\perp H_{i,T}$

$$PH_T = RH_T + (1 - \delta_h)PHT \quad (4.34)$$

- Zero profit condition for  $t = 1..T$  for the armington aggregate  $\perp A_{i,t}$

$$\Pi_{i,t}^A = \left( b_i p_{i,t}^{1-\frac{1}{\sigma_A}} + (1 - b_i) p_{m_{i,t}}^{1-\frac{1}{\sigma_A}} \right)^{\frac{1}{1-\frac{1}{\sigma_A}}} - p_{A_{i,t}} \geq 0 \quad (4.35)$$

- Zero profit condition for  $t = 1..T$  for imported goods  $\perp m_{i,t}$

$$\Pi_{i,t}^{IMP} = p_t^{FT} - p_{m_{i,t}} \geq 0 \quad (4.36)$$

- Zero profit condition for  $t = 1..T$  for exported goods  $\perp ex_{i,t}$

$$\Pi_{i,t}^{EXP} = p_{x_{i,t}} - p_t^{FT} \geq 0 \quad (4.37)$$

- Zero profit condition for  $t = 1..T$  for intratemporal utility  $\perp Cons_t$

$$\Pi_t^{Cons} = p_{A_{j,t}} - p_{const} \geq 0$$

- Zero profit condition for intertemporal utility  $\perp U$

$$\Pi^U = CES(p_{const}; \rho) - p^U \geq 0 \quad (4.38)$$

#### *Market clearance conditions*

- Market clearance condition for  $t = 1..T$  for all goods  $\perp p_{j,t}$

$$y_{i,t} = \tilde{I}_{i,t} + \tilde{R}_{i,t} + Cons_{i,t} + \sum_{j=1}^n x_{i,j,t} \quad (4.39)$$

- Market clearance condition for  $t = 1..T$  for the primary factor labor  $\perp w_t$

$$L_t = \sum_{i=1}^n \frac{\delta \Pi_{i,t}}{\delta w_t} y_{i,t} \quad (4.40)$$

- Market clearance condition for  $t = 1..T$  for the physical capital services  $\perp r_{kt}$

$$V_{K_t} = \frac{r_{kt} K_t}{r + \delta_k} = \sum_{i=1}^n \frac{\delta \Pi_{i,t}}{\delta R K_t} y_{i,t} \quad (4.41)$$



- Market clearance condition for  $t = 1..T$  for human capital services  $\perp r_{ht}$

$$V_{H_t} = \frac{r_{ht}H_t}{r + \delta_h} = \sum_{i=1}^n \frac{\delta \Pi_{i,t}}{\delta R H_t} y_{i,t} \quad (4.42)$$

- Market clearance condition for  $t = 1..T - 1$  for physical capital stock  $\perp PK_{t+1}$

$$K_{t+1} = (1 - \delta_k)K_t + I_t \quad (4.43)$$

- Terminal market clearance condition in the post terminal period  $T$  for physical capital stock  $\perp PKT$

$$KT = (1 - \delta_k)K_T + I_T \quad (4.44)$$

- Market clearance condition for  $t = 1..T - 1$  for human capital stock  $\perp PH_{t+1}$

$$H_{t+1} = (1 - \delta_h)H_t + R_t \quad (4.45)$$

- Terminal market clearance condition in the post terminal period  $T$  for human capital stock  $\perp PHT$

$$HT = (1 - \delta_h)H_T + R_T \quad (4.46)$$

- Market clearance condition for  $t = 1..T$  for import aggregate  $\perp p_{m_{i,t}}$

$$m_{i,t} = \frac{\delta \Pi_{i,t}^A}{\delta p_{m_{it}}} A_{i,t} \quad (4.47)$$

- Market clearance condition for  $t = 1..T$  for Armington aggregate  $\perp p_{A_{i,t}}$

$$A_{i,t} = \frac{\delta \Pi_{i,t}}{\delta p_{A_{it}}} y_{i,t} \quad (4.48)$$

- Market clearance condition for  $t = 1..T$  intratemporal utility  $\perp p_{cons_t}$

$$Cons_t = \frac{\delta \Pi^U}{\delta p_{cons_t}} U \quad (4.49)$$

- Market clearance condition for utility  $\perp p_u$

$$U = \frac{BUDG}{p_u} \quad (4.50)$$

– Balance of Payment for  $t = 1..T$

$$BOP_t = \sum_i \frac{\delta \Pi_{i,t}^{IMP}}{\delta p_t^{FT}} IMP_t - \sum_i \frac{\delta \Pi_{i,t}^{EXP}}{\delta p_t^{FT}} EXP_t \quad (4.51)$$

*Income balance condition*

The income balance condition, with  $RH_t V_{H_t} = r_{ht} H_t$  and  $RK_t V_{K_t} = r_{kt} K_t$  is given by :

$$\begin{aligned} \sum_{t=0}^T (w_t L_t + RH_t V_{H_t} + RK_t V_{K_t}) - (PKT * KT - PK_0 K_0) \\ -(PHT * HT - PH_0 H_0) + \sum_{t=0}^T p_t^{FT} BOP_t = BUDG \end{aligned} \quad (4.52)$$

*Endowments*

– Labor for  $t = 1..T$

$$L_t = (1 + g)^{t-1} L_0 \quad (4.53)$$

– Balance of Payments for  $t = 1..T$

$$BOP_t = (1 + g)^{t-1} BOP_0 \quad (4.54)$$

*Terminal capital condition*

We suppose that on the post terminal time  $T$  investment in physical capital and investment in human capital grow like consumption :

$$\frac{Const_T}{Const_{T-1}} = \frac{I_T}{I_{T-1}} = \frac{R_T}{R_{T-1}} \quad (4.55)$$

This is the dual definition of the CGE model.

## ANNEXE E : The Model Code

Presentation of the model code in GAMS and MPSGE, for the forward looking model with Induced Technological Change

\$TITLE MODEL \_F

table sam(\*,\*) 1995 social accounting matrix for france – million 1995 ecu

	Agric	Coal	Oil	Gas	Elect	FerNf	ChemPro	Onjint
Agric	1.042564577286E+04	6.708274962737E+00	0.000000000000E+00	0.000000000000E+00	1.993198933886E+00	2.511753059850E-01	4.926324313111E+01	2.773035535719E+02
Coal	0.000000000000E+00	6.221639034038E+02	0.000000000000E+00	0.000000000000E+00	4.174518704158E+02	8.181797300197E+02	4.968583969357E+01	9.537380293460E+01
Oil	1.844950328609E+03	3.295108714210E+01	1.147706836183E+04	1.111068982670E+01	7.275130951293E+01	3.863930675792E+02	2.450326066008E+03	9.162150070291E+02
Gas	6.546764316964E+01	0.000000000000E+00	0.000000000000E+00	3.235039476988E+01	7.967286703750E+01	2.196071991529E+02	6.018275604741E+02	8.504059024159E+02
Elect	2.929777401449E+02	7.913037591052E+01	2.508732670133E+02	2.714604061526E+01	4.186150042415E+03	1.368244449867E+03	1.269429635608E+03	2.146970405185E+03
FerNf	1.486411979822E+02	4.240429432550E+00	1.205334837463E+01	0.000000000000E+00	5.869762660178E+01	1.131133285086E+04	0.000000000000E+00	5.925115504124E+03
ChemPro	4.707359199728E+03	4.402148377507E+01	8.320345489943E+02	0.000000000000E+00	5.586555387238E+01	6.289450350552E+02	1.416707798832E+04	2.600753765790E+03
Onjint	3.287146215786E+02	2.729498545959E+02	1.350128933093E+03	8.838339805561E+01	9.791516247208E+02	1.295157314385E+03	4.689453945888E+03	2.893984486256E+04
Elecg	1.282274996084E+01	1.907597804235E+01	2.646679047835E+02	1.527588517985E+01	5.370895259691E+02	2.873073892438E+02	1.886033676238E+02	1.12883963848E+03
transequ	1.127309890993E+02	0.000000000000E+00	8.660338140420E+00	2.296376970165E+00	1.799580204798E+01	1.256581300470E+01	5.709805740711E+01	2.919558150731E+02
Oequg	9.827565101875E+02	9.911799387011E+01	1.032416304686E+02	2.087384611455E+01	1.458030858416E+02	2.795958419223E+02	5.215482521455E+02	1.360791287743E+03
Cgoodsind	7.401704069117E+03	7.293153108551E+01	1.182440701522E+02	0.000000000000E+00	1.959573828417E+01	5.982590535245E+01	3.802158849083E+03	1.750997408438E+03
Cons	2.191392630286E+02	4.942323804122E+01	6.518959108245E+01	2.936275672524E+02	8.425241276412E+02	5.280731035803E+01	1.279094992933E+02	7.240398946578E+02
TelServ	1.161807225045E+01	1.096068694238E+01	6.067068819840E+01	4.578893688938E+01	2.210247269594E+02	1.975930857961E+02	5.635449525040E+02	1.064803179625E+03
Trans	4.568479478749E+02	5.864426018611E+01	7.637363384710E+02	2.677981023396E+02	3.307632972622E+02	9.049918423628E+02	2.683426928339E+03	6.370862654933E+03
Servred	3.094035526874E+02	6.718564614030E-01	1.539525744916E+02	3.873432003623E+00	1.235049115358E+02	2.250595043305E+02	6.225946928748E+02	7.240398946578E+02
OMS	7.032701070623E+03	7.161793618190E+02	4.711399458617E+03	9.040719798945E+02	4.614433614195E+03	3.077254352818E+03	1.200068188346E+04	1.479734030473E+04
NMS	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00
VA_TAX	8.052192549550E+02	6.827361927502E+01	3.308407278879E+03	7.144019732718E+02	1.641364747419E+03	2.981494466186E+01	1.561943238909E+02	4.206315508823E+03
DUTIES	1.159449919036E+02	1.095495940639E+00	1.747697607294E+02	2.104133736627E+02	2.880796164620E+01	7.202499489606E+01	1.493236489579E+02	2.357601457001E+02
ID_TAX	1.137007352176E+03	1.204261241307E+02	1.921216146873E+04	2.313040707452E+02	3.166813345867E+03	6.512662268072E+02	1.644553605921E+03	2.719886614637E+03

	Cgoodsind	Cons	TelServ	Trans	Servred	OMS	NMS	FOONS
Agric	2.825410486768E+04	0.000000000000E+00	2.946957154190E-01	0.000000000000E+00	0.000000000000E+00	1.264992763950E+03	1.532673178552E+03	1.862333320239E+04
Coal	2.055724182749E+01	3.499294872790E-01	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	5.064089712352E+02
Oil	2.792656269643E+03	1.654272483602E+03	2.574731495473E+02	4.721215800287E+03	6.769785257081E+02	4.521752522000E+03	7.307555784050E+03	1.749472142630E+04
Gas	3.785817386140E+02	8.052364734887E+02	4.104185509472E-01	0.000000000000E+00	1.485013368962E+00	2.934220266722E+02	3.334912448116E+02	4.336249340243E+03
Elect	1.122332361848E+03	1.221448894648E+02	3.151964011707E+00	2.66223993902E+02	9.373331759368E+00	1.298692631152E+03	1.366949910132E+03	1.801754725629E+04
FerNf	4.975143833326E+02	3.145022064146E+03	0.000000000000E+00	1.063599869198E+02	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	2.239786058420E+02
ChemPro	6.642836770119E+03	1.161907702490E+03	0.000000000000E+00	4.137517554156E+01	0.000000000000E+00	1.184797010606E+03	5.823880808176E+03	2.125486060991E+04
Onjint	6.441424548441E+03	1.568193577015E+04	2.349038269058E+02	3.241160185251E+02	2.016170455719E+03	1.415366637758E+04	5.080633829580E+03	1.835913962198E+04
Elecg	8.511079902573E+01	4.981323294430E+03	6.76855447922E+02	1.219568313403E+02	0.000000000000E+00	2.157550082354E+03	5.393723072147E+03	1.004917138557E+04
transequ	1.7643374746450E+02	1.898971039372E+02	8.127552664936E+01	2.11686272301E+03	0.000000000000E+00	1.594396793098E+03	1.053365407085E+04	3.064507842205E+04
Oequg	1.524012653388E+03	4.486220832330E+03	0.000000000000E+00	1.306915895692E+02	1.777455111763E+01	2.342408528255E+03	3.988446030085E+03	3.384654622982E+03
Cgoodsind	3.226294305313E+04	6.768912708578E+03	1.536522650722E+02	5.490437821478E+02	7.24192327373E+01	7.036919291220E+03	8.674306310172E+03	1.171852566674E+05
Cons	1.349239219918E+02	6.325695508668E+01	4.432015307831E+01	1.169317891437E+02	3.953239335609E+03	1.174895503903E+03	1.014339851821E+04	6.460085286479E+03
TelServ	8.598934369856E+02	5.901856272420E+02	2.350705436574E+03	4.004229016027E+02	3.405669356727E+03	7.419104616404E+03	3.897174873696E+03	1.086682858259E+04
Trans	2.315905196133E+03	3.913550622150E+03	4.552797510501E+02	7.918305081644E+03	3.86723259980E+02	1.426387960988E+04	3.325448056208E+03	1.709316929431E+04
Servred	1.000601759727E+03	2.281223889283E+03	0.000000000000E+00	7.631725594075E+02	3.046380602222E+04	2.395289136711E+03	4.797671767130E+04	6.900144740689E+03
OMS	3.543460742427E+04	3.238415798840E+04	1.499284250927E+03	8.280198350514E+03	3.474866652063E+04	7.461669217194E+04	3.858705886216E+04	3.465062625967E+05
NMS	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	2.948738243670E+05
K	3.177143524232E+04	2.104520913324E+04	1.408410301399E+04	1.741858183707E+04	6.268669882443E+03	2.066733717862E+05	-7.1632235198E+03	
L	3.231395673827E+04	3.297891953273E+04	1.08719490602E+04	1.842896522384E+04	7.289102859724E+03	1.231469128055E+05	0.8004365210394E+05	
SUBSIDY	-4.46607324648E+03	-8.234438778283E+02	-1.387062783638E+00	-3.725656251357E+03	-9.554810929426E+02	-7.849393725649E+03	0.000000000000E+00	
VA_TAX	6.588062483819E+03	1.644714350887E+04	2.452706314043E+03	1.816425583436E+03	0.000000000000E+00	3.124163657949E+04	0.000000000000E+00	
DUTIES	4.230877870763E+02	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	
ID_TAX	7.650328877582E+03	3.301401056096E+03	4.564334249757E+02	2.068097239101E+03	3.800616561621E+03	3.863242023002E+04	1.059467868727E+04	

	INV	DSTOCK	EXPORTS	IMPORT
Agric	4.957410111139E+02	-2.058489963455E+03	1.211775741266E+04	-7.398125715715E+03
Coal	0.000000000000E+00	6.842739378849E+02	3.453485217834E+01	-7.418999224922E+02
Oil	0.000000000000E+00	-1.131969790647E+03	2.789573933757E+03	-1.260366428173E+04
Gas	0.000000000000E+00	0.000000000000E+00	7.293284488104E+01	-4.044484493536E+03
Elect	0.000000000000E+00	0.000000000000E+00	2.891610996057E+03	-1.767838967380E+02
FerNf	0.000000000000E+00	-4.278069475966E+03	1.434017120867E+04	-1.056756661619E+04
ChemPro	0.000000000000E+00	3.382704403880E+03	2.892279897124E+04	-2.384893241017E+04
Onrjint	8.251995163340E+03	-1.145162576588E+04	2.216068673002E+04	-2.289721069686E+04
Elecg	1.475927871833E+04	2.002533159279E+04	1.849506213775E+04	-2.212904177311E+04
transequ	1.572025891829E+04	3.235823944016E+04	4.706929322252E+04	-3.823313600215E+04
Oequg	3.918085173001E+04	1.277312430019E+04	2.703493152155E+04	-3.058972198871E+04
Cgoodsind	2.185659879334E+03	-1.836274386713E+03	4.158237616872E+04	-4.602442036409E+04
Cons	1.199111728848E+05	5.589266433913E+03	0.000000000000E+00	0.000000000000E+00
TelServ	0.000000000000E+00	1.118613172294E+02	1.747782702548E+02	-3.006253289319E+02
Trans	0.000000000000E+00	-4.691283187357E+03	4.943086177790E+03	-4.367452593555E+03
Servcred	0.000000000000E+00	-7.056495736885E+02	2.012540791908E+03	-4.815954022535E+03
OMS	2.276749169483E+04	-1.824955335634E+05	2.511245363242E+04	-8.602739729366E+03
NMS	0.000000000000E+00	1.390768462810E+05	1.762538012763E+04	-1.374317016413E+04
K				
L				
SUBSIDY				
VA_TAX				
DUTIES				
ID_TAX				

;

\* Creation of a SAM with seventeen sectors, where Oserv (Other services) is the sum of OMS (Other market services) and NMS (Non market services).

sets

orig Original Sectors in SAM /

- Agric      Agriculture
- Coal      Coal
- Oil        Oil
- Gas        Gas
- Elect      Electricity
- FerNf      Ferrous and non ferrous metals
- ChemPro   Chemical products
- Onrjint    Other energy intensive
- Elecg      Electric goods
- transequ   Transport equipment
- Oequg      Other equipment goods
- Cgoodsind Consumer goods industries
- Cons       Construction
- TelServ    Telecommunication services
- Trans      Transport
- Servcred   Service of credit and insurances
- OMS        Other market services
- NMS        Non market services

/

## i New Aggregated Sectors /

Agric	Agriculture
Coal	Coal
Oil	Oil
Gas	Gas
Elect	Electricity
FerNf	Ferrous and non ferrous metals
ChemPro	Chemical products
Onrjint	Other energy intensive
Elecg	Electric goods
transequ	Transport equipment
Oeug	Other equipment goods
Cgoodsind	Consumer goods industries
Cons	Construction
TelServ	Telecommunication services
Trans	Transport
Servcred	Service of credit and insurances
Oserv	Other services

/

## mapi(iorig,i) mapping from original to aggregate sectors/

Agric.Agric	Agriculture
Coal.Coal	Coal
Oil.Oil	Oil
Gas.Gas	Gas
Elect.Elect	Electricity
FerNf.FerNf	Ferrous and non ferrous metals
ChemPro.ChemPro	Chemical products
Onrjint.Onrjint	Other energy intensive
Elecg.Elecg	Electric goods
transequ.transequ	Transport equipment
Oeug.Oeug	Other equipment goods
Cgoodsind.Cgoodsind	Consumer goods industries
Cons.Cons	Construction
TelServ.TelServ	Telecommunications services
Trans.Trans	Transport
Servcred.Servcred	Service of credit and insurances
(OMS,NMS).Oserv	Other and Non market services

/;

\* Extraction of values from the SAM

sets

```

f      factors                /L, K/
d      demands                /Fcons, Inv, Dstock, Exports, Import/
tou    tax type               /subsidy, id_tax, duties, va_tax/
e(i)   energy                 /coal, oil, gas, elect/
ec(i)  energy without coal    /oil, gas, elect/
fe(i)  fossil fuel energy     /coal, oil, gas/
eis(i) energy-intensive industries /fernf, chempro, onrjint/
eise(i) energy and energy intensive /fernf, chempro, onrjint, coal, oil, gas, elect/
neise(i) non covered sectors  /agric,elec,transequ,oequg,cgoodsind
                                           ,cons,telserv,trans,servcred,oserv/
;

sets

t /1995*2012/, tfirst(t), tlast(t);
tfirst(t)=yes$(ord(t) eq 1);
tlast(t)=yes$(ord(t) eq card(t));
alias (iorig,jorig) , (i,j) , (f,ff) , (j,jj),(e,z);

parameters
xbar  benchmark intermediate transaction matrix
vbar  benchmark factor supply matrix
gbar  benchmark final demand matrix
cbar  benchmark aggregate consumption

*    Taxes
zbar  benchmark distortions matrix
tot_id  Total id taxes
tot_su  Total subsidies
tot_du  Total duties
tot_tp  Total value added tax

*    Values in the SAM

```

ybar0	benchmark output
endl	labor used in production : found in the SAM
ibar	benchmark aggregate investment positive values
xinv	exogenous investment demand vector
tin	positive values of investment
impt	benchmark imports
impts	benchmark imports sum
expt	benchmark exports
bopdef0	balance of payments deficit in the benchmark
bopdef	balance of payments deficit
em0	benchmark energy materials bundle
ma0	benchmark materials bundle
n0	benchmark energy supply
f0	benchmark fossil fuel supply
a0	benchmark armington supply
d0	benchmark demand
mu	Share of government demand in total demand
carblim	limit on endowment of carbon emission certificates per sector
gdp0	benchmark gdp in ecu

\* Wage parameter

wp wage premium

;

scalars

esubl	Elasticity of consumption for leisure versus consumption	/0.3/
subsnrj	Elasticity of substitution between electricity fossil fuels	/0.7/
subs	Elasticity of substitution between fossil fuels	/1.5/
u0	benchmark unemployment rate for all workers in 1995	/0.125/
ra0	benchmark national income spent on consumption	/0/
vk	benchmark aggregate capital	
endogsav	flag to turn on endogenous saving	/0/
ncalib	flag to specify non-calibration run	/0/
carblim90	carbon emissions in 1990	/103/
carblim0	benchmark 1995 endowment of carbon emission certificates	
bmkscale	scale benchmark by 1e-3	/1e-3/
ecuscale	benchmark year ecu-usd conversion	
gamma	gdp growth rate (oecd economic outlook 1997)	/0.01/

;

\* We multiply everything by bmkscale because the values in the SAM are too

big.

\* There may be negative values, therefore, when extracting the values from the SAM, we take the maximum between 0

\* and the value in the SAM.

$$\begin{aligned} \text{vbar}(f,j) &= \text{bmkscale} * \text{sum}(\text{jorig}\$ \text{mapi}(\text{jorig},j), \text{sam}(f,\text{jorig})); \\ \text{xbar}(i,j) &= \text{bmkscale} * \text{sum}((\text{iorig},\text{jorig})\$(\text{mapi}(\text{iorig},i) \text{ and } \text{mapi}(\text{jorig},j)) \\ &\quad , \text{sam}(\text{iorig},\text{jorig})); \\ \text{gbar}(i,d) &= \text{bmkscale} * \text{sum}(\text{iorig}\$ \text{mapi}(\text{iorig},i), \text{sam}(\text{iorig},d)); \\ \text{zbar}(\text{tou},j) &= \text{bmkscale} * \text{sum}(\text{jorig}\$ \text{mapi}(\text{jorig},j), \text{sam}(\text{tou},\text{jorig})); \\ \text{gdp0} &= \text{sum}(i,d,\text{gbar}(i,d)); \\ \text{ecuscale} &= 6.55957/6.52; \end{aligned}$$

\* We multiply everything by ecuscale to convert ecu to euros as all our calculations are in euros.

$$\begin{aligned} \text{vbar}(f,j) &= \text{ecuscale} * \text{vbar}(f,j); \\ \text{xbar}(i,j) &= \text{ecuscale} * \text{xbar}(i,j); \\ \text{gbar}(i,d) &= \text{ecuscale} * \text{gbar}(i,d); \\ \text{zbar}(\text{tou},j) &= \text{ecuscale} * \text{zbar}(\text{tou},j); \\ \text{wp} &= 639.02 * \text{ecuscale}; \end{aligned}$$

\* Wage premium calculation A. Gubian (DARES) / Sophie Ponthieux : "Emplois non qualifiés, emplois a bas salaires

\* et mesures d'allegement du cout du travail"

$$* \quad 0.6 = \text{NQ W} / \text{Q W} \rightarrow \text{Q W} - 0.4 * \text{Q W} = \text{NQ W}$$

$$* \quad \text{NQ W} = 958.53 \text{ ecus}$$

$$* \quad \text{The wage premium} = 0.4 * \text{Q W} = 639.02$$

$$* \quad \text{In euros WAGE PREMIUM} = 639.02 * \text{ecuscale}$$

display vbar, xbar, gbar, zbar;

\* Output gross of tax  $\rightarrow$  all taxes are included except those on imports

$$\text{ybar0}(j) = \text{sum}(i,\text{xbar}(i,j)) + \text{sum}(f,\text{vbar}(f,j)) + \text{tot\_id}(j) + \text{tot\_su}(j) + \text{tot\_tp}(j);$$

\* Energy supply, per sector

$$\text{n0}(i) = \text{sum}(e,\text{xbar}(e,i));$$

\* Fossil fuel energy supply per sector

$$\text{f0}(i) = \text{sum}(fe,\text{xbar}(fe,i));$$

\* Materials bundle



$ma0(j)=\text{sum}(i,xbar(i,j))-\text{sum}(fe,xbar(fe,j))-xbar("elect",j);$

\* Energy materials bundle

$em0(j)=n0(j)+ma0(j);$

\* Consumption

$cbar=\text{sum}(i,gbar(i,"Fcons"));$

\* Extracting negative investment values

$xinv(i)=\text{min}(0,gbar(i,"Inv")+gbar(i,"Dstock"));$

\* Extracting positive investment values

$tinv(i)=\text{max}(0,gbar(i,"Inv")+gbar(i,"Dstock"));$

\* Aggregate investment and capital returns

$ibar=\text{sum}(i,tinv(i));$

\* Physical capital services

$vk=\text{sum}(j,vbar("k",j));$

\* Endowment of labor

$endl=(\text{sum}(i,vbar("l",i)))/(1-u0);$

\* Exports

$expt(i)=gbar(i,"exports");$

\* Imports

$impt(i)=-gbar(i,"import");$

\* Balance of payments deficit : net demand

$bopdef0 = \text{sum}(i,impt(i)-expt(i));$

$bopdef = bopdef0;$

\* Extraction of values of taxes from SAM

$tot\_su(j)=zbar("subsidy",j);$

$tot\_id(j)=zbar("id\_tax",j);$

$tot\_du(j)=zbar("duties",j);$

$tot\_tp(j)=zbar("va\_tax",j);$

\* Taxes on output are calculated on a gross revenue basis, while taxes on inputs are calculated on a net of tax

parameters

ty0 Output tax  
 tf0 Factor tax  
 tff Total factor taxes  
 tfe Tax rates on labor in fossil fuel sector  
 tots total factor taxes  
 tm0 Import tax  
 ty Output tax  
 tf Factor tax  
 tl total benchmark tax on labor  
 tm Import tax  
 pf0 Reference user cost of factor inputs  
 py0 Reference production price  
 pm0 Reference import price  
 ;

\* Output tax is the sum of subsidies and factor taxes divided by the value of output

$$ty0(i) \bar{y}_0(i) = (tot\_su(i) + tot\_tp(i)) / \bar{y}_0(i);$$

\* Factor tax equals total tax divided by the value of all factors

$$tf0(f,i) \sum(ff,vbar(ff,i)) = tot\_id(i) / (\sum(ff,vbar(ff,i)));$$

\* Import tax

$$tm0(i) \text{impt}(i) = tot\_du(i) / \text{impt}(i);$$

\* Total benchmark taxes

$$tots = (\sum(i, tot\_su(i) + tot\_tp(i) + tot\_id(i) + tot\_du(i)));$$

$$ty(i) = ty0(i);$$

$$tf(f,i) = tf0(f,i);$$

$$tm(i) = tm0(i);$$

\* Total benchmark taxes on labor

$$tl = \sum(j, tf("L", j));$$

$$\text{display } ty0, tm0, tf0, tot\_id;$$

\* Share of government demand

$$\mu = tots / \bar{c};$$

\* Data consistency check

parameters

colsum column sum

rowsum row sum

```

;
colsum(j) = ybar0(j)-sum(i,xbar(i,j))-sum(f,vbar(f,j))
           -(tot_su(j)+tot_id(j)+tot_tp(j));
rowsum(i) = ybar0(i)-sum(j,xbar(i,j))
           -(sum(d,gbar(i,d)))+tot_du(i);

```

display colsum, rowsum, ibar, endl, tots, n0, tl, nhle;

\* Armington good definition

```

a0(i) =sum(j,xbar(i,j))+gbar(i,"Fcons")+gbar(i,"Inv")+gbar(i,"Dstock");
d0(i) =a0(i)-(impt(i)*(1+tm(i)));

```

\*=====

\* EMISSION ACCOUNTING

\*=====

parameters

emiss0(fe) benchmark carbon emissions in 1995 (EIA 1999) /coal 15, oil 65, gas 17/

ccoef(fe) carbon emissions coefficient on each fossil fuel

tcl(t) total carbon limitations

tau\_c carbon tax in non-covered sectors

;

```

ccoef(fe) =emiss0(fe)/a0(fe);
carblim0 =sum(fe,emiss0(fe));
tcl(t) = 0;
carblim(j) =0;

```

\* We initially set the carbon tax to be nul in the benchmark

```

tau_c(j) = 0;

```



	Transequ	fernf	Oeug	Cgoodsind	Onrjint	Cons	Trans	Servcred	Oserv
Agric	0.071769	0.479172	0.240657	0.386925	0.467093	0.256756	0.000000	25.010787	10.608357
Coal	0.000000	0.522027	0.201072	0.192414	0.000000	0.319833	1.928202	0.870246	0.000000
Gas	0.000000	0.734262	0.282820	0.270642	0.000000	0.449864	2.712130	1.224052	0.000000
Elegc	392.964184	158.540180	638.339410	85.273040	5.359513	258.475870	91.295675	1107.729654	331.932361
Telserv	0.854348	0.000000	0.972760	2.732293	0.000000	0.306484	0.537793	17.215096	6.917320
Elect	38.109953	16.190560	43.271044	9.329331	2.294455	157.993163	1.938311	95.678207	49.495666
Chempro	83.993064	349.571161	154.762923	729.817859	628.006545	82.880242	13.159890	215.423810	2228.870943
Oil	23.871439	7.236546	11.923068	3.721368	0.369760	7.569507	17.997006	12.038886	0.200483
Transequ	3020.252728	1.790958	18.011727	3.322370	0.575040	14.361328	95.854128	40.940578	40.920216
fernf	165.766491	1049.147091	395.173317	184.758340	29.989052	1150.779880	60.213352	371.532284	175.501267
Oeug	478.621263	1072.362537	4518.484838	1871.497265	334.699681	631.340651	233.122161	1748.764443	1845.239806
Cgoodsind	97.258461	69.159540	154.402855	1726.795110	29.575594	498.829928	48.209910	446.883323	814.229723
Onrjint	112.096492	29.639883	60.231400	117.808788	570.239107	219.865498	38.182402	69.029800	96.126801
Cons	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Trans	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Servcred	20.140300	3.579513	69.352246	13.349778	0.620137	6.919554	5.147984	1192.561289	26.864706
Oserv	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

;

\* We determine labor that is not human capital by multiplying the estimate of the number of non qualified workers in 1995

\* by the wage of non qualified workers in 1995 in euros

\* <http://www.insee.fr/fr/indicateur/smic.htm>

NHLE(j)	estimates of industry inputs of non-human-capital labor in billion euros /
agric	2.78499
coal	0.02089
oil	0.39695
gas	0.00548
elect	0.05612
fernf	0.12864
chempro	1.37037
onrjint	0.51275
elegc	1.11762
transequ	1.87629
oeug	0.99636
cgoodsind	6.01287
cons	0.08309
telserv	5.16287
trans	0.56562
servcred	9.86080
oserv	23.54669/

\* Re-scale nhle(servcred) as this value is larger than total value of labor in this

sector.

```
nhle("servcred")= 0.75 * nhle("servcred");
```

```
;
```

\* I multiply the average qualified wage in euros by the number of researchers

parameters

chercheurs(j)	Value of researchers per sector in billion euros/
agric	0.00853
coal	0.00187
oil	0.00187
gas	0.00187
elect	0.00187
fernf	0.00776
chempro	0.03892
onrjint	0.00847
elec	0.00952
transequ	0.05372
oequg	0.04319
cgoodsind	0.00449
cons	0.00166
telserv	0.02353
trans	0.00810
servcred	0.00734
oserv	0.00598/

\* Values of research and development per industry from the Centre de l'Informatique Statistique et de l'Aide à la Décision of the Ministère de l'éducation nationale, de l'enseignement supérieur et de la recherche

\* <http://cisad.adc.education.fr/reperes/>

\* For coal / oil/ gas/ elect I divided the total by the share of each sector in all energy

parameters

RD(i)	R&D per industry in billion euros/
agric	0.483
coal	0.01792
oil	0.33553
gas	0.02521
elect	0.25832
fernf	0.536
chempro	0.3026
onrjint	0.459
elec	0.598
transequ	0.4433
oequg	0.3055
cgoodsind	0.277
cons	0.126
telserv	0.1829
trans	0.506
servcred	0.2845
oserv	0.14616 /

;

\* Declaration of variables and equations for ITC

parameters

rd_sm	total research and development so that BGP functions for human capital
rdd_tot	total R&D in the model that does not satisfy the BGP
diff	difference between rdd_tot and rd_sum
rddf(i)	research and development that should be for the BGP to function

;

positive variables

HR(i,j)	benchmark R&D flows embodied in intermediate transactions table
HL(j)	benchmark knowledge embodied in labor : proxied by researchers
HLE(j)	benchmark skilled workers that are not researchers and not unskilled
H(j)	benchmark total knowledge per sector
xtilde(i,j)	intermediate transactions matrix net of R&D flows
vtilde(f,j)	factor supply matrix net of human capital and embodied technology
rdd	research and development column once itc method is in
hri	benchmark positive R&D flows in the matrix
hs0	aggregate knowledge services
ks0	aggregate capital services

\* Column and Row sum

colsumb	column sum with introduction of the itc method
rowsumb	row sum with the introduction of the itc method

;

\*=====

\* HUMAN CAPITAL EXTRACTION FROM SAM

\*=====

\* Determination of the matrix

$$HR.l(i,j) = (RD(i) * pp(i,j)) / \text{sum}(jj,pp(i,jj));$$

\* We PROXY human capital as the number of researchers in the economy

$$HL.l(j) = \text{chercheurs}(j);$$

\* Skilled workers in the model that are used in the production and not in the research and development

$$HLE.l(j) = \text{vbar}("L",j) - NHLE(j) - HL.l(j);$$

\* Definition of sectoral knowledge

\* This is the sum of knowledge embodied in labor and knowledge embodied in the interindustry transaction matrix

\* We use this definition of xtilde, where only values that are positive are taken into account

$$\text{xtilde}.l(i,j) = \text{xbar}(i,j) - HR.l(i,j) \$(\text{xbar}(i,j) - HR.l(i,j) > 0);$$

\* Determination of vtilde which is the sum of skilled (not researchers) and unskilled labor engaged in production

$$\text{vtilde}.l("L",j) = \text{vbar}("L",j) - HL.l(j);$$

$$\text{vtilde}.l("K",j) = \text{vbar}("K",j);$$

\* Determination of just the positive values of the hr matrix

$$\text{hri}.l(i,j) = \text{xbar}(i,j) - \text{xtilde}.l(i,j);$$

\* The human capital row is the sum of the positive values of hr and hl

$$H.l(j) = \text{sum}(i,\text{hri}.l(i,j)) + \text{hl}.l(j);$$



\* Determination of the value of the r&d vector when the hr matrix is positive.

$$\text{RDD.l}(i) = \text{sum}(j, \text{hri.l}(i, j));$$

\*This value of RD is smaller than the total value of RetD that is given in the statistics

$$\text{rdd\_tot} = \text{sum}(i, \text{sum}(j, \text{hri.l}(i, j)));$$

\* Check for the maintenance of overall row-column balance

\* column sum should be equal to 0

$$\begin{aligned} \text{colsumb.l}(j) = & \text{ybar0}(j) - \text{H.l}(j) - (\text{tot\_id}(j) + \text{tot\_su}(j) + \text{tot\_tp}(j)) - \text{sum}(f, \text{vtilde.l}(f, j)) \\ & - \text{sum}(i, \text{xtilde.l}(i, j)); \end{aligned}$$

\* rowsum which should be equal to 0

$$\text{rowsumb.l}(i) = \text{ybar0}(i) - (\text{sum}(d, \text{gbar}(i, d))) + \text{tot\_du}(i) - \text{sum}(j, \text{xtilde.l}(i, j)) - \text{RDD.l}(i);$$

\* Physical capital did not change because we did not extract anything from the k

$$\text{ks0.l} = \text{sum}(j, \text{vtilde.l}("k", j));$$

\* computing the sum of all human capital that has been extracted from the labor and the

\* interindustry transaction matrix

$$\text{hs0.l} = \text{sum}(j, \text{h.l}(j));$$

\*=====

\* APPLICATION OF THE INTEREST RATE TO HK

\*=====

\* The interest rate of the economy is chosen to be the one that derives from the physical capital in the SAM

$$\text{ir} = \text{ks0.l} * (\text{gamma} + \text{deltak}) / \text{ibar} - \text{deltak};$$

\* We apply this interest rate to the equations with human capital to derive total R&D on the BGP

$$rd\_sm = hs0.1 * (\gamma + \delta h) / (ir + \delta h);$$

\* We then calculate the difference between rd\_sm (value necessary for BGP) and rdd\_tot (value in the SAM)

$$diff = rd\_sm / rdd\_tot;$$

\* We determine the value of the R&D column that is needed so that the BGP should be satisfied

$$rddf(i) = rdd.l(i) * diff;$$

parameter tottrddf;

$$tottrddf = \text{sum}(i, rddf(i));$$

\* After introducing this new column in the SAM, the whole SAM is unbalanced

\*=====

\*           POSITIVITY OF RESIDUALS

\*=====

\* Once we have extracted the value of human capital from the interindustry transaction matrix, there must always be a minimum of 10% of the value of the cells that

\* are tangible assets.

$$xtilde.lo(i,j) = 0.1 * xbar(i,j);$$

$$vtilde.lo(f,j) = 0.1 * vbar(f,j);$$

\* positivity of intangible inputs (lower bound of zero)

$$HR.lo(i,j) = 0;$$

$$HL.lo(j) = 0;$$

```
display hr.l, h.l, hl.l, vtilde.l, xtilde.l, hs0.l, ks0.l, hri.l,colsumb.l, rowsumb.l, rd_sm,
rdd_tot, diff, rddf, ir, totrddf;
```

```
display ybar0;
```

```
*=====
```

```
*          CREATION OF A NEW SAM
```

```
*=====
```

```
sets
```

```
rownew      new row names  /agric,coal, oil, gas, elect, fernf, chempro,
                        onrjint, elecg,transequ,oequg,cgoodsind,cons,
                        telserv,trans,servcred,oserv,
                        SL,UL, K,Hum,
                        subsidy, id_tax, duties, va_tax/
```

```
colnew      new col names  /agric,coal, oil, gas, elect, fernf, chempro, onrjint,
                        elecg,transequ,oequg,cgoodsind,cons,telserv,
                        trans,servcred,oserv, Fcons, Inv, Dstock,
                        Exports, Import, rddf/
```

```
;
```

```
parameter
```

```
SAMNEW      Unbalanced SAM that is created when we changed the values in the
R&D column;
```

```
SAMNEW(i,j)      = xtilde.l(i,j);
SAMNEW(i,d)      = gbar(i,d);
SAMNEW(i,"rddf") = rddf(i);
SAMNEW(tou,j)    = zbar(tou,j);
SAMNEW("K",j)    = vtilde.l("K",j);
SAMNEW("SL",j)   = HLE.l(j);
SAMNEW("UL",j)   = NHLE(j);
SAMNEW("Hum",j)  = H.l(j);
```

```
display samnew;
```

```
*=====
```

```
*          FIRST REBALANCING OF THE SAM
```

```
*=====
```

\* I have calculated the amount of research and development that needs to be taken out of the SAM and put in the RD column. Now both physical capital and human

capital grow on the balanced growth path. SAMNEW is not balanced though because of this change I rebalance the SAM according to the Model Library Method : SAM-BAL.GMS. My new SAM, which is balanced is called SAMBAL.

```

Variables
  sambal(*,*)  SAM that has been rebalanced and that we will use in the mpsge model
  totals      estimated totals
  dev         deviations
;

Equations
  rbal(rownew)  new row balance
  cbal(colnew)  column balance
  devsqr       definition of square deviations
  pos         positive values of the SAMBAL except for subsidy
;

*   Equations for the rebalancing of the SAM
  devsqr.. dev =e=  sum((rownew,colnew), (sqr(sambal(rownew,colnew)
                        -samnew(rownew,colnew))
                        / samnew(rownew,colnew))$(samnew(rownew,colnew)))
                        + sum(rownew, (sqr(ybar0(rownew)- totals(rownew))
                        /ybar0(rownew))$(ybar0(rownew)))
                        + sum(colnew, (sqr(ybar0(colnew)- totals(colnew))
                        /ybar0(colnew))$(ybar0(colnew)));

  rbal(rownew).. totals(rownew) =e=  sum(colnew$samnew(rownew,colnew)
                        , sambal(rownew,colnew));

  cbal(colnew).. totals(colnew) =e=  sum(rownew$samnew(rownew,colnew)
                        , sambal(rownew,colnew));

  model bal /rbal, cbal, devsqr/;
  solve bal using nlp minimizing dev;
  display sambal.l;

*=====
*           SECOND REBALANCING OF THE SAM
*=====

equations

```

```

k_acc
h_acc
rbal2
cbal2
devsqr2
;
k_acc..      sum(j$samnew("K",j),sambal("K",j))
              / sum(i, max(0,sambal(i,"INV")$samnew(i,"inv")
              +sambal(i,"dstock")$samnew(i,"dstock")))
              =e= ((ir + deltak) / (gamma + deltak));

h_acc..      sum(j$samnew("hum",j),sambal("Hum",j))
              / (sum(i$samnew(i,"rdff"),sambal(i,"rdff")))
              =e= ((ir + deltah) / (gamma + deltah));

rbal2(rownew)..  totals(rownew) =e= sum(colnew$samnew(rownew,colnew)
              , sambal(rownew,colnew));

cbal2(colnew)..  totals(colnew) =e= sum(rownew$samnew(rownew,colnew)
              , sambal(rownew,colnew));

devsqr2..      dev =e= sum((rownew,colnew), (sqr(sambal(rownew,colnew)
              -samnew(rownew,colnew))
              / samnew(rownew,colnew))$(samnew(rownew,colnew)))
              + sum(rownew, (sqr(ybar0(rownew)- totals(rownew))
              /ybar0(rownew))$(ybar0(rownew)))
              + sum(colnew, (sqr(ybar0(colnew)- totals(colnew))
              /ybar0(colnew))$(ybar0(colnew)));
model essai /k_acc,h_acc,rbal2,cbal2,devsqr2/;
solve essai using dnlp minimizing dev;
display sambal.1;

*=====
*           PARAMETER DEFINING IN SAMBAL
*=====

parameters

```

xbarbal	values of the xbar matrix in the balanced SAM
vbarbal	values of the vbar matrix in the balanced SAM
gbarbal	values of the gbar matrix in the balanced SAM
cbarbal	consumption in the balanced SAM
zbarbal	values of the zbar matrix in the balanced SAM
ybar0bal	benchmark output in the balanced SAM
labs0bal	benchmark labor supply : unemployed and workers i.e. total labor force in economy
labskibal	supply of all skilled workers : total skilled labor force
skibal	skilled workers in the economy
totskibal	total skilled workers in the economy
totnskibal	total non skilled workers in the economy
endlbal	endowment of labor
ibarbal	aggregate investments in the balanced SAM
rdbarbal	aggregate investment in human capital the balanced SAM
xinvbal	exogenous investments in the demand vector
tinvtbal	positive values of investment in the balanced SAM
imptbal	benchmark imports in the balanced SAM
imptsbal	benchmark imports sum in the balanced SAM
exptbal	benchmark exports in the balanced SAM
bopdef0bal	balance of payments deficit in the benchmark of the balanced SAM
bopdefbal	balance of payments deficit in the balanced SAM
em0bal	benchmark energy materials in the balanced SAM
ma0bal	benchmark materials bundle in the balanced SAM
n0bal	benchmark energy supply in the balanced SAM
f0bal	benchmark fossil fuel supply in the balanced SAM
a0bal	benchmark armington supply in the balanced SAM
d0bal	benchmark demand in the balanced SAM
vkbal	value of capital returns in the balanced SAM
vhbal	value of human capital returns in the balanced SAM
totsbal	total taxes in the balanced SAM
mubal	share of government demand
;	

\* We create an additional line in the factors matrix, and create therefore an additional set of factors which includes

\* human capital as another factor of production

\* In the same way we create an additional set dh, including the usual demands as well as investment in research

\* and development

```

sets
  v    factors of production including human capital  /K,SL,UL,Hum/
  fu   skilled and unskilled labor and capital      /K,SL,UL/
  dh   demand including R&D                        /Fcons, Inv, Dstock,
;                                                Exports, Import, rdff/

;

alias (vv,v), (fufu,fu);

* Determination of the different parts of SAMBAL
vbarbal(v,j)    = sambal.l(v,j);
xbarbal(i,j)    = sambal.l(i,j);
gbarbal(i,dh)   = sambal.l(i,dh);
zbarbal(tou,j)  = sambal.l(tou,j);

* Energy supply, per sector
n0bal(i)=sum(e,xbarbal(e,i));

* Fossil fuel energy supply per sector
f0bal(i)=sum(fe,xbarbal(fe,i));

* Materials bundle
ma0bal(j)=sum(i,xbarbal(i,j))-sum(fe,xbarbal(fe,j))-xbarbal("elect",j);

* Energy materials bundle
em0bal(j)=n0bal(j)+ma0bal(j);

* There is NO tax on consumption
cbarbal=sum(i,gbarbal(i,"Fcons"));

* Extracting negative investment values
xinval(i)=min(0,gbarbal(i,"Inv")+gbarbal(i,"Dstock"));

* Extracting positive investment values
tinval(i)=max(0,gbarbal(i,"Inv")+gbarbal(i,"Dstock"));

* Aggregate investment and capital returns
ibarbal=sum(j,tinval(j));

* Aggregate investment and capital returns
rdbarbal=sum(i,gbarbal(i,"rdff"));

* Flows of physical capital services

```

```

vkbal=sum(j,vbarbal("k",j));
* Flows of physical capital
vhbal=sum(j,vbarbal("hum",j));
* Endowment of all labor
endlbal=(sum(j,vbarbal("U1",j))+sum(j,vbarbal("S1",j)))/(1-u0);
* skilled labor in the economy without counting the researchers
skibal(j)= vbarbal("SL",j);
* Total input of skilled laborers actually working in the economy
totskibal = (sum(j,skibal(j)));
* Total input of non skilled laborers actually working in the economy
totnskibal= (sum(j,vbarbal("UL",j)));
* labor supply, all those that are unemployed and all workers
labs0bal = (sum(i,(vbarbal("S1",i)+vbarbal("U1",i))/(1-u0)));
* Exports
exptbal(i)=gbarbal(i,"exports");
* Imports
imptbal(i)=-gbarbal(i,"import");
* Balance of payments deficit : net demand
bopdef0bal = sum(i,imptbal(i)-exptbal(i));
bopdefbal = bopdef0bal;

* Tax
parameter
tot_subal
tot_idbal
tot_dubal
tot_tpbal
ty0bal

```



```

tf0bal
tm0bal
tlbal
tybal
tfbal
tmbal
;
tot_subal(j) = zbarbal("subsidy",j);
tot_idbal(j) = zbarbal("id_tax",j);
tot_dubal(j) = zbarbal("duties",j);
tot_tpbal(j) = zbarbal("va_tax",j);

* Tax definition in SAMBAL
ybar0bal(j) = sum(i,xbarbal(i,j))+sum(v,vbarbal(v,j))
+tot_idbal(j)+tot_subal(j)+tot_tpbal(j);

ty0bal(i)$ybar0bal(i) = (tot_subal(i)+tot_tpbal(i))/ybar0bal(i);

tf0bal(fu,i)$sum(fufu,vbarbal(fufu,i)) = tot_idbal(i)/sum(fufu,vbarbal(fufu,i));

tm0bal(i)$imptbal(i) = tot_dubal(i)/imptbal(i);

tybal(i) = ty0bal(i);

tfbal(fu,i) = tf0bal(fu,i);

tmbal(i) = tm0bal(i);

totsbal = sum(j,sum(tou,zbarbal(tou,j)));

tlbal = sum(j,tfbal("UL",j))+sum(j,tfbal("SL",j));

* Armington good definition
* To the armington definition we now add the demand for research and development

```

```

a0bal(i) =sum(j,xbarbal(i,j))+gbarbal(i,"Fcons")+gbarbal(i,"Inv")
          +gbarbal(i,"Dstock")+gbarbal(i,"rdff");

d0bal(i) =a0bal(i)-(imptbal(i)*(1+tmbal(i)));
* Share of government demand

mubal=totsbal/cbarbal;

* check if sambal balanced

parameter

checkcol

checkrow

;
checkcol(j) = ybar0bal(j)-sum(i,xbarbal(i,j))-sum(v,vbarbal(v,j))
              -(tot_subal(j)+tot_idbal(j)+tot_tpbal(j));

checkrow(i) = ybar0bal(i)-sum(j,xbarbal(i,j))-(sum(dh,gbarbal(i,dh)))+tot_dubal(i);
display

checkcol

checkrow

;

*=====

*           A FORWARD LOOKING MODEL

*=====

*Declaration of the assumed parameters

scalar
r      interest rate
k0     initial capital stock
hk0    initial human capital stock
rk0    initial return to capital
rh0    initial return to human capital
iv0    initial investment in physical capital
ivh0   initial investment in human capital;
parameter qref(t) quantities

pref(t) prices;

```

\*=====

\* Physical Capital

\*=====

\*Interest rate of the economy is inferred by the growth theory

$$r = (\text{gamma} + \text{deltak}) * \text{vkbal} / \text{ibarbal} - \text{deltak};$$

\*Rental rate of capital in the base period

$$\text{rk0} = \text{deltak} + r;$$

\*Initial capital stock

$$\text{k0} = \text{vkbal} / \text{rk0};$$

\*Initial investment

$$\text{iv0} = (\text{deltak} + \text{gamma}) * \text{k0};$$

\*=====

\* Human capital

\*=====

\*Interest rate of the economy is inferred by the growth theory

$$r = (\text{gamma} + \text{deltah}) * \text{vhbal} / \text{rdbarbal} - \text{deltah};$$

\*Rental rate of human capital in the base period

$$\text{rh0} = \text{deltah} + r;$$

\*Initial human capital stock

$$\text{hk0} = \text{vhbal} / \text{rh0};$$

\*Initial investment in human capital

$$\text{ivh0} = (\text{deltah} + \text{gamma}) * \text{hk0};$$

\* On the BGP, all quantities increase at the same growth rate gamma

\* On the BGP, all prices decrease at the rate of the interest rate r

\* We have  $\text{ord}(t)-1$  as an exponent to represent the fact that in the base year

$q_{\text{ref}}$  et  $p_{\text{ref}}$  are equal to one and grow thereafter.

$$q_{\text{ref}}(t) = (1 + \text{gamma})^{**(\text{ord}(t)-1)};$$

$$\text{pref}(t) = (1/(1+r))^{**}(\text{ord}(t)-1);$$

\* Computation of the difference of the two interest rates. The difference should be nul.

parameter

difference;

$$\text{difference} = (\text{gamma} + \text{deltak}) * \text{vkbal}/\text{ibarbal} - \text{deltak} \\ - ((\text{gamma} + \text{deltah}) * \text{vhbal}/\text{rdbarbal} - \text{deltah});$$

option r :7;

display r, difference;

\*=====

\* MPSGE MODEL

\*=====

\$ontext

\$model : modelf

\$commodities :

p(i,t)!	Price index for commodities
pfb(j,t)!	Price of fossil bundle
pnb(j,t)!	Price of the energy bundle
px(t)!	Price for small open economy
px(j,t)\$(expt(j))!	Export price
pm(j,t)\$(impt(j))!	Import price
pva(j,t)!	Price index for value-added by sector
pa(j,t)!	Armington price
pinv(t)!	Price of investment
pinvt!	Price of investment the last period (market for a post term K)
rk(t)!	Rental rate for physical capital
rhk(t)!	Rental rate for human capital
pcons(t)!	Price of consumption
pg(t)!	Price of government good
pl(t)!	Wage rate for labor
pem(j,t)!	Price of energy materials bundle

pma(j,t)! Price of materials bundle  
 pklem(j,t)! Price of capital labor energy bundle  
 pac(fe,t)! Gross-of-carbon-tax price of coal oil and gas  
 ptcl(t)\$tcl(t)! Price of carbon emission rights  
 prd(t)! Price of research and development  
 prdt! Price of research and development at the last period

## \$sectors :

carbon(fe,t)! Dummy sector for carbon emissions accounting  
 klem(j,t)! capital labor energy bundle  
 nb(j,t)! Production of energy bundle per sector j  
 fb(j,t)! Production of fossil bundle  
 y(j,t)! Production by sector  
 va(j,t)! Value added by sector  
 em(j,t)! Energy Materials bundle  
 m(j,t)! Materials bundle sector  
 arm(j,t)! Armington supply  
 expo(j,t)\$expt(j)! Exports  
 imp(j,t)\$impt(j)! Imports  
 ka(t)! Capital  
 hka(t)! Human capital  
 inv(t)! Aggregate investment  
 G(t)! Aggregate government good  
 cons(t)! Aggregate private consumption  
 rdi(t)! Aggregate research and development

## \$consumers :

ra! Representative agent  
 govt(t)! Tax collector

## \$auxiliary :

tk! Terminal capital stock  
 thk! Terminal human capital stock

\* report variables

## \$report :

v :taxt(t) i :pg(t) prod :cons(t)! Total taxes  
 v :labsect(j,t) i :pl(t) prod :va(j,t)! Skilled labor per sector  
 v :dpro(j,t) o :p(j,t) prod :y(j,t)! Production for domestic use  
 v :epro(j,t) o :px(j,t) prod :y(j,t)! Production for export use  
 v :con(t) o :pcons(t) prod :cons(t)! Consumption  
 v :ex(j,t) o :pfx(t) prod :expo(j,t)! Exports  
 v :im(j,t) i :pfx(t) prod :imp(j,t)! Imports

v :agginv(t)	o :pinv(t)	prod :inv(t)!	Q of aggregate inv.
v :aggrd(t)	o :prd(t)	prod :rdi(t)!	Q of aggregate R&D inv.
v :t_inv(i,t)	i :pa(i,t)	prod :inv(t)!	Inv. affected by tax
v :tang(j,t)	i :pklem(j,t)	prod :y(j,t)!	Tangible inputs in prod. function
v :materials(j,t)	i :pma(j,t)	prod :em(j,t)!	Materials in the production
v :cap_serv(j,t)	i :rk(t)	prod :va(j,t)!	Sectoral use of capital services
v :hum_serv(j,t)	i :rhk(t)	prod :y(j,t)!	Sectoral use of HK services
v :inv_fe(i,t)\$fe(i)	i :pa(i,t)	prod :inv(t)!	Inv in PK in the FF sector
v :rd_fe(i,t)\$fe(i)	i :pa(i,t)	prod :rdi(t)!	Inv. in RD in the FF sector
v :p_cons(i,t)\$fe(i)	i :pa(i,t)	prod :cons(t)!	Emissions from private consumption
v :g_cons(i,t)\$fe(i)	i :pa(i,t)	prod :G(t)!	Emissions from gov. consumption
v :sect_fe(fe,j,t)\$eise(j)	i :pac(fe,t)	prod :fb(j,t)!	sectoral FF (covered sectors)
v :sect_fe(fe,j,t)\$neise(j)	i :pa(fe,t)	prod :fb(j,t)!	sectoral FF (non-covered sectors)

\* carbon accounting sector only for covered sectors by the PNAQ

\$prod :carbon(fe,t) s :0

o :pac(fe,t) q :(sum(eise,xbarbal(fe,eise)))  
i :pa(fe,t) q :(sum(eise,xbarbal(fe,eise)))  
i :ptcl(t)\$tcl(t) q :(ccoef(fe) \* sum(eise,xbarbal(fe,eise)))

\* CES production function (KL EM)H

\$prod :y(j,t) elat :2

o :px(j,t)\$ (exptbal(j)) q :exptbal(j)\$ (exptbal(j)) p :py0(j) a :govt(t) t :tybal(j)  
o :p(j,t) q :d0bal(j) p :py0(j) a :govt(t) t :tybal(j)  
i :pklem(j,t) q :(em0bal(j)+(sum(fufu,vbarbal(fufu,j))+tot\_idbal(j))) elat :  
i :rhk(t) q :vbarbal("Hum",j) elat :

\* production of the bundle (KL EM)

\$prod :klem(j,t)

o :pklem(j,t) q :(em0bal(j)+(sum(fufu,vbarbal(fufu,j))+tot\_idbal(j)))  
i :pem(j,t) q :em0bal(j)  
i :pva(j,t) q :(sum(fufu,vbarbal(fufu,j))+tot\_idbal(j))

\* creation of an EM bundle

\$prod :em(j,t) s :0.75

o :pem(j,t) q :em0bal(j)  
i :pnb(j,t) q :m0bal(j)  
i :pma(j,t) q :ma0bal(j)

\* creation of a materials bundle

\$prod :m(j,t) s :0.6

```

    o :pma(j,t)          q :ma0bal(j)
    i :pa(i,t)$ (not e(i))  q :xbarbal(i,j)
* creation of an energy bundle

$prod :nb(j,t) s :0.7
    o :pnb(j,t)          q :n0bal(j)
    i :pfb(j,t)          q :f0bal(j)
    i :pa("elect",t)    q :xbarbal("elect",j)
* creation of a fossil fuel bundle

$prod :fb(j,t) s :1
    o :pfb(j,t)          q :f0bal(j)
    i :pac(fe,t)$eise(j)  q :xbarbal(fe,j)
    i :pa(fe,t)$neise(j)  q :xbarbal(fe,j) a :govt(t) t :tau_c(fe,t)
* value added

$prod :va(j,t) s :1
    o :pva(j,t)          q :(sum(fufu,vbarbal(fufu,j))+tot_idbal(j))
    i :rk(t)             q :vbarbal("K",j) P :pf0("K",j) a :govt(t) t :tfbal("k",j)
    i :pl(t)             q :vbarbal("SL",j) P :pf0("SL",j) a :govt(t) t :tfbal("SL",j)
    i :pl(t)             q :vbarbal("UL",j) P :pf0("UL",j) a :govt(t) t :tfbal("UL",j)
* armington good

$prod :arm(j,t) s :3
    o :pa(j,t)           q :a0bal(j)
    i :p(j,t)            q :d0bal(j)
    i :pm(j,t)           q :(imptbal(j)$ (imptbal(j))*(1+tmbal(j)))
* exports

$prod :expo(j,t)$ (exptbal(j))
    o :pfx(t)            q :exptbal(j)
    i :px(j,t)           q :exptbal(j)
* imports

$prod :imp(j,t)$ (imptbal(j))
    o :pm(j,t)           q :(imptbal(j)$ (imptbal(j))*(1+tmbal(j)))
    i :pfx(t)            q :imptbal(j)$imptbal(j) P :pm0(j) a :govt(t) t :tmbal(j)
* human capital

$prod :hka(t)
    o :prd(t+1)          q :((1-deltah)*hk0)
    o :prdt$tlast(t)     q :((1-deltah)*hk0)
    o :rhk(t)            q :vhbal
    i :prd(t)            q :hk0
* physical capital

```

```

$prod :ka(t)
  o :pinv(t+1)      q :((1-deltak)*k0)
  o :pinvt$tlast(t) q :((1-deltak)*k0)
  o :rk(t)          q :vkbal
  i :pinv(t)        q :k0
* aggregate investment in human capital

$prod :rdi(t) s :1
  o :prd(t+1)      q :ivh0
  o :prdt$tlast(t) q :ivh0
  i :pa(i,t)       q :gbarbal(i,"rdff") a :govt(t) t :tau_c(i,t)$fe(i)
* aggregate investment : only positive values

$prod :inv(t) s :1
  o :pinv(t+1)      q :iv0
  o :pinvt$tlast(t) q :iv0
  i :pa(i,t)       q :tinvbal(i) a :govt(t) t :tau_c(i,t)$fe(i)
* Aggregated private consumption

$prod :cons(t) s :1
  o :pcons(t)      q :((1-mubal)*cbarbal)
  i :pa(i,t)       q :((1-mubal)*gbarbal(i,"Fcons")) a :govt(t) t :tau_c(i,t)$fe(i)
* aggregate government consumption

$prod :G(t) s :1
  o :pg(t)         q :totsbal
  i :pa(i,t)       q :(mubal*gbarbal(i,"Fcons")) a :govt(t) t :tau_c(i,t)$fe(i)
* Final private demand of the representative agent

$demand :ra
  d :pcons(t)      q :(((1-mubal)*cbarbal) * qref(t)) p :pref(t)
  e :pl(t)         q :((sum(j,vbarbal("SL",j))) * qref(t))
  e :pl(t)         q :((sum(j,vbarbal("UL",j))) * qref(t))
  e :pinv(tfirst)  q :k0
  e :pinvt         q :(-1) r :tk
  e :prd(tfirst)   q :hk0
  e :prdt         q :(-1) r :thk
  e :pfx(t)        q :(bopdefbal*qref(t))
  e :pa(j,t)       q :(-xinvbal(j)*qref(t))
  e :ptcl(t)$tcl(t) q :tcl(t)
* Government demand

$demand :govt(t)
  d :pg(t)         p :pref(t)
  e :pg(t)         q :totsbal

```



\* The last year ( $t_{\text{last}}(t)$ ) the increase of investment in physical capital must equal to the increase of production

\$constraint : tk

$$\text{sum}(t_{\text{last}}(t), \text{inv}(t)/\text{inv}(t-1) - ((\text{sum}(j, y(j, t)))/(\text{sum}(j, y(j, t-1))))) = e = 0;$$

\* The last year ( $t_{\text{last}}(t)$ ) the increase of investment in human capital must equal the increase of production

\$constraint : thk

$$\text{sum}(t_{\text{last}}(t), \text{rdi}(t)/\text{rdi}(t-1) - ((\text{sum}(j, y(j, t)))/(\text{sum}(j, y(j, t-1))))) = e = 0;$$

\$offtext

\*=====

\* BENCHMARK REPLICATION AND FREE SOLVE

\*=====

\$sysinclude mpsgeset modelf

\* Quantities increase on the balanced growth path

y.L(j,t) =qref(t);  
 klem.L(j,t) =qref(t);  
 va.L(j,t) =qref(t);  
 arm.L(j,t) =qref(t);  
 expo.L(j,t) =qref(t);  
 imp.L(j,t) =qref(t);  
 inv.L(t) =qref(t);  
 rdi.L(t) =qref(t);  
 nb.L(j,t) =qref(t);  
 m.L(j,t) =qref(t);  
 em.L(j,t) =qref(t);  
 fb.L(j,t) =qref(t);  
 ka.L(t) =qref(t);  
 hka.L(t) =qref(t);  
 cons.L(t) =qref(t);  
 g.L(t) =qref(t);  
 govt.L(t) =qref(t);  
 carbon.L(fe,t) =qref(t);  
 tk.L =k0\*(1+gamma)\*\*card(t);  
 thk.L =hk0\*(1+gamma)\*\*card(t);

\* Prices decrease on the balanced growth path

$p.L(i,t) = \text{pref}(t);$   
 $pem.L(j,t) = \text{pref}(t);$   
 $pklem.L(j,t) = \text{pref}(t);$   
 $pma.L(j,t) = \text{pref}(t);$   
 $pfb.L(j,t) = \text{pref}(t);$   
 $pnb.L(j,t) = \text{pref}(t);$   
 $px.L(j,t) = \text{pref}(t);$   
 $pm.L(j,t) = \text{pref}(t);$   
 $pva.L(j,t) = \text{pref}(t);$   
 $pac.L(fe,t) = \text{pref}(t);$   
 $pa.L(j,t) = \text{pref}(t);$   
 $pcons.L(t) = \text{pref}(t);$   
 $rk.L(t) = \text{pref}(t);$   
 $rhk.L(t) = \text{pref}(t);$   
 $pl.L(t) = \text{pref}(t);$   
 $pg.L(t) = \text{pref}(t);$   
 $ptcl.L(t) = \text{pref}(t);$   
 $pinv.L(t) = (1+r)*\text{pref}(t);$   
 $pinvt.L = \text{sum}(tlast, pinv.L(tlast)/(1+r));$   
 $prd.L(t) = (1+r)*\text{pref}(t);$   
 $prdt.L = \text{sum}(tlast, prd.L(tlast)/(1+r));$

\* set carbon price to zero in benchmark

$ptcl.l(t) = 0;$

\* set reference user cost for factor prices

$pf0(fu,j) = 1 + tfbal(fu,j);$   
 $py0(j) = 1 + tybal(j);$   
 $pm0(j) = 1 + tmbal(j);$

\* MPSGE does not take into account the constraint and considers all taxes as

exogenous when  $\tau.fx=1$

\* $lsupply.l=1;$

\* $\tau.fx(t)=1;$

\* SOLVING OF THE MODEL

\*option nlp pathnlp;

option mcp=path;

\* benchmark replication

```
modelf.iterlim=0;
$include modelf.gen
solve modelf using mcp;
* No calibration
abort$(ABS(modelf.OBJVAL) GT 1.E-4)
"*** benchmark does not calibrate.";
* benchmark national income
ra0 = ra.l;
* FREE SOLVE
*tau.l(t)=0;
modelf.iterlim=10000;
$include modelf.gen
solve modelf using mcp;
$ontext

*=====
*           BUSINESS AS USUAL
*=====

parameter
tot_neisfi
emiss_bau
eis_emiss_bau
ener_emiss_bau
neise_emiss_bau
eise_emiss_bau
bau_emiss_a0
bau_invk
bau_invr
```

```

inc_bau
sector_emiss_bau
gdp_bau
tot_hum_serv
hum_serv_sect
hum_serv_sect_eise
hum_serv_sect_neise
tot_cap_serv
cap_serv_sect
pro
tot_lab_bau
product
impact
tangi
material
productneise
producteise
;
sector_emiss_bau(j,t) = sum(fe, ccoef(fe) * sect_fe.l(fe,j,t));
emiss_bau(t)          = sum(fe,emiss0(fe) * carbon.l(fe,t));
eis_emiss_bau(t)      = sum(eis, sector_emiss_bau(eis,t));
ener_emiss_bau(t)     = sum(e, sector_emiss_bau(e,t));
neise_emiss_bau(t)    = sum(neise, sector_emiss_bau(neise,t));
eise_emiss_bau(t)     = ener_emiss_bau(t) + eis_emiss_bau(t);

```

\* Emissions that come from non covered sectors and derive from Investment and consumption

$$\begin{aligned} \text{tot\_neisfi}(t) = & \text{sum}(\text{neise}, \text{sector\_emiss\_bau}(\text{neise}, t)) \\ & + \text{sum}(\text{fe}, \text{ccoef}(\text{fe}) * \text{p\_cons.l}(\text{fe}, t)) + \text{sum}(\text{fe}, \text{ccoef}(\text{fe}) * \text{g\_cons.l}(\text{fe}, t)) \\ & + \text{sum}(\text{fe}, \text{ccoef}(\text{fe}) * \text{inv\_fe.l}(\text{fe}, t)) \\ & + \text{sum}(\text{fe}, \text{ccoef}(\text{fe}) * \text{rd\_fe.l}(\text{fe}, t)); \end{aligned}$$

$$\text{bau\_emiss\_a0}(t) = \text{tot\_neisfi}(t) + \text{eis\_emiss\_bau}(t) + \text{ener\_emiss\_bau}(t);$$

$$\text{inc\_bau}(t) = \text{ra.l};$$

$$\text{tangi}(j, t) = \text{tang.l}(j, t);$$

$$\text{material}(j, t) = \text{materials.l}(j, t);$$

$$\text{productneise}(t) = \text{sum}(\text{neise}, \text{epro.l}(\text{neise}, t) + \text{dpro.l}(\text{neise}, t));$$

$$\text{producteise}(t) = \text{sum}(\text{eise}, \text{epro.l}(\text{eise}, t) + \text{dpro.l}(\text{eise}, t));$$

$$\begin{aligned} \text{gdp\_bau}(t) = & (\text{pcons.l}(t) * \text{con.l}(t)) + (\text{agginv.l}(t) * \text{pinv.l}(t)) \\ & + (\text{aggrd.l}(t) * \text{prd.l}(t)) + \text{sum}(j, \text{ex.l}(j, t) * \text{pfx.l}(t)) \\ & - \text{sum}(j, \text{im.l}(j, t) * \text{pfx.l}(t)); \end{aligned}$$

$$\text{product}(j, t) = \text{epro.l}(j, t) + \text{dpro.l}(j, t);$$

\* Human capital and physical capital services

$$\begin{aligned} \text{tot\_hum\_serv}(t) & = \text{sum}(j, \text{hum\_serv.l}(j, t)); \\ \text{hum\_serv\_sect\_eise}(t) & = \text{sum}(\text{eise}, \text{hum\_serv.l}(\text{eise}, t)); \\ \text{hum\_serv\_sect\_neise}(t) & = \text{sum}(\text{neise}, \text{hum\_serv.l}(\text{neise}, t)); \\ \text{tot\_cap\_serv}(t) & = \text{sum}(j, \text{cap\_serv.l}(j, t)); \\ \text{hum\_serv\_sect}(j, t) & = \text{hum\_serv.l}(j, t); \\ \text{cap\_serv\_sect}(j, t) & = \text{cap\_serv.l}(j, t); \end{aligned}$$

\* Production

$$\text{pro}(t, j) = \text{dpro.l}(j, t) * \text{p.l}(j, t) + \text{epro.l}(j, t) * \text{px.l}(j, t);$$

\* Labor

$$\text{tot\_lab\_bau}(j, t) = \text{labsect.l}(j, t);$$

\* Price of human capital services and physical capital

$$\text{impact}(t, \text{"prhkser"}) = \text{rhk.l}(t);$$

$$\text{impact}(t, \text{"prpkser"}) = \text{rk.l}(t);$$

option sector\_emiss\_bau :5;  
option eis\_emiss\_bau :5;  
option ener\_emiss\_bau :5;  
option neise\_emiss\_bau :5;  
option eise\_emiss\_bau :5;  
option inc\_bau :5;  
option emiss\_bau :5;  
option tot\_neisfi :5;  
option bau\_emiss\_a0 :5;  
option gdp\_bau :5;  
option tot\_hum\_serv :5;  
option hum\_serv\_sect :5;  
option hum\_serv\_sect\_eise :5;  
option hum\_serv\_sect\_neise :5;  
option bau\_invk :5;  
option bau\_invr :5;  
option tot\_cap\_serv :5;  
option cap\_serv\_sect :5;  
option tot\_lab\_bau :5;  
option impact :5;  
option product :5;  
option tangi :5;  
option producteise :5;  
option productneise :5;  
option material :5;

```
display  emiss_bau, inc_bau, sector_emiss_bau,  
         gdp_bau, eis_emiss_bau, ener_emiss_bau,  
         eise_emiss_bau, neise_emiss_bau, pro,bau_emiss_a0,  
         impact, tot_neisfi, emiss_bau,  
         tot_lab_bau, tot_hum_serv, tot_cap_serv,  
         hum_serv_sect, cap_serv_sect,  
         hum_serv_sect_eise, hum_serv_sect_neise,  
         bau_invk, bau_invr, product, tangi, material;
```

parameter

gdp\_bau\_rep

emiss\_bau\_rep

eis\_bau\_rep

eise\_bau\_rep

ener\_bau\_rep

neise\_bau\_rep

tot\_bau\_rep

tot\_bau\_emiss\_a0\_rep

tot\_hum\_bau

hum\_serv\_bau

tot\_cap\_bau

cap\_serv\_bau

bau\_invk\_rep

bau\_invr\_rep

productneise\_bau

producteise\_bau

material\_bau

;

```

gdp_bau_rep(t,"a")      =gdp_bau(t);
emiss_bau_rep(t,"d")    =emiss_bau(t);
eis_bau_rep(t,"e")      =eis_emiss_bau(t);
ener_bau_rep(t,"f")     =ener_emiss_bau(t);
eise_bau_rep(t,"g")     =eise_emiss_bau(t);
neise_bau_rep(t,"h")    =neise_emiss_bau(t);
tot_bau_emiss_a0_rep(t,"i") =bau_emiss_a0(t);
tot_hum_bau(t,"b")      =tot_hum_serv(t);
tot_cap_bau(t,"k")      =tot_cap_serv(t);
bau_invk_rep(t,"l")     =bau_invk(t);
bau_invr_rep(t,"m")     =bau_invr(t);
productneise_bau(t,"n") =productneise(t);
producteise_bau(t,"o")  =producteise(t);

option gdp_bau_rep :5;
option eis_bau_rep :5;
option neise_bau_rep :5;
option eise_bau_rep :5;
option tot_bau_emiss_a0_rep :5;
option tot_hum_bau :5;
option tot_cap_bau :5;
option bau_invk_rep :5;
option bau_invr_rep :5;
option producteise_bau :5;
option productneise_bau :5;

display  gdp_bau_rep,emiss_bau_rep,eis_bau_rep, eise_bau_rep,ener_bau_rep,
         neise_bau_rep,tot_bau_emiss_a0_rep, tot_hum_bau,
         tot_cap_bau, bau_invk_rep, bau_invr_rep,
         producteise_bau, productneise_bau;
$offtext
*$ontext

*=====
*
*           POLICY CASE

```



\*=====

\* We constrain only the sectors that are constrained by the NAP

parameter

impact      Vector of impact of policy shock

;

parameter

ener\_emiss\_con    NAP constraint on the energy producing sectors

eis\_emiss\_con     NAP constraint on the energy intensive sectors

;

ener\_emiss\_con(t) = 17.72;

eis\_emiss\_con(t) = 15.88;

\* PNAQ data for France for 2005 - 2007 + BANKING

tcl(t)\$ (ord(t)=11) = 37.40414 - 0.25209;

tcl(t)\$ (ord(t)=12) = 38.15223 - 0.26389;

tcl(t)\$ (ord(t)=13) = 38.91527 - 0.27299;

\* PNAQ data for France for 2008 - 2012 + BANKING, with NAP not constrained

no Kyoto

tcl(t)\$ (ord(t)=14) = 39.69358 - 1.30449;

tcl(t)\$ (ord(t)=15) = 40.48745 - 1.37549;

tcl(t)\$ (ord(t)=16) = 41.29720 - 1.49549;

tcl(t)\$ (ord(t)=17) = 42.12314 - 1.59849;

tcl(t)\$ (ord(t)=18) = 42.96560 - 1.72849;

\* PNAQ data for France for 2008 - 2012 + BANKING, with NAP not constrained

with Kyoto

\* tcl(t)\$ (ord(t)=14) = -;

\* tcl(t)\$ (ord(t)=15) = -;

\* tcl(t)\$ (ord(t)=16) = -;

\* tcl(t)\$ (ord(t)=17) = -;

\* tcl(t)\$ (ord(t)=18) = -;

\* PNAQ data for France for 2008 - 2012 + BANKING, with NAP constrained to

32 with Kyoto

```
* tcl(t)$(ord(t)=14) = - ;
* tcl(t)$(ord(t)=15) = - ;
* tcl(t)$(ord(t)=16) = - ;
* tcl(t)$(ord(t)=17) = - ;
* tcl(t)$(ord(t)=18) = - ;

* PNAQ data for France NO BANKING
* tcl(t)$(ord(t) >= 11) = ener_emiss_con(t) + eis_emiss_con(t) ;

* PNAQ data for France in the case where the NAP is constrained, NO BANKING
* tcl(t)$(ord(t) >= 14) = 32 ;

* PNAQ data + Kyoto 2008 - 2012
* carbtax(t)$(ord(t) >= 14) = 8.5 ;
* tau_c(fe,t) = carbtax(t) * 1e-3 * ccoef(fe) ;

$include modelf.gen

solve modelf using mcp ;

parameter
emiss_pol
eis_emiss_pol
ener_emiss_pol
neise_emiss_pol
eise_emiss_pol
tot_emiss_pol
inc_pol
sector_emiss_pol
gdp_pol
tot_hum_serv_pol
hum_serv_sect_eise_pol
```

```

hum_serv_sect_neise_pol
hum_serv_sect_pol
tot_cap_serv_pol
cap_serv_sect_pol
tot_neisfi_pol
pro
tot_lab_pol
pol_invk
pol_invr
product
tangi
producteise
productneise
material
;
tot_neisfi_pol(t) = sum(neise, sector_emiss_pol(neise,t))
                  + sum(fe,ccoef(fe)*p_cons.l(fe,t))+ sum(fe,ccoef(fe)*g_cons.l(fe,t))
                  + sum(fe,ccoef(fe)*inv_fe.l(fe,t))
                  + sum(fe,ccoef(fe)*rd_fe.l(fe,t));
tot_emiss_pol(t) = eise_emiss_pol(t)+tot_neisfi_pol(t);
inc_pol(t)       = ra.l;
tangi(j,t)      = tang.l(j,t);
material(j,t)    = materials.l(j,t);
productneise(t) = sum(neise, epro.l(neise,t) + dpro.l(neise,t));
producteise(t)  = sum(eise, epro.l(eise,t) + dpro.l(eise,t));
gdp_pol(t)      = (pcons.l(t)*con.l(t))+ (agginv.l(t)*pinv.l(t))
                  + (aggrd.l(t)*prd.l(t))+sum(j,ex.l(j,t)*pfx.l(t))
                  -sum(j,im.l(j,t)*pfx.l(t));
product(j,t)    = epro.l(j,t) + dpro.l(j,t);
pro(t,j)        = dpro.l(j,t)*p.l(j,t)+epro.l(j,t)*px.l(j,t);
tot_lab_pol(j,t) = labsect.l(j,t);

```

```

sector_emiss_pol(j,t) = sum(fe, ccoef(fe) * sect_fe.l(fe,j,t));
emiss_pol(t)         = sum(fe,emiss0(fe) * carbon.l(fe,t));
eis_emiss_pol(t)     = sum(eis, sector_emiss_pol(eis,t));
ener_emiss_pol(t)    = sum(e, sector_emiss_pol(e,t));
neise_emiss_pol(t)   = sum(neise, sector_emiss_pol(neise,t));
eise_emiss_pol(t)    = ener_emiss_pol(t) + eis_emiss_pol(t);
tot_hum_serv_pol(t)  = sum(j,hum_serv.l(j,t));
hum_serv_sect_pol(j,t) = hum_serv.l(j,t);
hum_serv_sect_eise_pol(t) = sum(eise,hum_serv.l(eise,t));
hum_serv_sect_neise_pol(t) = sum(neise,hum_serv.l(neise,t));
tot_cap_serv_pol(t)  = sum(j,cap_serv.l(j,t));
cap_serv_sect_pol(j,t) = cap_serv.l(j,t);
impact(t,"pc $/ton") = 1000 * ptcl.l(t);
impact(t,"welf level") = ra.l;
impact(t,"pr. HK serv") = rhk.l(t);
impact(t,"pr. PK serv") = rk.l(t);

```

```

option sector_emiss_pol :5;
option eis_emiss_pol :5;
option ener_emiss_pol :5;
option neise_emiss_pol :5;
option eise_emiss_pol :5;
option tot_emiss_pol :5;
option tot_neisfi_pol :5;
option inc_pol :5;
option emiss_pol :5;
option gdp_pol :5;
option impact :5;
option tot_hum_serv_pol :5;
option product :5;
option hum_serv_sect_pol :5;
option hum_serv_sect_neise_pol :5;
option hum_serv_sect_eise_pol :5;
option tot_cap_serv_pol :5;

```

option cap\_serv\_sect\_pol :5;

option tot\_lab\_pol :5;

option pol\_invr :5;

option pol\_invk :5;

option tangi :5;

option producteise :5;

option productneise :5;

option material :5;

display emiss\_pol, inc\_pol, sector\_emiss\_pol, gdp\_pol, eis\_emiss\_pol, ener\_emiss\_pol,  
eise\_emiss\_pol, neise\_emiss\_pol,

tot\_emiss\_pol, impact, tot\_lab\_pol, hum\_serv\_sect\_pol, cap\_serv\_sect\_pol,  
tot\_hum\_serv\_pol, tot\_cap\_serv\_pol, pro,

hum\_serv\_sect\_neise\_pol, hum\_serv\_sect\_eise\_pol, pol\_invr, pol\_invk, prod-  
uct, sambal.l, tangi, producteise, productneise, material;

parameter

gdp\_pol\_rep

unski\_pol\_rep

uski\_pol\_rep

emiss\_pol\_rep

eis\_pol\_rep

eise\_pol\_rep

ener\_pol\_rep

neise\_pol\_rep

tot\_pol\_rep

tot\_pol\_emiss\_a0\_rep

tot\_hum\_pol

hum\_serv\_pol

```

tot_cap_pol
cap_serv_pol
pol_invr_rep
pol_invk_rep
producteise_pol
productneise_pol
;

gdp_pol_rep(t,"a")           = gdp_pol(t);
emiss_pol_rep(t,"d")        =emiss_pol(t);
eis_pol_rep(t,"e")          =eis_emiss_pol(t);
ener_pol_rep(t,"f")         =ener_emiss_pol(t);
eise_pol_rep(t,"g")         =eise_emiss_pol(t);
neise_pol_rep(t,"h")        =neise_emiss_pol(t);
tot_pol_emiss_a0_rep(t,"i") =tot_emiss_pol(t);
tot_hum_pol(t,"b")          =tot_hum_serv_pol(t);
tot_cap_pol(t,"k")          =tot_cap_serv_pol(t);
pol_invk_rep(t,"l")         =pol_invk(t);
pol_invr_rep(t,"m")         =pol_invr(t);
productneise_pol(t,"n")     =productneise(t);
producteise_pol(t,"o")      =producteise(t);
option gdp_pol_rep :5;

option eis_pol_rep :5;

option neise_pol_rep :5;

option eise_pol_rep :5;

option tot_pol_emiss_a0_rep :5;

option tot_hum_pol :5;

option tot_cap_pol :5;

option pol_invr_rep :5;

option pol_invk_rep :5;

option productneise_pol :5;

option producteise_pol :5;

display gdp_pol_rep,emiss_pol_rep,eis_pol_rep, eise_pol_rep,ener_pol_rep,

```

neise\_pol\_rep,tot\_pol\_emiss\_a0\_rep,tot\_hum\_pol,tot\_cap\_pol,pol\_invr\_rep,  
pol\_invk\_rep, producteise\_pol, productneise\_pol;

\*\$offtext

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# Conclusion Générale

In this thesis, we sought to deepen our understanding of the mechanisms underlying the process of induced technological change. After having made an overview in the first chapter of this thesis of the different techniques to model technological change in energy-economy models, we build a CGE model for the French economy in the second chapter where we model technological change as an exogenous process. We determine in detail the impact on the economy of a policy similar to the French National Allocation Plan and address the different model reactions to such a policy in the case where firms cannot have access to technological change. We address the shortcomings of modeling technological change as an exogenous process in such a specification, specifically in that it is impossible with such a model to define the effect of an emission constraint on technological change, nor its impact on the rest of the economy. In the third chapter we model in a partial theoretical model introduced by Nordhaus in 1968, an energy constraint, and show that the optimal direction of technological change can indeed be expected to be influenced by such a policy. However, in such a partial framework we do not assess the impacts on the whole economy of such an emission constraint. For this reason, in the fourth chapter of this thesis, we determine a method for modeling technological change through the stock of knowledge approach in a forward looking version of the general equilibrium model for France described in the second chapter of this thesis. By so doing we manage to determine the effect of the National Allocation Plan on technological change, as well as the effect of technological change on the rest of the economy.

We show that, in a general equilibrium framework the negative impact of the revenue effect, limits the positive effect of technological change on the covered sectors. Moreover, while the process of technological change indeed slightly limits the negative impacts of the environmental policy on the economy, the effect on production and emissions are very small and are a short lived process. Technological change appears the first years of the constraints and disappears rapidly in the following years leaving the economy on a path where substitutions are the only reaction possibility of the model. Indeed, with our specification of induced technological change, the conventional substitutions between tangible inputs detailed in the second chapter of this thesis, are the firms' only solution to facing the emission constraints. With such model behavior, we support the proposition that technological change has less effect on the economy than the conventional substitution between tangible inputs. In our frame of work, in order for technological change to play a major role in the model's reactions, it is necessary for the emission constraint to increase each year and not be stable over a period of time. Finally, we also show that an eviction effect may lead to the fall in the investment in physical capital when the investment in human capital increases.

Such small results the first years of the introduction of the constraints may be due to the type of emission constraint that we introduced in the model, whereby the National Allocation Plan is indeed a very loose constraint. It would be interesting to study, for instance, the effect on the model of introducing the Kyoto constraint on the non covered sectors in the second simulation period, or simply a stronger emission constraint than the NAP on covered sectors. Another cause for these small reactions could be linked to the value of the elasticities of substitution between the tangible inputs. Indeed, minimizing the substitution possibilities may also be a means to enhancing the impact on human capital services of an environmental policy. For this reason a sensitivity analysis would be interesting to undertake.

In our specification of the production function, technological change is Hicks-neutral

in the sense that it increases the productivity of all inputs to production in a similar fashion. Therefore, by modifying the production function, it would be particularly interesting to study how technological change may increase the productivity of energy alone or reduce the emission / output relationship.

In terms of the data extraction, in the process of extracting human capital from the SAM we chose to concentrate on human capital embodied in the interindustry transaction matrix as well as in the value of labor found in the SAM. We recognize here that human capital may also be extracted from physical capital services and extracting human capital services from this factor would refine the analysis. Such refinement would be useful if this technique for modeling technological change is further studied.

Finally, one of our main constraints in this thesis being the lack of precise data for our date of calibration, namely 1995, it is almost needless to add that such analysis would gain in accuracy with more up-to-date and accurate values for the different parameters that we used in this thesis.



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# Résumé de Thèse

Dans cette thèse, nous avons cherché à déterminer l'effet de la prise en compte du progrès technique endogène sur l'étude des répercussions économiques d'une contrainte environnementale.

En effet, aujourd'hui les dégâts environnementaux, conséquences de nos comportements ne peuvent plus être ignorés. Nos comportements enracinés dans une forte préférence pour le présent, et notre capacité à ignorer les conséquences futures de nos actions, plus ces conséquences sont lointaines dans le temps, se traduisent par des choix de consommation de plus en plus égoïstes. Il y a encore une centaine d'années, nul ne prenait conscience du fait que l'industrialisation grandissante de notre économie pouvait avoir des répercussions néfastes sur l'environnement. Aujourd'hui, alors que nos consciences commencent à être rodées, il est particulièrement frappant que ce qui motive l'homme dans sa volonté de protéger l'environnement est non pas cette prise de conscience mais simplement le fait que l'on commence déjà à voir et à ressentir les conséquences de nos choix de vie. Ainsi, l'on peut bien chercher à démontrer que nos actions auront de graves répercussions sur le bien-être de nos enfants ou petits enfants, mais ceci ne nous incitera pas réellement à changer de comportement. C'est bien l'imminence et la palpabilité de ces répercussions qui pourra nous faire remettre nos comportements en question. Mais il faut aussi bien avouer que l'homme, face aux conséquences de ses choix de vie, ne désire pas réellement modifier ses choix de consommation profondément enracinés dans ses habitudes, et réduire son bien-être aujourd'hui, même s'il sait que cela augmentera son bien-être demain.

Cette réticence se traduit par le comportement frileux de certains gouvernements qui, soumis au culte de la croissance quantitative craignent de la contraindre en soumettant leur économie à des politiques environnementales. En effet, peu acceptent de mettre en péril la croissance de leur économie pour le bien-être environnemental du monde demain. D'ailleurs, le comportement de nos gouvernements reflète ceux des hommes qui la composent. Si se limiter aujourd'hui dans ses choix de consommation est pénible, risquer de corrompre la croissance, inconcevable. D'autant plus que se mêlent à ces choix gouvernementaux les considérations personnelles des personnages politiques, qui voient en une croissance soutenue aujourd'hui la condition sine qua non à leur réélection demain.

C'est peut-être d'ailleurs au fond, devant ce constant d'échec que l'on a du chercher en autre chose que dans la modification de nos comportements, la solution au problème du changement climatique. En effet, même si le concept et l'existence même du progrès technique est loin d'être nouveau, il a trouvé au coeur de cette problématique une nouvelle raison essentielle à son existence. Tout compte fait, n'est il pas le moyen idéal pour empêcher qu'une contrainte environnementale ait un impact négatif sur la croissance? Ainsi, pour ne pas risquer qu'agir pour la protection de l'environnement nous force à modifier nos choix de consommation, nous cherchons dans l'existence du progrès technique la solution à l'apparente dichotomie qui existe entre croissance et contrainte environnementale.

Et pourquoi pas d'ailleurs. Après tout, il est bien évident que le progrès technique est au coeur du fonctionnement de notre société et qu'il est d'ailleurs l'élément essentiel de la croissance. Ainsi, ne pas le prendre en compte dans les projections de nos modèles serait ne pas prendre en compte l'élément central à leur croissance. Mais la question qui est posée ici, est celle de l'endogénéité du progrès technique, à savoir, si et comment le progrès technique est influencé par les différentes contraintes d'une société, et si et comment il permet de lever les contraintes pour faire croître toujours plus.

C'est dans un contexte de modélisation que s'inscrit cette thèse et au coeur de ce débat entre politique environnementale, progrès technique et croissance.

Nous allons ainsi chercher à montrer comment la prise en compte d'une contrainte environnementale dans un modèle d'équilibre général calculable où le progrès technique est modélisé comme un processus exogène, affecte une économie. Nous adresserons ainsi les limitations qui sous-tendent la modélisation du changement technologique comme un processus exogène et chercherons à mettre en évidence les impacts du Plan National d'Allocation des Quotas, sur les différents secteurs de l'économie française. Ensuite, nous montrerons comment la direction du progrès technique est en fait affectée par une contrainte environnementale. Ceci nous permettra de soutenir l'idée qu'il est nécessaire de modéliser le progrès technique comme un processus endogène qui peut être influencé par une politique environnementale et qui canalise les effets de cette politique sur une économie. Enfin, nous reprenons le modèle d'équilibre général modélisé avec le progrès technique exogène et nous présentons une méthode pour modéliser le progrès technique de manière endogène à travers le l'approche par le "Stock de Connaissances". Nous étudions ensuite comment la prise en compte du progrès technique induit influence les résultats du modèle. Nous montrons, que finalement, le progrès technique induit a peu d'impacts sur le comportement de l'économie.

Dans le premier chapitre de cette thèse, nous donnons un état de l'art de la modélisation du progrès technique. Nous étudions comment le progrès technique est généralement modélisé dans les modèles économie - énergie, c'est à dire les modèles qui prennent en compte la dimension énergie de l'économie. Nous montrons qu'il existe deux méthodes fondamentalement différentes dans la modélisation du progrès technique; il est soit possible de le modéliser de façon exogène, soit de façon endogène. Modéliser le progrès technique de façon exogène sousentend que l'on suppose que le progrès technique dans sa direction ou dans son taux ne peut pas être affecté par une contrainte. En effet, il suit une tendance prédéterminée par le modélisateur. En revanche, modéliser le pro-

grès technique de façon endogène signifie que le modélisateur suppose que sa direction et son taux sont malléables et sont la conséquence de la situation économique.

Nous présentons dans ce chapitre deux méthodes pour modéliser le progrès technique exogène et deux méthodes pour modéliser le progrès technique endogène. Il est en effet possible de modéliser le progrès technique exogène par le paramètre "Autonomous Energy Efficiency Improvement", ou par les Technologies Backstop. Par ailleurs il est possible de modéliser le progrès technique endogène par le "Learning by Doing" et par l'approche par le "Stock de Connaissances". Nous détaillons mathématiquement la modélisation de ces quatre approches et présentons les avantages et les inconvénients liés à ces méthodes de modélisation.

Dans le deuxième chapitre de cette thèse nous construisons un modèle d'équilibre général calibré sur une matrice de comptabilité sociale, compilée par les chercheurs de GEM-E3 et EUROSTAT, représentant la France en 1995. Nous construisons une version dynamique récursive de ce modèle, et modélisons le progrès technique de manière exogène. L'objectif de ce chapitre est d'étudier comment une économie réagit dans le cas d'une contrainte environnementale libellée sous la forme du Plan National d'Allocation des Quotas (PNAQ), et dans le cas où le progrès technique n'est pas malléable. Pour ce faire, nous étudions trois politiques. La première est l'introduction du PNAQ en 2005 et jusqu'en 2012, sans contrainte supplémentaire. La deuxième est l'introduction du PNAQ en 2005 et jusqu'en 2012 couplée avec l'introduction des contraintes de Kyoto en 2008 et jusqu'en 2012. La troisième est l'introduction du PNAQ en 2005 et jusqu'en 2007, rendue plus contraignante entre 2008 et 2012, et couplée avec l'introduction des contraintes de Kyoto en 2008.

Nous montrons à travers la modélisation du PNAQ jusqu'en 2012, que cette politique est peu contraignante, et que le prix des permis est proche de 1.2\$ MtC la première période et 8.5\$ MtC la deuxième période. Nous montrons que la production des secteurs

couverts (secteurs visés par le PNAQ) chute pendant le temps où la contrainte est active par rapport au BAU (Business as Usual) alors que la production des secteurs non couverts (secteurs non visés par le PNAQ) croît relativement au BAU. Nous mettons simplement ici en évidence le phénomène principal qui sous-tend ce modèle, à savoir les possibilités de substitutions. En effet, alors que les secteurs couverts sont contraints dans leurs émissions, la production des secteurs non couverts est tout simplement plus demandée dans le processus de production des deux types de secteurs. Nous montrons de plus, que ce sont les secteurs dont la production est la plus intensive en pétrole et en gaz, qui achètent les permis sur le marché des permis d'émission négociables au prix de 1.2\$ MtC la première période et 8.5\$ MtC la deuxième période. En effet, ces secteurs peuvent difficilement substituer assez de leurs inputs pour satisfaire les contraintes d'émission. Les secteurs dont la production est la moins intensive en pétrole et en gaz sont vendeurs de permis sur le marché, car leurs simples substitutions leur permettent de polluer moins.

Nous montrons à travers la deuxième politique environnementale, que l'introduction du PNAQ jusqu'en 2012, couplé en 2008 avec les contraintes de Kyoto (approximées par une taxe sur les secteurs non couverts de 26\$ MtC) modifient ces premiers résultats. Dans la première période, le prix des permis des secteurs couverts est de 1.2\$ MtC tandis que ce prix n'atteint que 3.4\$ MtC la deuxième période (contrairement à 8.5 \$ MtC dans la première politique). Ceci vient du fait que les contraintes reposant sur les secteurs non couverts les forcent cette fois à réduire leurs émissions. Ainsi les secteurs non couverts utilisent dans leur production encore moins de charbon, pétrole et gaz (énergies fossiles polluantes), ce qui leur permet de réduire leurs émissions. La production totale des secteurs couverts chute ainsi mécaniquement comme leur demande chute. Le prix des permis d'émissions négociables que s'échangent les secteurs couverts, tombe forcément. Il apparaît ici que les secteurs qui se portent vendeurs de permis d'émissions négociables dans la deuxième période sont maintenant les secteurs

du charbon, du pétrole et du gaz. En effet, leur demande chute tellement qu'ils se trouvent en état d'excédent de permis alors que les autres secteurs se portent acheteurs de permis en raison du léger accroissement de leur production.

Nous montrons à travers la troisième politique environnementale, que l'introduction du PNAQ jusqu'en 2007, rendu plus contraignant (1.45 MtC en moins que la contrainte initiale) en 2008 et couplé avec les contraintes de Kyoto (approximées cette fois par une taxe de 8\$ MtC sur les secteurs non couverts) modifient encore ces résultats. Nous montrons que le prix des permis la première période est de 1.2\$ MtC tandis que ce prix atteint à la deuxième période 25\$ MtC. Cette croissance des prix provient du fait que la contrainte est accrue sur les secteurs couverts. La production total des secteurs couverts chute encore plus fortement que dans les deux premières politiques et ce en raison du fait que le PNAQ est plus contraignant. La production des secteurs non couverts croît encore plus que dans les deux politiques précédentes en raison des phénomènes de substitution d'inputs en leur faveur. Cette fois, les secteurs couverts qui achètent leurs permis sur le marché des permis d'émissions négociables sont à nouveau les même secteurs que dans la première politique, à savoir les secteurs qui sont les plus intensifs en pétrole et gaz. Les autres se portent vendeurs sur le marché, car ils ont réussi à substituer leurs inputs suffisamment pour réduire leurs émissions. Ce qui apparaît ici est le fait que contraindre encore plus le PNAQ dans la deuxième période fait chuter la taxe sur les secteurs non couverts. Elle est tout simplement moins forte car les contraintes de Kyoto sont presque atteints grâce au PNAQ.

Dans le troisième chapitre de cette thèse nous étudions à l'aide d'un modèle théorique introduit par Nordhaus en 1968, la direction du progrès technique dans le cas où il existe une contrainte sur l'utilisation d'énergie. Ainsi, l'objectif de ce chapitre est de montrer que la direction du progrès technique repose sur les facteurs de production qui sont contraints et n'est donc pas indépendant de l'introduction de politiques environnementales.

Pour ce faire nous reprenons le cadre de travail de Nordhaus et introduisons dans la fonction de production simple du producteur comprenant le capital (facteur accumule dans le temps) et le travail (facteur non reproductible), un facteur de production supplémentaire, l'énergie (facteur reproductible). Dans ce cas, nous montrons que le résultat canonique de Nordhaus est à nouveau vérifié, à savoir que sur le sentier de croissance de long terme le progrès technique est neutre au sens de Harrod ; il repose sur le facteur de production non reproductible. Nous montrons de plus que les conditions nécessaires qui sous-tendent ce résultat sont suffisantes quand l'élasticité de substitution entre l'agrégat capital-énergie et le travail est inférieure à 1. Dans le cas où il est supérieur à 1, nous montrons que sur le sentier de croissance de long terme, le progrès technique neutre au sens de Harrod n'est plus optimal. Enfin, nous montrons que sur ce sentier, tous les facteurs intensifs croissent au taux de croissance du progrès technique, ce qui signifie que les émissions provenant de l'utilisation de l'énergie croîtront sans contrainte.

Nous introduisons ensuite une contrainte sur l'utilisation d'énergie, et nous supposons qu'à long terme l'utilisation d'énergie ne peut pas dépasser un certain seuil. Nous montrons dans ce cas que sur le sentier de croissance de long terme il est impossible que le progrès technique soit neutre au sens de Harrod. Il faut en effet que le progrès technique repose en partie sur l'agrégat capital-énergie. En effet, nous montrons que dans le cas où la part du capital dans l'agrégat capital-énergie tend vers l'unité (c'est à dire est grande), le progrès technique tendra vers la neutralité au sens de Harrod. En effet, nous tendons à retrouver le cas de Nordhaus à deux facteurs de production. En revanche, si la part du capital dans l'agrégat capital-énergie tend vers 0 (c'est à dire est faible), le progrès technique tendra vers la neutralité au sens de Hicks. Enfin, nous notons que la force de la contrainte ne joue aucun rôle sur la direction du progrès technique et que le progrès technique sera toujours plus fort sur le travail que sur l'agrégat, et ce quelle que soit la contrainte sur l'énergie.



Dans le quatrième chapitre de cette thèse, nous prenons acte des conclusions des trois premiers chapitres, à savoir que de ne pas prendre en compte le progrès technique comme un processus endogène limite la puissance explicative du modèle. Le modèle ne peut pas expliquer comment le progrès technique est affecté par une contrainte environnementale. De plus, il ne permet pas de rendre compte de toutes les différentes réactions qu'une économie peut avoir face à une contrainte environnementale. Enfin, nous prenons acte des conclusions du premier chapitre relatives aux avantages et limitations dans la modélisation du progrès technique dans les modèles économie-énergie. Nous présentons ainsi une nouvelle méthode pour modéliser le progrès technique endogène à travers l'approche par le Stock de Connaissances.

Nous reprenons ainsi le modèle d'équilibre général détaillé dans le deuxième chapitre de cette thèse. Nous modifions tout d'abord la matrice de comptabilité sociale (MCS) sur laquelle est calibré le modèle de façon à y extraire une estimation du capital humain compris dans les valeurs de la matrice.

Pour ce faire nous utilisons des données relatives aux investissements en recherche et développement en 1995 pour chaque secteur donné dans la MCS. Nous multiplions ces données avec une matrice représentant les flux de brevets en France autour de cette période. Nous obtenons ainsi une méthode pour estimer comment les investissements en R&D d'une entreprise  $i$  ont été "distribués" ou "spill-over" en 1995 vers les autres secteurs de l'économie. Nous appelons cette matrice, la matrice de flux technologiques. Nous extrayons cette matrice de la matrice d'échanges inter-industriels de la MCS et la sommions sur  $i$  et sur  $j$ . Nous créons ainsi une nouvelle colonne dans la MCS représentant les investissements en R&D par secteur et une nouvelle ligne représentant la valeur des services de capital humain utilisés comme facteur de production.

Or, nous savons que le capital humain est aussi compris dans la valeur du travail que l'on trouve dans la MCS. Pour en extraire une estimation, nous multiplions le nombre

de chercheurs employés dans chaque secteur par le salaire d'un travailleur qualifié. Nous retirons ces valeurs obtenues de la valeur du travail dans la MCS et les ajoutons à la nouvelle ligne représentant les services de capital humain. Nous obtenons donc une nouvelle matrice de comptabilité sociale entièrement équilibrée.

Or le problème qui se pose à nous est celle de la méthode à utiliser pour calibrer un modèle dynamique sur cette matrice. En effet, pour que le stock de capital physique et le stock de capital humain croissent tous deux au taux de croissance de l'économie, il faut qu'il y ait un seul taux d'intérêt qui satisfasse les conditions de croissance des deux stocks. Or, il apparaît que le taux d'intérêt nécessaire pour que le stock de capital physique croisse sur le sentier de croissance de long terme est différent de celui nécessaire pour que le stock de capital humain croisse aussi sur le sentier de croissance de long terme. Pour résoudre cette difficulté, nous choisissons comme taux d'intérêt de référence, celui du capital physique et déterminons les valeurs de l'investissement en R&D nécessaires pour que le stock de capital humain croisse sur le sentier de croissance de long terme avec ce taux d'intérêt. Nous modifions les valeurs de la colonne investissement en R&D, pour que l'équilibre soit satisfait. Cette manipulation sur la matrice de comptabilité sociale la déséquilibre. Pour la rééquilibrer nous utilisons un algorithme permettant de recalculer les valeurs de toute la matrice de comptabilité sociale, en minimisant le carré de la différence entre l'ancienne et la nouvelle matrice et en rajoutant comme contrainte que les valeurs du capital humain et du capital physique de la nouvelle matrice permette de définir cette croissance de long terme. La matrice est à nouveau équilibrée.

Nous calibrons ensuite notre modèle sur cette nouvelle matrice ainsi que sur l'ancienne matrice. Nous construisons ainsi deux versions du même modèle dyanmique, un avec le capital physique comme seul stock qui croît sur le sentier de croissance de long terme, et l'autre avec le capital physique et le capital humain qui croissent tous deux sur le sentier de croissance de long terme. Ainsi, nous pouvons étudier l'introduction

du PNAQ dans une version du modèle avec progrès technique endogène et dans une version du modèle sans progrès technique.

Face à une contrainte environnementale, une entreprise peut substituer entre ses différents facteurs de production tangibles tels le travail, la capital physique, l'énergie, les matériaux, mais peut aussi substituer ces facteurs de production tangibles pour un facteur de production intangible, le capital humain. Cette dernière substitution est le processus de progrès technique endogène.

Dans cette spécification nous montrons que comme Nordhaus (2002), dans le cas où on introduit le Plan National d'Allocation des Quotas dans la version du modèle avec changement technologique induit, l'effet du progrès technique induit est moins important que les effets de substitution entre les inputs de production tangibles qui ont lieu les années qui suivent l'introduction de la contrainte. Le détail de ses effets de substitutions sont donnés dans le chapitre deux de cette thèse.

Par ailleurs, nous montrons comme le fait Sue Wing (2001), que dans le cas où on a modélisé le progrès technique comme un processus endogène, les secteurs qui ne sont pas soumis au PNAQ vont accroître leur demande de services de capital humain par rapport au BAU plus que ne le feront les secteurs qui sont visés par la contrainte énergétique. Ceci est dû aux effets de substitution qui fait que la production des secteurs non contraints croît suite à l'introduction de la contrainte énergétique sur les secteurs couverts, car les deux types de secteurs demandent leur production comme facteur de production. Cette croissance de leur production leur permet de mécaniquement accroître leur demande de facteurs de production et donc de services de capital humain.

Nous montrons aussi l'existence d'un effet d'éviction ou effet de "crowding out", qui relie la demande de services de capital humain à la demande de services de capital physique. En effet, nous montrons que dans le cas où l'investissement en R&D augmente ceci entraîne une chute de l'investissement en capital physique. C'est pourquoi les

demandes de services de capital physique et de capital humain suivent des graphiques inversés.

Enfin, nous montrons dans la lignée de Popp (2002), qu'il existe des pics de demande de services de capital humain les premières années de l'introduction du PNAQ, et ce pour les deux types de secteurs. Ceux ci disparaissent les années qui suivent alors même que la contrainte est encore active.

Le progrès technique est donc un processus à courte espérance de vie, moins efficace que les effets de substitution face à une contrainte environnementale qui ne peut être induit qu'à force de politiques de plus en plus contraignantes.

# Résumé

La réalité du réchauffement climatique ne fait plus aucun doute aujourd'hui. Les hommes ont pris conscience de l'imminence des conséquences de leurs comportements sur l'environnement ainsi que de la nécessité de prendre des mesures efficaces pour réduire les gaz à effet de serre provenant de la production industrielle. Ainsi il est important d'étudier les effets d'une politique environnementale sur le fonctionnement de l'économie. Dans ce contexte, la question des moyens à mettre en oeuvre pour éviter qu'une politique de protection environnementale ne déclenche une réduction de la croissance économique, se pose naturellement. Dans cette thèse nous cherchons étudier si le progrès technique peut remédier à la dichotomie qui existe entre croissance économique et contrainte environnementale. Nous montrons à travers un modèle d'équilibre général calculable représentant l'économie française, comment une contrainte d'émissions similaire au Plan National d'Allocation des Quotas affecte l'économie de la France si celle-ci ne peut y répondre que par des substitutions entre facteurs de production. Nous montrons de plus comment la direction du progrès technique peut vraisemblablement être influencée par une contrainte d'émissions. Ne pas prendre en compte cet effet sur le progrès technique mènerait à la sous-estimation des capacités de réaction d'une économie. Nous proposons enfin une réflexion sur les effets du progrès technique induit par une contrainte environnementale dans un cadre d'équilibre général. Le progrès technique est ici défini comme une demande croissante du facteur de production intangible en réaction à une contrainte d'émissions, ce qui permet l'augmentation de l'efficacité des facteurs de production tangibles.

Today few people doubt the reality of global warming. We have understood that our economic choices and behavior influence our environment visibly and rapidly, and see the necessity for efficient measure to reduce greenhouse gas emissions stemming from industrial production. For this reason, it is important to study the likely effects that an environmental policy may have on the economy. In this context it is important to investigate how an economy may counter the negative impacts of an environmental constraint on economic growth. In this thesis, we seek to determine whether technological progress may be a remedy to the expected dichotomy between economic growth and environmental protection. We show, through a general equilibrium model representing the French economy, how a constraint similar to the French National Allocation Plan affects the French economy when the latter's only possible reactions are substitutions between production factors. We then show how the direction of technological change can be expected to be influenced by an environmental constraint. To oversee this effect would lead to underestimating the capacity of an economy to react. Finally, we describe the effects of technological change induced by an environmental constraint in a general equilibrium framework. Technological change is here modeled as an increased demand for the intangible production factor following an environmental constraint, which leads to an increase in the efficiency of tangible production factors.