"Stochastic scenarios for energy transition"

Durand-Lasserve, Olivier

ABSTRACT

This dissertation studies how uncertainty affects technology choice and investment decision in the context of a transition towards low-carbon economies. We use multi-region dynamic applied general equilibrium models and stochastic programming. Chapter 1 deals with the uncertainty about post-2020 regional emission reduction targets. In Chapter 2, uncertainty is about the time the global economy will need to recover from the 2008 financial crisis. In Chapter 3, we propose an economic interpretation of the constraints that we imposed to limit the penetration of some technologies. In Chapter 4, we explain how the modeler's views of the about future structural changes are translated into benchmark scenarios and embedded in the calibration of the general equilibrium model. We also stress that these expectations affect counterfactual policy analysis. Chapter 5 illustrates this point by proposing analyzes of the impact of a carbon policy on the French economy, under alternative benchmarks scenarios that are contrasted in terms of energy efficiency gains and share of energy-intensive activities in the economy.

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STOCHASTIC SCENARIOS FOR ENERGY TRANSITION

an Applied General Equilibrium Approach

Olivier Durand-Lasserve

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du grade de
Docteur en Sciences Économiques et de Gestion

Composition du jury:
Promoteur: Prof. Yves Smeers (Université catholique de Louvain)
Promoteur: Dr. Axel Pierru (KAPSARC, Saudi Arabia)
Prof. Valentina Bosetti (Bocconi University and FEEM, Milan)
Prof. Raouf Boucekkine (Université catholique de Louvain and Université Aix-Marseille II)
Prof. Nadia Maïzi (Ecole des Mines ParisTech)
Prof. Thomas Rutherford (University of Wisconsin-Madison)

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The views expressed do not necessarily reflect the opinions of UCL, IFPEN or GDF SUEZ.
And yet all the alternative avenues of research were already well known before 1970: solar energy, the exploitation of bituminous schists, geothermal energy sources, gas from vegetable fermentation, alcohol-based petroleum substitutes - were all explored during the last war, and rapidly developed by improvised methods. Then they fell into neglect. The difference is that today a major general crisis (one of the ' secular crisis' to which I shall be referring again) has confronted all the developed economies with the dramatic choice between innovation, death or stagnation. They will undoubtedly choose the path of innovation. No doubt some such fear of disaster preceded each of the major advances in economic growth over the centuries - and technology always came up with an answer. In this sense, technology is indeed a queen: it does change the world.

Fernand Braudel, Civilization and Capitalism, The structure of Everyday Life
To my Parents,
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General Introduction

Energy transition and uncertainty

Over the years, there has been an accumulation of evidence about the impact on climate of greenhouse gas (GHG) emissions induced by the human activities [IPCC [2007a]]. IEA scenarios, that assume additional but moderate efforts to reduce GHG emissions (in the New Policy scenario, [IEA, 2010b]), are consistent with a temperature rise of more than 3.5°C on the long run. The continuation of the current dynamics of GHG emissions and limited action will lead with little doubt to unmanageable climate change, with a global temperature increase and a multiplication of extreme weather events such as droughts or floods. The potential consequences are considerable. Sea-level rise, desertification, change in crop yields, modification of land and oceanic ecosystems can exaggerate the competition for natural resources [IPCC, 2007b], increase the political tensions and threaten global security.

Energy-related CO\textsubscript{2} emissions largely contribute to global GHG emissions\textsuperscript{1}. Therefore any action for climate stabilization will require a transition of the regional energy systems towards low carbon emissions.

The concern about climate change and the need for global action resulted in the creation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and subsequently, in 1997, the Kyoto Protocol where some parties committed themselves to limit their GHG emissions for the period 2008-2012. The Copenhagen Accord, in December 2009, has set the non-binding objective of limiting collectively the average global temperature rise to 2°C above the pre-industrial level, and some parties made binding emissions limitation commitments for 2020. On the one hand, the results of the Copenhagen Accord and of the following rounds of international climate negotiations are mitigated. Some old questions remain unsolved, for instance how initial permits have to be allocated and

\textsuperscript{1}Energy-related CO\textsubscript{2} emissions account for 61% of global GHG emissions in CO\textsubscript{2} equivalent in 2005 [IEA, 2008b]
newly-created mechanisms, such as the Green Climate Fund, create additional bones of contention issues.

But on the other hand, one can state that beyond the framework of international negotiations, climate policies are progressing\(^2\). Some regions, such as the European Union, have enacted climate policies with instruments and objective in compliance with the UNFCCC. In the United States, the renewable energy sector has been substantially developed during the last decades on the basis of state-level green permit market initiatives and other state-level actions have been launched to reduce emissions. In China, action plans are taken with targets about CO\(_2\) intensity, installed solar and wind capacity, and with the elaboration of some pilot emission cap and trade projects at the province level. These efforts add up to several other national or regional initiatives and show that the energy transition is a reality.

The restructuring of the energy systems towards low carbon emissions requires substantial investment in equipments with long lifetimes and long payoff periods. Therefore, uncertainty on the long-run evolution of the energy markets is an essential issue for energy transition. Looking back to the past; when considering the shale gas boom, the 2008 financial crisis, or the Fukushima nuclear accident; we can seen how volatile the energy markets’ perspectives can be.

**Modeling approach**

This research work aims at producing and analyzing the impact that some uncertainties can have on technology deployment and commodity prices in a context of energy transition. The framework chosen is the Arrow-Debreu representation of the economy [Arrow and Debreu, 1954].

It is important to be clear that the approach is rather descriptive than prescriptive. We do not intend to represent how society as a whole should relate to the issue of climate change. We simply try to portray the results of the choices that individuals make, given some behavioral assumptions. This motivation differs from the public economics literature related to climate change, such as Gollier et al. [2000], Gollier [2010], Guéant et al. [2012] or Weitzman [2010].

As we needed to represent complex energy systems, we have used applied general equilibrium models and numerical simulations, instead of analytical models with closed-form solutions, such as option models of technology adoption under uncertainty [Pommeret and Schubert, 2009, Hugonnier et al., 2006]. More precisely, this dissertation is based on multi-region multi-period dynamic optimization general equilibrium models.

\(^2\)See [IEA, 2010c] for an outlook of emissions policies
The models we used have at least four features that are worth mentioning in this introduction and that position them between the economic and the engineering literature. First, they are non-stationary, as they are supposed to represent equilibrium paths with resource depletion or decreasing energy intensity. Second, they are "strongly calibrated": they contain several time-dependent parameters. These parameters represent how the technologies and the preferences are assumed to evolve. Third, they are exogenous growth models: the technological progress is fully embedded in the calibration of the models’ parameter and cannot be affected by learning by doing or R&D. Last, the models are focused of the representation of the energy sector. A particular attention is paid to the modeling of the energy production and consumptions activities. The other aspects of the models, those that affect only indirectly energy supply and demand are represented in a simplistic way. For instance, the interregional capital flows are unrestricted, the firms and the households are homogeneous within a regions, the government is not explicitly represented and tax revenues are simply lump-sum transferred to the households.

Indeed, these types of models are based on paradigms that seem to be outdated compared with the topics studied in more stylized frameworks. In particular, endogenous technological change and restricted capital flows should impact economic growth. But the paradigm shifts for applied models are limited by the need to preserve appropriate numerical properties for solution search.

However, applied models are quite useful in practice to simulate energy price and technology trajectories that "pass the laugh test", or to conduct sensitivity analysis to tangible elements of environmental policy and energy technologies. In particular, the non-stationarity and the "strong calibration" of the models make them fit to represent energy efficiency improvements or the emergence of new technologies. These are the main reasons why we decided to use these applied models. We tried to show that they can tell us a lot about uncertainty and energy transition.

Applied general equilibrium models are voluminous and difficult to build. Hopefully, we did not start from scratch. The Chapters 1 to 2 are based on models derived from MERGE [Manne et al., 1995] and on the computation of stochastic scenarios. MERGE represents a linkage between an exogenous growth interregional model and energy submodels, with a view on energy technology adoption. MERGE considers a description of the world economy divided in different regions. It separates the energy and non-energy sectors, uses an aggregated representation of the economy and a technological representation of the energy sector. We have re-calibrated and developed the energy-economy content of the MERGE model, but we put aside the climate sub-model. The environmental constraints
consist in limitations of energy-related CO$_2$ emissions. There is no feedback effect of emissions on human activities through a damage function and we remain in a cost-effective framework. The absence of feedback is problematic when simulating no-policy emission scenarios where emissions keep on increasing with potential dramatic effect on climate. However, we have restricted our analysis to scenarios where significant GHG mitigation action is enforced.

**Outline**

Chapter 1 has been published in The *Journal of Energy Policy* [Durand-Lasserve et al., 2010] and is based on the idea that persistent uncertainty about mid-century CO$_2$ emissions targets is likely to affect not only the technological choices that energy-producing firms will make in the future but also their current investment decisions. We illustrate this effect on CO$_2$ price and global energy transition within a MERGE-type general-equilibrium model framework, by considering simple stochastic CO$_2$ policy scenarios. In these scenarios, economic agents know that credible long-run CO$_2$ emissions targets will be set in 2020, with two possible outcomes: either a "hard cap" or a "soft cap". Each scenario is characterized by the probabilities assigned to the possible caps. We derive consistent stochastic trajectories - with two branches after 2020 - for prices and quantities of energy commodities and CO$_2$ emissions permits. The impact of uncertain long-run CO$_2$ emissions targets on prices and technological trajectories is discussed. In addition, a simple marginal approach allows us to analyze the Hotelling rule with risk premia observed in stochastic scenarios.

Chapter 2 corresponds to the first sections of a MIT CEEPR Working paper [Durand-Lasserve et al., 2011]. It examines the impact that uncertainty over economic growth may have on global energy transition and CO$_2$ prices. Again, we use a general-equilibrium model derived from MERGE, and define several stochastic scenarios for economic growth. Each scenario is characterized by the likelihood of a rapid global economic recovery. More precisely, during each decade, global economy may - with a given probability - shift from a low-economic-growth path to a high-economic-growth path. The climate policy considered corresponds in the medium run to the commitments announced after the Copenhagen conference, and in the long run to a 25% reduction in global energy-related CO$_2$ emissions (with respect to 2005). For the prices of CO$_2$ and electricity, as well as for the implementation of CCS, the branches of the resulting stochastic trajectories appear to be heavily influenced by agents’ initial expectations of future economic growth and by the economic growth actually realized.

Chapter 3 is a revised version of the last sections of [Durand-Lasserve et al.,
It examines the consistency of the equilibrium computed in Chapter 2 with a decentralized framework. We show that within each region, the model internalizes some portfolio constraints (mainly maximum expansion rate and maximum market share) through endogenous power generation costs that ensure some rationing for given power generation capacities. The endogenous costs are computed for wind capacity on the basis of the results of Chapter 2.

Equilibrium models need to be calibrated. When models are used for assessing the immediate effects of policies or comparing economies (e.g., comparing flexibilities of EU and US economies), calibration is usually done on benchmark data that were observed in the past, typically social accounting data. The calibration problem is different when dealing with long-run issues such as climate change. Various policies are put in place and we are not sure of their success. In addition, the evolution of preferences and technologies remains uncertain. There are thus different possible benchmarks generally reflected in studies produced by international organizations. The dependence of the policy assessment to the choice of the benchmark scenario can be shown analytically for a particular class of dynamic general equilibrium models.

The last two Chapters use the dynamic CGE model framework [Babiker et al., 2008, Bernstein et al., 1999] to deal with the problem of the dependence between the response to a policy shock and non-stationary benchmark equilibrium trajectories that have to be defined by the modeler. What is illustrated with CGE models is actually largely relevant for dynamic AGE models such as those derived from MERGE and used in Chapters 1, 2 and 3.

Chapter 4 studies the role of the calibration for dynamic computable general equilibrium models (CGE) that measure the impact of environmental policies. We show that dynamic CGE models can be expressed as dynamic systems of policy-induced deviations from a benchmark scenario path. The path is highly uncertain, especially on the long run. In general it is chosen so as to match with some "relevant" outcome. With this approach, we can understand the dynamic CGE calibration procedure as the production of equilibria corresponding to a "vision of the future" born by the modeler.

These conclusions are illustrated numerically in Chapter 5. We show the dependence of the policy evaluation results to the benchmark scenario with a dynamic CGE model of carbon leakage in the French economy. Carbon leakage is an interesting problem since the effect of unilateral environment policies is largely related to the long run-evolution of the structure of the economy, in particular to total or sectoral improvements of energy-efficiency. These important factors are not well documented in institutional projections and remain largely at the modeler’s discretion.
GENERAL INTRODUCTION

We build and describe three alternative benchmark scenarios: (i) technological stagnation, (ii) energy efficiency, (iii) deindustrialization. We show that depending on the benchmark considered, the simulated impact of a unilateral increase in carbon tax can be significantly different. The magnitude of the deviations, therefore the effect of the policy, depends in most of the cases of the evolution of the benchmark scenario.
Chapter 1

Energy transition under uncertain long-run emission policy

1.1 Introduction

This chapter shows how the current uncertainty about the 2020-2050 CO$_2$ emissions targets may affect CO$_2$ and energy prices as well as technological choices in the energy sector.

To assess the cost of reducing GHG emissions, applied general-equilibrium models linking aggregated descriptions of economies and detailed energy sectors together$^1$ have been developed. Some of them, for instance MERGE [Manne et al., 1995], GEMINI [Bernard and Vielle, 2003], IGSM [Sokolov et al., 2005] and WITCH [Bosetti et al., 2006], have been used by IPCC [2007a] and USCCSP [2007] to evaluate climate change policies. So far, the issue of agents’ behavior under uncertainty has been addressed in these models through sensitivity analysis [Löschel and Otto, 2009, Magné et al., 2010], Monte-Carlo simulation [Kypreos, 2006] and stochastic formulations where agents hedge themselves against some probabilistic outcomes. This last approach was first introduced by Manne and Richels [1992] and Manne and Olsen [1996] who studied the effect of a low-probability climate catastrophe on agent’s behavior. More recently$^2$, Bosetti and Tavoni [2009] investigate the impact of uncertain energy-related R&D activities and Loulou et al. [2009] derive different EMF 22 radiative forcing scenarios by assuming an uncertain sensitivity of climate to emissions.

In this chapter, we use a stochastic approach to illustrate how the persistent

$^1$The so-called "top-down/bottom-up" models.

$^2$See also the survey by Labriet et al. [2009].
uncertainty about the 2050 CO$_2$ emissions caps impacts prices and technological choices in the energy sector\textsuperscript{3}. These energy prices are especially useful to understand agents’ behavior and assess the relevance of our model’s results. In a deterministic model, the agents plan their actions with a perfect knowledge of the future, and the efficient (or clean) technologies expand at the optimal rate in the economy. In our model, until 2020, the agents have to invest before knowing the full sequence of emissions caps imposed to regional economies, by trading off the gain in postponing the adoption of efficient but expensive technologies against the risk of being tied to some detrimental technological choice once the actual emissions caps are set.

The model we use is a modified stochastic version of the MERGE model\textsuperscript{4}. For the sake of illustration, here uncertainty only involves two political outcomes, with, at the end of 2020, the setting of either a "hard-cap" policy or a "soft-cap" policy for energy-related CO$_2$ emissions. Each policy defines series of regional quotas which are linearly-decreasing until 2050 and constant after this date. Until 2050 the hard-cap and soft-cap quotas are respectively consistent with the IPCC [2007a]'s 450 and 550 ppm atmospheric-GHG-concentration scenarios. However, over the model’s whole horizon, the hard-cap and soft-cap policies are less stringent than the two IPCC’s scenarios since complying with these scenarios would involve post-2050 emissions reductions [IPCC, 2007a, IEA, 2008b].

In our model, all agents (i.e., firms and households) are forward looking, in the sense that firms (households) always act so as to maximize their expected present value (expected sum of discounted utilities) under rational expectations. In other words, in each date firms base their current decisions on consistent subsequent prices of inputs and outputs (or, in the case of decisions made until 2020, consistent subsequent prices in each possible outcome), i.e., prices that precisely result from the decisions currently made.

Firstly, our approach makes possible an explicit modeling of agents behavior in the presence of long-run CO$_2$ policy uncertainty. Secondly, it yields stochastic scenarios of energy prices - for CO$_2$, oil, gas, power - with two possible sequences for post-2020 prices, that are consistent with the stochastic political scenario under consideration. Note that the unique pre-2020 sequence and the two possible post-2020 sequences obtained for the price of a given energy commodity may broadly differ from the two deterministic sequences of prices that would be determined by successively considering each CO$_2$ target as certain from the beginning (i.e., 2005 in our model). In addition, as illustrated later, a stochastic price scenario is not necessarily bounded by the corresponding two deterministic sequences of prices. This shows the interest of a stochastic-scenario-based approach for studying the energy transition when long-run CO$_2$ emissions targets are uncertain.

\textsuperscript{3}The energy sector represents 76% of total direct CO$_2$ emissions in 2005 [IEA, 2008b]

\textsuperscript{4}See Manne et al. [1995] for a presentation of the MERGE model.
Section 1.2 presents the stochastic CO₂-emissions policy scenarios under consideration and motivates our approach. The structure, calibration and computation of our stochastic general equilibrium model are discussed in section 5.1. The simulation results are studied in section 1.4, with an emphasis on the impact of uncertainty on prices and technology trajectories. The last section concludes.

1.2 A stochastic-scenario approach for long-run emissions targets

The forthcoming energy transition, that will result from the technological choice made by the economic agents, will crucially depend on CO₂ emission targets. If current negotiations can set credible regional emissions targets on the short and intermediate runs, uncertainty on long-run targets (i.e. up to the middle of the century and beyond) is likely to persist. In addition, economic agents are likely to consider these long-run emissions targets as credible only once they have been transposed into regional energy policies (since, meanwhile, any long-run commitment might be offset by possible political, economic or environmental shocks [Frankel, 2009]). In our model, we therefore assume that the agents have currently an incomplete information. They know the emissions targets set until 2020 but they consider that credible mid-century emissions targets will be set in 2020 only.

Therefore, until 2020 they face an uncertainty which impacts not only their future but also their current technological choices and investments. For example, the uncertainty on long-term emissions targets can lead the firms to delay costly investment in clean technologies, although this might cause very high CO₂ emissions costs if restrictive emissions targets are finally set. Indeed this effect is not taken into account in a deterministic model where agents plan their actions with a perfect knowledge of the future and clean technologies expand at the optimal rates in the economy.

Since our primary goal is to illustrate the effect of uncertain long-run CO₂ emissions targets on CO₂ price and energy transition, we consider here a simple stochastic scenario, in the sense that agents are aware that either a hard-cap or a soft-cap target will be set for mid-century energy-related CO₂ emissions. As earlier explained, agents consider that the political choice between the hard and soft caps will be definitely made in a credible way in year 2020. To better illustrate the effect of uncertainty, different assumptions about the relative probabilities of these two possible caps are considered.
More precisely, in our model, the CO$_2$ emissions targets are enforced through a cap-and-trade mechanism. There are two successive series of linearly decreasing emissions caps. These series are reported in Table 1.1. For every OECD region, the first series, which spans from 2010 to 2020, sets an emission cap for every period. These caps decrease linearly so as to converge towards the 2020 emissions target. For each OECD or non-OECD region, the second series of emissions caps concern the post-2020 periods. The caps linearly decrease from 2020 to 2050, so as to reach either the hard-cap or the soft-cap emission stabilization level in 2050, and after remain constant.

The OECD countries commit themselves to known reduction levels of energy-related CO$_2$ emissions for 2020. The European Union agrees on a reduction of 20% with respect to 1990. North America (USA, Canada and Mexico) agrees to reduce emissions by 17% with respect to 2005 [IHT, 2009]. The Pacific OECD countries (Japan, South Korea, Australia and New Zealand) are assumed to commit themselves to the same target as North America. Until 2020, the emissions of the non-OECD countries are not limited.

The climate negotiations for the period 2025-2050 are assumed to be finalized in 2020, and to yield at that date either the hard-cap or the soft-cap climate agreement. Therefore, until 2020, households and firms ignore which one of these two caps will be set. In the hard-cap outcome, every OECD region has to cut emissions in 2050 by a factor 4 with respect to 2005. Every non-OECD region commits to a 27% emission reduction by 2050 with respect to 2005. Globally, these commitments correspond to a halving of energy-related CO$_2$ emissions by 2050 with respect to 2005.

If the soft cap is set, every OECD region has to cut emissions in 2050 by a factor 3 with respect to 2005. Every non-OECD region commits to increase its emissions in 2050 by no more than 14% with respect to 2005. The soft cap corresponds to a 25% decrease in global emissions in 2050 with respect to 2005. Until 2050 the emissions corresponding to the hard and soft caps are respectively consistent with the 450 and 550 ppm scenarios proposed by IEA [2008b] on the basis of IPCC [2007a]. However, when considering the model’s whole horizon, the hard and soft caps are less constraining than the 450 and 550 ppm scenarios since here, after 2050, emissions are only assumed to be stabilized.
1.2 A STOCHASTIC-SCENARIO APPROACH

<table>
<thead>
<tr>
<th>Region</th>
<th>First series of caps</th>
<th>Second series of caps</th>
<th>Soft cap</th>
<th>Hard cap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005$^a$ ... 2020</td>
<td>2025 ... 2050-2100</td>
<td>2025 ... 2050-2100</td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>6.88 ... 5.71 (-17%)</td>
<td>5.26 ... 2.92 (-67%)</td>
<td>4.91 ... 1.72 (-75%)</td>
<td></td>
</tr>
<tr>
<td>European Union</td>
<td>4.10 ... 3.32 (-19%)</td>
<td>3.07 ... 1.53 (-67%)</td>
<td>2.51 ... 1.10 (-67%)</td>
<td></td>
</tr>
<tr>
<td>Pacific OECD</td>
<td>2.19 ... 1.82 (-17%)</td>
<td>1.68 ... 0.73 (-67%)</td>
<td>1.57 ... 0.55 (-75%)</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>5.46</td>
<td>7.63 ... 6.22 (+14%)</td>
<td>7.36 ... 4.00 (-27%)</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>1.23</td>
<td>1.72 ... 1.40 (+14%)</td>
<td>1.66 ... 0.90 (-27%)</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>1.57</td>
<td>2.20 ... 1.79 (+14%)</td>
<td>2.12 ... 1.15 (-27%)</td>
<td></td>
</tr>
<tr>
<td>Middle East</td>
<td>1.32</td>
<td>1.84 ... 1.50 (+14%)</td>
<td>1.77 ... 0.96 (-27%)</td>
<td></td>
</tr>
<tr>
<td>Asia non-OECD$^b$</td>
<td>1.50</td>
<td>2.09 ... 1.70 (+14%)</td>
<td>2.02 ... 1.10 (-27%)</td>
<td></td>
</tr>
<tr>
<td>Latin America</td>
<td>1.00</td>
<td>1.40 ... 1.14 (+14%)</td>
<td>1.35 ... 0.74 (-27%)</td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>0.86</td>
<td>1.20 ... 0.98 (+14%)</td>
<td>1.16 ... 0.63 (-27%)</td>
<td></td>
</tr>
<tr>
<td>rest of the world</td>
<td>1.20</td>
<td>1.68 ... 1.37 (+14%)</td>
<td>1.62 ... 0.88 (-27%)</td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>27.3</td>
<td>29.8 ... 20.5 (-25%)</td>
<td>28.4 ... 13.7 (-50%)</td>
<td></td>
</tr>
</tbody>
</table>

Figures in brackets give the relative change with respect to emissions in 2005.

$^a$...$^a$ denotes a linear decrease in the cap.

$^a$ Figures are historical emissions (computed from IEA [2007b]).

$^b$ Asia non-OECD excludes China and India.

Table 1.1: CO₂ emissions caps (in billion tons per year)
CHAPTER 1. UNCERTAIN LONG-RUN EMISSION POLICY

Unused emissions permits can be banked (ensuring inter-temporal efficiency) from 2010 on for OECD regions and from 2025 on for non-OECD regions. From 2060 on, banked permits can no longer be used. Inter-regional trade of emissions permits (i.e. a global CO$_2$ emission permits market that ensures spatial efficiency) occurs only after 2020.

In the stochastic CO$_2$ policy scenarios considered here, the two possible post-2020 series of caps represent two distinct states of the world, as illustrated in plain line on the left-side of Figure 1. As in Manne and Olsen [1996], we can oppose a "Learn then Act" model (where the scenario is deterministic) to an "Act then Learn" model (where the scenario is stochastic and takes the form of a probability tree). Our stochastic scenario is common knowledge shared by all agents of the model who are equally informed. These agents - households who maximize expected utilities and firms who maximize expected profits - are forward looking in the sense that they base current decisions on expected prices and quantities. They are assumed to have a perfect foresight, so that their state-conditional expectations are true. In other words, they take their decisions knowing the prices and quantities they would face in each branch, but ignoring until 2020 which branch will materialize. At equilibrium, both price and quantity of every commodity follow a stochastic trajectory, with a unique branch (two possible branches) until 2020 (after 2020), as illustrated in plain line on the right side of Figure 1. Our approach therefore yields stochastic trajectories which are consistent with the underlying stochastic policy scenario. For the sake of illustration, in Figure 1, the one-branch trajectory corresponding to each deterministic CO$_2$ policy scenario (i.e., when either the hard cap or the soft cap is set from the very start) is also indicated in dashed line.

1.3 Presentation of the general equilibrium model

To assess the impact of uncertain mid-century CO$_2$ emissions targets on current and future energy transition, we use a model derived from MERGE [Manne et al., 1995]. More specifically, unlike MERGE, our model contains no modeling of the impact of GHG emissions on climate change, but mere accounting relations between CO$_2$ emissions and energy technology use. The model’s horizon extends from 2005 (base year) to 2100, with 5-year time periods. The world is divided into eleven regions: North America, European Union, OECD Pacific, China, India, non-OECD Asia, Russia, Middle East, Latin America, Africa and rest of the world. Recent data (e.g., IEA [2008a], IEA [2008b], EIA [2007]) have been used to calibrate the model. In addition, our model is stochastic as it allows agents to consider different possible outcomes for long-run CO$_2$ emissions targets.

Following Manne et al. [1995], an intuitive solution would be to introduce
1.3. PRESENTATION OF THE GENERAL EQUILIBRIUM MODEL

![Diagram showing deterministic and stochastic scenarios with examples of resulting equilibrium trajectories]

Figure 1.1: Deterministic and stochastic scenarios with examples of resulting equilibrium trajectories for prices or quantities

uncertainty in our model by means of non-anticipativity constraints. However, in the wake of Meeraus and Rutherford [2005], we use a tighter formulation which limits the number of variables and constraints by taking into account the recursive structure of the model. Apart these elements, the formulation and the solution methods for the deterministic and the stochastic versions of our model are quite similar. For this reason, the following section is devoted to a presentation of the model in a deterministic framework.

1.3.1 Description of the model

In each region, a representative household sells its labor force, owns four firms, the whole capital stock, the stock of in-situ natural resources (underground reserves) and the quota of emissions permits (i.e., the volume of emissions that satisfies the targeted cap.) Therefore, the household’s revenue consists in firms’ profits, interests on capital, rents from natural resource exploitation, and the

---

5Let us for instance consider that mid-century CO₂ emissions targets are assumed to be set in 2020, and that agents (correctly) anticipate two possible outcomes. This stochastic scenario could then be handled by duplicating every variable, as there are two possible states of the world. The non-anticipativity constraints would force every variable and its duplicate to be equal until 2020.

6Each firm represents one of the following four industrial sectors: final sector producing the composite good, electric production, non-electric energy production, natural resources (oil, gas and coal) extraction.
CHAPTER 1. UNCERTAIN LONG-RUN EMISSION POLICY

revenue from the emission permits market\(^7\). Each region \(i\) maximizes the sum of its discounted utilities of consumption, defined as follows:

\[
\sum_{t=0}^{T} \beta_{i,t} L_{i,t} \log \left( \frac{C_{i,t}}{L_{i,t}} \right)
\]

\(C_{i,t}\) is the total consumption in region \(i\) at period \(t\). \(L_{i,t}\) is the population of region \(i\) at period \(t\) (the size of the household). The utility function therefore depends on the logarithm of the per-capita consumption, with:

\[
\frac{\partial (L_{i,t} \log \left( \frac{C_{i,t}}{L_{i,t}} \right))}{\partial C_{i,t}} = \frac{1}{(C_{i,t}/L_{i,t})}
\]

In every period, the region’s marginal utility is thus inversely proportional to its per-capita consumption. \(\beta_{i,t}\) is the discount factor for utility in region \(i\) for period \(t\), with \(\beta_{i,t} = \beta_{i,t-1} e^{-\rho_{i,t}}\), where \(\rho_{i,t}\) is the region’s rate of time preference for utility. This rate is calibrated so as to reproduce at equilibrium a benchmark growth differential among the regions and a benchmark interest rate\(^8\), more detail about the calibration of the rate of time preference is given in section 2.2.4.

The good consumed by the households represents a composite of all items\(^9\) produced outside the energy sector [Manne et al., 1995]. It serves as numéraire in the model, and it is measured in terms of units of purchasing power for the year 2005. This composite good can be used for consumption (by households), capital accumulation (investment in firms), or for intermediate consumption (in the four industrial sectors). The composite good is produced in a final industrial sector represented with putty-clay technologies [Boucekkine et al., 2008]. Different generations (vintages) of equipment are use. Each of them produces the same composite good and requires capital (\(k\)), labor (\(l\)), electric (\(e\)) and non-electric energy (\(n\)) as inputs. At each period, to increase its production capacity, the firm of the final sector can install a new vintage with flexibility in the relative quantities

\(^7\)The quota of emissions permits is sold by the household to the two energy firms of the region. Since the household owns these firms, this is equivalent to ignoring this revenue and considering firm’s profits on a before-CO\(_2\)-emission-cost basis. Nevertheless, the model implicitly considers a regional CO\(_2\) emission permit market, which influences the technological choices made by the firms.

\(^8\)Note that in the model, the perfect mobility of capital (implied by the perfect mobility of the consumption) ultimately leads at equilibrium to a unique interest rate and to consumption per capita growth differentials across regions strictly equal to the differentials in regional discount rates.

\(^9\)This includes all intermediate and consumption goods and services, as well as all the final energy needs of the economy (firms and households).
of inputs. The vintages decay at an exogenous exponential rate\textsuperscript{10}. However, it can no longer adjust the quantity of inputs once the vintage is installed. As a result, at every period, the substitution between inputs is only possible for the new generation of equipment. Thus, the final sector is somehow locked in the short-run by previous technical choices. Each vintage undergoes an (exogenous) exponential scrapping Manne et al. [1995]. The production function corresponding to a new vintage at period $t$ is described by a nested Constant-Elasticity-of-Substitution function (for ease of notation, the subscript $i$ is here omitted):

$$F_t(k,l,e,n) = \left[ a_t[k^\alpha (A_t l_t)^{1-\alpha}]^{\sigma-1} + b_t[e^{\beta n_i n^{1-\beta}}]^{\sigma-1} \right]^{\frac{1}{\sigma-1}}$$

The parameter $A_t$ introduces an exogenous improvement in labor productivity. $\alpha$ is the optimal value share of capital in the labor/capital pair and $\beta$ is the optimal value share of electric energy in the electric/non-electric energy pair. The elasticity of substitution between energy and non energy inputs is $\sigma$. This can be considered as a long-run elasticity, whereas in every period the short-run elasticity depends on existing vintages. The time-dependent scaling factors $a_t$ and $b_t$ reflect exogenous energy-efficiency improvements. These parameters calibrated on the basis of the projections of [IEA, 2010b]. The calibration on projections will be presented with further details in Chapter 4.

Electric and non-electric inputs are supplied by two distinct industrial sectors that use different Leontief technologies to transform fossil fuels and composite goods (used as intermediate goods) into energy for the final sector. The technologies available in these sectors are presented in Tables 1.2 and 1.3. The combustion of fossil fuels produces CO$_2$ emissions which must be covered by the emissions quota available for the period. Each technology is characterized by a type of fuel input (oil, coal, gas, or none\textsuperscript{11} for renewable), a fuel efficiency, an emission rate and a non-fuel cost. Unlike Magné et al. [2010] and Manne and Richels [2004], we consider exogenously given non-fuel costs (with no learning-by-doing effect). Some constraints render technologies not perfectly substitutable in both electric and non-electric energy sectors. Firstly, the use of technologies can be subject to some exogenous caps reflecting, for example, technological bottlenecks. Secondly, the market share of some technologies can be limited, as is the case for the wind technologies in order to maintain a stable electric supply. Last, there are constraints on the expansion and decline of each technology. The constraints on maximum expansion (which take the form of a maximum growth rate in technology use from one period to the other)

\textsuperscript{10}The exponential specification of decay was chosen for calibration reasons. Note that one-hoss-shay decay instead of exponential decay might be more realistic, but this would increase the path dependence to investments made in distant period, and therefore require accurate calibration of investment decisions prior to the base year of the model.

\textsuperscript{11}Nuclear is a special case in the model since there is no explicit modeling of uranium production.
reflects real-world frictions for installing new capacity. The maximum decline constraints limit unrealistic massive abandonment of already-installed capacities. These constraints smooth the activity levels of the various technologies and facilitate the coexistence of technologies with different marginal costs in the electric and non-electric sectors. Furthermore, they generate irreversibility in the model since pre-2020 technological trajectories constrain post-2020 trajectories. Note that the coexistence of different vintages in the final sector implies another type of irreversibility, since pre-2020 investments impact the possible substitutions between capital and energy - and between electric and non-electric energies - after 2020.

The electric and non-electric energy firms are supplied in fossil fuels by a mining sector which extracts oil, coal and gas. This extraction requires in situ reserves, as well as composite goods to pay the extraction costs. All these mineral reserves are finite and can be exhausted. Moreover, extraction is subject to an upper limitation in every period. This reflects the complexity of undertaking new development projects in the oil and gas industry.

All regions are linked together by the international trade of composite goods, oil, gas and (after 2020) emission permits. Transportation costs generate differences between certain regional prices.

In any period, the emissions of the electric and non-electric energy sectors must be smaller than the regional quota (i.e. the cap endowed to the region for the period considered) increased by the emission permits banked in previous periods and (after 2020) by the purchase of emissions permits from other regions.

1.3.2 Calibration

The exogenous level of effective labor is adjusted so as to obtain at steady state a level of economic growth close to IEA [2008b] assumptions. The rates of time preference for utility are chosen so as to obtain some pre-specified levels of interest rate at steady state [Manne et al., 1995]. The elasticity of substitution $\sigma$

---

12 According to Pindyck [2006], "irreversibility will affect current decisions if it would constrain future behavior under plausible outcomes". Let us take the example of a clean-but-expensive technology. The constraint on its maximum expansion (contraction) rate should favor a greater (lower) optimal pre-2020 use of this technology as a precaution against possible high (low) post-2020 CO$_2$ prices. A similar analysis, with constraints working in opposite directions, can be made for cheap-but-highly-emitting technologies.

13 No interregional coal trade is taken into account, since every region is assumed to own sufficient reserves.

14 Because of the absence of distinction between capital and consumption goods, the perfect mobility of the composite goods is equivalent to the perfect mobility of capital. Therefore, at equilibrium, all regional interest rates are equal.
### 1.3. PRESENTATION OF THE GENERAL EQUILIBRIUM MODEL

<table>
<thead>
<tr>
<th>Technology</th>
<th>Non-Fuel Cost&lt;sup&gt;a&lt;/sup&gt; ($/Mwh)</th>
<th>Heating Rate (Gj/Mwh)</th>
<th>Emission Rate (TCO₂/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>2050</td>
<td>2005</td>
</tr>
<tr>
<td>hydro</td>
<td>36-40</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>remaining oil</td>
<td>20</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>remaining nuclear</td>
<td>45-50</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>new nuclear</td>
<td>80-90</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>remaining gas</td>
<td>5.4-6</td>
<td>6</td>
<td>6.6-11.1</td>
</tr>
<tr>
<td>new gas</td>
<td>27-30</td>
<td>30</td>
<td>6.2-6.7</td>
</tr>
<tr>
<td>new gas CCS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>61-66</td>
<td>55</td>
<td>6.63-7.05</td>
</tr>
<tr>
<td>remaining coal</td>
<td>22-25</td>
<td>25</td>
<td>9.3-14</td>
</tr>
<tr>
<td>remaining coal CCS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>60-65</td>
<td>65</td>
<td>10.9-18.3</td>
</tr>
<tr>
<td>new coal</td>
<td>45-50</td>
<td>50</td>
<td>8.2-8.8</td>
</tr>
<tr>
<td>new coal CCS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>79-86</td>
<td>75</td>
<td>9-9.6</td>
</tr>
<tr>
<td>on-shore wind</td>
<td>70-80</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>solar&lt;sup&gt;c&lt;/sup&gt;</td>
<td>300-600</td>
<td>60-120</td>
<td>-</td>
</tr>
<tr>
<td>biomass</td>
<td>92-102</td>
<td>85</td>
<td>-</td>
</tr>
</tbody>
</table>

Sources: IEA [2008a,b], EIA [2007].

"-" separates the lowest and highest regional values.

<sup>a</sup> Non-fuel costs include investment and operating costs but exclude fuel costs.

<sup>b</sup> CCS technologies are available from 2015 on in the model.

<sup>c</sup> Solar technology also embodies off-shore wind, geothermal and ocean energy.

Table 1.2: Non-fuel cost, heating and emission rates of electric technologies
between non-energy and energy inputs is set to .5 in every region. The value share \( \alpha \) of capital in the capital-labor input bundle is set to .28. The value share of electricity \( \beta \) in the energy bundle is set to .30. The scaling factor \( a_t \) and \( b_t \) are calibrated along a benchmark trajectory derived from institutional projections and assumed to result from cost minimization in the final sector. In particular, the gross regional products stem from IMF [2008] and IEA [2008b], the energy consumptions and prices are taken from IEA [2008b] reference scenario.

The decay rate of vintages in the final sector is 5% per year. The maximum annual expansion and contraction rates are set to 10% for electric and non-electric technologies. The exceptions are nuclear, with an annual growth rate limited to 2.5%, and non-electric oil and gas technologies whose annual expansion and contraction rates are limited to 5% in the OECD regions. In addition, prior to 2030, the uses of fossil-fuel-fired technologies are capped. During the first periods, these caps are close to the level of technology use in IEA [2008b] reference scenario. This reference scenario is also used to define upper bounds for oil and gas extraction (in addition to constraints expressed as maximum production-to-reserves ratios). The costs of electric and non-electric energy technologies are calibrated from IEA [2008b], IEA [2007a] and IEA [2008a]. Initial inter-regional cost differences are assumed to fade away throughout time (due to global economic convergence). As shown by Tables 1.2 and 1.3, the cost of certain new technologies is assumed to decrease throughout time.

Using IEA [2008a], a technical progress improving the heating rate of the various energy technologies has been introduced. The base-year regional heating rates have been computed from the observed fuel consumptions and electricity production. In each region, the fossil fuel resources are split into 10 different categories, according to their production cost. The breakdown of resources is derived from IEA [2008b], EIA [2007], and WoodMackenzie [2007]. In dollars per barrel, the cost of oil production ranges from 10 (Middle East) to 100 (Arctic regions). In dollars per barrel of oil equivalent, the cost of gas production ranges from 3 to 40. According to the region considered, the production cost of coal in dollars per barrel of oil equivalent varies from 10 to 20. The production cost of synthetic fuel is 80 $ per barrel. Emissions rates, that account for the \( \text{CO}_2 \) emissions, are estimated on the basis of IEA [2008b] projections.

\[ \text{15This remains in line with the elasticities of substitution of } .4 \text{ to .5 used by Blanford et al. [2007] in MERGE.} \]

\[ \text{16Except in the case of solar technologies since the cost of solar photovoltaic energy depends on solar irradiation intensity.} \]
1.3. PRESENTATION OF THE GENERAL EQUILIBRIUM MODEL

<table>
<thead>
<tr>
<th>Technology</th>
<th>Non-Fuel Cost$^{a}$</th>
<th>Emission Rate (TCO$_2$/Gj)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>2050</td>
</tr>
<tr>
<td>Oil for direct use</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gas for direct use</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Coal for direct use</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Coal for direct use CCS$^{b}$</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Bio-fuels</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Synthetic fuels$^{c}$</td>
<td>18.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Backstops$^{d}$</td>
<td>40</td>
<td>25</td>
</tr>
</tbody>
</table>

Sources: IEA [2008a,b, 2007a], WoodMackenzie [2007].

$^{a}$ Non-fuel costs include investment and operating costs but exclude fuel costs.

$^{b}$ Coal for direct use CCS is available from 2015 on in the model.

$^{c}$ Synthetic fuels include coal-to-liquid and non-conventional oil.

$^{d}$ The backstop technologies include second-generation bio-fuels and hydrogen produced from wind and solar energy.

Table 1.3: Non-fuel cost and emission rates of non-electric technologies

1.3.3 Computational issues

The model is solved as a non-linear program$^{17}$ using GAMS and the CONOPT3 solver. Nevertheless, as the model is not integrable, there is no means to derive analytically a maximization problem whose primal and dual solutions would yield the consumptions, activity levels and prices of the competitive general equilibrium. However, as in [Manne and Olsen, 1996], we assume that there exist some regional weights such that the maximization of the sum of weighted regional utilities under technological constraints and the absence of excess demand gives the competitive-general-equilibrium consumptions, activity levels and prices$^{18}$. The appropriate regional weights are determined iteratively using the method described by Rutherford [1999].

Another important computational aspect is that albeit the model is in infinite time the use of purely numerical solution methods requires a finite-time horizon approximation. Because of the inter-temporal structure of the model, the approximation of an infinite-time model by a finite-time model can lead to undesired effects at the end of the horizon which, in turn, influence earlier periods of the model. To take this into account, as suggested by Manne [1970],

$^{17}$This model could also be solved as a Mixed Complementary Problem, including the first-order conditions of each agent’s maximization problem, the absence of excess demand and the satisfaction of budgets constraints. However, this formulation would complicate the maintenance of the model, since lagrangian’s derivatives are susceptible to change when a constraint is modified.

$^{18}$For more insight about Negishi weights, see Ginsburgh and Keyzer [2002].
we apply a multiplier for the last-period utility and we introduce a constraint for the investment in the last period so as to mimic the steady state 19.

1.4 Analysis and discussion of results

The general equilibrium is computed for various stochastic scenarios, characterized by the probability, denoted as \( p \), that the hard-cap target is enforced in 2020. For the sake of clarity, we consider in most figures the following five scenarios: a deterministic hard cap (\( p = 1 \)), a deterministic soft cap (\( p = 0 \)), equiprobable hard and soft caps (\( p = 0.5 \)), a low-probability hard cap (\( p = 0.05 \)), a low-probability soft cap (\( p = 0.95 \)).

Subsection 1.4.1 gives a brief overview of CO2 prices and emissions trajectories. A simple analytical approach is proposed in subsection 1.4.2 in order to explain the Hotelling rule and risk premia observed in the model. Furthermore, additional comments on CO2 and energy prices are made. The impact of uncertainty on technological trajectories is discussed in subsection 1.4.3.

19See for instance Lau et al. [2002] for an in-depth presentation of this method.
1.4. ANALYSIS AND DISCUSSION OF RESULTS

1.4.1 Preliminary comments on CO\textsubscript{2} prices and emissions trajectories

Figure 1.2 shows that, in all scenarios, the stock of banked permits is maximum in 2035 in all soft-cap branches and in 2040 in all hard-cap branches, as cheap abatement options (for instance the replacement of old coal-fired plants) are exploited until these dates. During the following periods, the previously-banked permits serve to relax the emissions caps in order to avoid expensive abatement costs such as those incurred in the non-electric energy sector.

The CO\textsubscript{2} price trajectories in the European Union (corresponding to the world price after 2020) are given by Figure 1.3 for various stochastic scenarios, those in all OECD regions are supplied for the deterministic and the $p = 0.5$ scenarios in Table 1.4. The 2020 CO\textsubscript{2} prices in the hard-cap and soft-cap deterministic scenarios - equal to $64 per ton for the hard cap and between $28 and $42 per ton for the soft cap - are in line with those obtained by the EMF-22 models$^{20}$ [Clarke et al., 2009]. In general, until 2020, the CO\textsubscript{2} prices yielded by stochastic scenarios are bounded by both deterministic prices. Between periods 2025 and 2055, as one would expect, the CO\textsubscript{2} price is higher in hard-cap than in soft-cap

$^{20}$More specifically, we here refer to the EMF-22 scenarios with 450 and 550 ppm targets, concentration overshooting and delayed participation of non industrialized countries to emissions reduction. Prices obtained in the deterministic scenarios in 2030 ($47 for the soft cap and $105 for the hard cap) are significantly lower than those proposed by IEA [2008b] at this date for equivalent targets ($90 for 550 ppm and $180 for 450 ppm), as, unlike IEA [2008b], we have assumed that all non-OECD regions rejoin the cap-and-trade system for emissions permits, that this cap-and-trade system covers all the energy-related CO\textsubscript{2} emissions, and that no emissions reduction is required after 2050.
CHAPTER 1. UNCERTAIN LONG-RUN EMISSION POLICY

branches. In addition, as could also be expected, prices are higher (lower) in the hard-cap (soft-cap) branches of the stochastic scenarios than in the hard-cap (soft-cap) deterministic scenario. After 2055, in the soft-cap branches, the price sharply increases (with a price peak in 2060) and then slowly decreases before stabilizing, while in the hard-cap branches the price decreases and then stabilizes more rapidly.
### Table 1.4: Regional pre-2020 CO$_2$ prices and world post-2020 CO$_2$ price (in dollars per ton) in the deterministic and $p = 0.5$ scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Region</th>
<th>Regional Prices</th>
<th>World Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2010</td>
<td>2015</td>
</tr>
<tr>
<td>Deterministic</td>
<td>European Union</td>
<td>40</td>
<td>33</td>
</tr>
<tr>
<td>Soft Cap $(p=0)$</td>
<td>North America</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Pacific OECD</td>
<td>49</td>
<td>37</td>
</tr>
<tr>
<td>Deterministic</td>
<td>European Union</td>
<td>39</td>
<td>49</td>
</tr>
<tr>
<td>Hard Cap $(p=1)$</td>
<td>North America</td>
<td>39</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Pacific OECD</td>
<td>39</td>
<td>49</td>
</tr>
<tr>
<td>Equiprobable</td>
<td>European Union</td>
<td>48</td>
<td>35</td>
</tr>
<tr>
<td>$(p=0.5)$</td>
<td>North America</td>
<td>27</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Pacific OECD</td>
<td>47</td>
<td>35</td>
</tr>
</tbody>
</table>

$^a$ Price in the soft-cap branch.

$^b$ Price in the hard-cap branch.
## World Interest Rate and Regional Consumption Growth Rates in the $p = 0.5$ Scenario

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interest rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>soft cap</td>
<td>4.875</td>
<td>5.220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hard cap</td>
<td>5.096</td>
<td>5.148</td>
<td>5.160</td>
<td></td>
<td></td>
<td></td>
<td>4.989</td>
</tr>
<tr>
<td><strong>Consumption growth rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>1.886</td>
<td>2.064</td>
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<tr>
<td>hard cap</td>
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<td>1.889</td>
<td>1.848</td>
<td>2.154</td>
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<tr>
<td>soft cap</td>
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<td>2.080</td>
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<td>1.991</td>
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<tr>
<td>soft cap</td>
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<td>8.074</td>
<td>7.430</td>
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<td>hard cap</td>
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<td>5.358</td>
<td>4.372</td>
<td>3.204</td>
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</tbody>
</table>

*In percent, averaged on an annual basis, and calculated with respect to the previous 5-years period in the model.*

Table 1.5: World interest rate and regional consumption growth rates in the $p = 0.5$ scenario
1.4. ANALYSIS AND DISCUSSION OF RESULTS

1.4.2 Hotelling rule, risk premia and emission-permits markets convergence

At the general equilibrium of the model, the representative household of each region implicitly considers every possible action (such as the banking of emissions permits, capital investment, or the use of exhaustible natural resources like oil) as a marginal investment decision. Since uncertain long-run emission caps are susceptible to generate uncertainty about economic growth, risk premia may have to be considered by households when discounting revenues expected from these actions. To get further insight about this issue, let us note \( C_{i,t} \) the optimal consumption in region \( i \) in every period \( t \) (observed at the general equilibrium of the model) and \( x_t \) the random cash flow (expressed in numeraire) generated in every period \( t \) by a given marginal project. This marginal project should be undertaken if it increases the total discounted utility of region \( i \), i.e. if we have:

\[
\sum_{t=0}^{T} \beta_{i,t} L_{i,t} E(\log((C_{i,t} + x_t)/L_{i,t})) \geq \sum_{t=0}^{T} \beta_{i,t} L_{i,t} E(\log(C_{i,t}/L_{i,t})) \geq 0 \quad (1.1)
\]

By using a first-order Taylor expansion of the left-hand side of (1.1), the project is profitable when :

\[
\sum_{t=0}^{T} \beta_{i,t} L_{i,t} E(x_t/C_{i,t}) \geq 0 \quad (1.2)
\]

(1.2) can be rewritten as follows :

\[
\sum_{t=0}^{T} (\beta_{i,t} E(L_{i,t}/C_{i,t}))(E(x_t) + cov(x_t, 1/C_{i,t} E(1/C_{i,t}))) \geq 0 \quad (1.3)
\]

According to (1.3), the expected cash flow \( E(x_t) \), adjusted with the risk premium \(-cov(x_t, 1/C_{i,t} E(1/C_{i,t}))\), is discounted at the social discount factor \( \beta_{i,t} E(L_{i,t}/C_{i,t}) \).

Let us note that whatever the stochastic scenario considered in the model, prices (and therefore cash flows) are certain until 2020 (period 3 of the model). Consequently, let us first consider either a deterministic scenario, or a stochastic scenario with \( t \leq 2020 \), and let \( g_{i,t} \) be the growth rate of per-capita consumption in region \( i \) from period \( t - 1 \) to period \( t \), with \( C_{i,t-1}/C_{i,t-1} = e^{g_{i,t}} \). Since there is no uncertainty, the social discount factor from period \( t - 1 \) to period \( t \) is then:

\[
\frac{\beta_{i,t-1}(L_{i,t-1}/C_{i,t-1})}{\beta_{i,t} E(L_{i,t}/C_{i,t})} = e^{\rho_{i,t} + g_{i,t}} \quad (1.4)
\]
In addition, the risk premium is equal to 0. (1.4) is a standard result: $\rho_{i,t} + g_{i,t}$ is the social discount rate of region $i$ from $t-1$ to $t$. This social discount rate, which is the rate of interest of the economy, is also equal to the marginal productivity of capital (Ramsey’s rule). This equality is ensured by considering a marginal project consisting in consuming one less dollar in $t-1$ to invest this dollar in capital during one period. Furthermore, as long as banking is profitable, one should always consider the marginal project consisting in banking one more ton of CO$_2$ in $t-1$ in order to release one additional ton in $t$. By applying (1.3) to this marginal project, and by using (1.4), banking in $t-1$ should stop when:

$$P_{CO_2,t-1} = P_{CO_2,t} e^{-\rho_{i,t} - g_{i,t}}$$  \hspace{1cm} (1.5)

(1.5) is the Hotelling [1931] rule, which is for instance perfectly followed by the CO$_2$ price in the European Union from 2010 to 2055 - after this date, banking is no longer possible - in the deterministic hard-cap scenario (as shown by Figure 1.3 and Table 1.4). In the deterministic soft-cap scenario, the world CO$_2$ price follows the Hotelling rule from 2025 to 2055 since there is banking (and use of banked permits) during the whole period at the world level, as shown by Figure 1.2.

Let us now focus on the stochastic scenarios where the setting of caps at the end of the 2020 period represents an external random shock susceptible to impact the consumption in the various regions. However as shown by table 1.5, this shock has a very small effect on consumption. For region $i$, the risk premium to be applied to the CO$_2$ price expected in 2025 is equal to $-\text{cov}(P_{CO_2,2025}, C_{i,2025}, E(C_{i,2025}))$. By applying (1.3), banking should stop in 2020 when we have:

$$P_{CO_2,2020} = \frac{\beta_{i,2025}}{\beta_{i,2020}} \left( \frac{E(L_{i,2025})}{E(L_{i,2020})} \right) (E(P_{CO_2,2025}) - \text{cov}(P_{CO_2,2025}, C_{i,2025}, E(C_{i,2025}))$$  \hspace{1cm} (1.6)

For all regions and stochastic scenarios, this risk premium is positive but extremely small (always less than 0.2 cents per ton of CO$_2$ for the European

---

21Note that the logarithmic utility function considered here has a relative risk aversion equal to 1.

22Since there is no inter-temporal emissions "borrowing" allowed in the model, the CO$_2$ price can decrease or increase at a rate lower than the economy’s interest rate during certain periods.

23Setting the hard-cap in 2020 leads to more energy conservation in 2025. Since energy and capital are complementary inputs, this (slightly) reduces the marginal productivity of capital (with an interest rate of 5.148% instead of 5.182% in Table 1.5). Households therefore invest less and consume more in 2025 (CO$_2$ prices and consumption are positively correlated). However, they consume less in the following periods as shown by Table 1.5.
1.4. ANALYSIS AND DISCUSSION OF RESULTS

Union as indicated in table 1.6). This is an illustration of the fable of the elephant and the rabbit popularized by Hogan and Manne [1977], i.e. the regional economies are so important that the emissions caps have little effect on consumption\(^{24}\). As a result, the expected value of the CO\(_2\) price almost follows a Hotelling law between 2020 and 2025. For instance, if we consider the \(p = 0.5\) scenario, from Table 1.5 let us approximate the effective social discount factor from 2020 to 2025 as follows:

\[
\frac{\beta_i,2025}{\beta_i,2020} \frac{E(L_{i,2025}/C_{i,2025})}{E(L_{i,2020}/C_{i,2020})} \simeq 1.05095
\]

As expected, the prices given by Table 1.4 satisfy (1.6) since we have:

\[
45 \simeq (0.5 \times 29) + (0.5 \times 86) / (1.05095)^5
\]

Figure 1.4 shows that emissions permits are banked until 2020 in the European Union when \(p \geq 0.4\). Consistently, the expected CO\(_2\) price increases at the social discount rate (economy’s rate of interest) between 2020 and 2025. In North America, emissions permits are banked before 2020 even in the deterministic soft-cap scenario \((p = 0)\) because of relatively-high pre-2020 emissions quotas and cheap abatement opportunities. In the Pacific OECD region, emissions permits are banked until 2020 when \(p \geq 0.2\). Therefore, when \(p \geq 0.4\) all the OECD regions bank emissions permits prior to 2025. As illustrated by Table 1.4, for \(p = 0.5\), we then have a convergence of pre-2020 CO\(_2\) prices in all OECD regions (although the inter-regional trade of emissions permits does not yet exist). This convergence of emissions-permits markets is backwardly induced by the Hotelling rule (from a unique world price in 2025). Figure 1.3 shows that the expected value of CO\(_2\) price follows this Hotelling rule until 2055 in all scenarios (and along each branch of every scenario).

For oil and gas, the observation\(^{25}\) of the Hotelling rule is hindered by constraints imposed on the production of these natural resources (especially maximum production-to-reserve ratios) that limit inter-temporal arbitrage in extraction decisions. Trajectories of price and consumption for oil, gas, coal, and power in various scenarios are provided by A.1.

\(^{24}\)This statement has nevertheless to be qualified as both scenarios compared here require a serious curb in emissions. A comparison between a business-as-usual and the hard-cap scenario would probably yield a much bigger impact on consumption.

\(^{25}\)Note that, for oil and gas, the Hotelling rule corresponds to a reserve-value increase at the economy’s interest rate (if the reserve considered is exhausted at the end of the model’s horizon).
Probability of the hard cap | 5%  | 20%  | 50%  | 80%  | 95%  |
------------------------|-----|-----|-----|-----|-----|
CO$_2$ risk premium (cents per ton) | 0.093 | 0.186 | 0.148 | 0.049 | 0.039 |

Table 1.6: Risk premium on CO$_2$ price in 2025 for the European Union

Figure 1.4: Expected 2020-2025 CO$_2$ price increase and stock of banked emissions permits in 2020 in the European Union, with respect to the hard-cap probability
1.4.3 Impact of uncertainty on technological trajectories

Table 1.7 gives the obtained energy mix in periods 2020 and 2050, for the deterministic and equiprobable \( p = 0.5 \) scenarios, at the world scale. Tables A.1, A.2 and A.3 are specific to the European Union, North America and China respectively.

Let us briefly comment on the technological trajectories obtained in deterministic scenarios. Until 2020, reduction in emissions is achieved by decreasing the carbon intensity in both electric and non-electric sectors. In the electric sector, the replacement of coal technologies by nuclear, gas and biomass generation is more pronounced in the hard-cap than in the soft-cap scenario. As a result, in 2020, only 20% of electricity is produced with coal without CCS in the hard-cap scenario, whereas 31% of electricity is produced with coal without CCS in the soft-cap scenario. The non-electric energy sector substitutes gas for oil. As a consequence, in 2020, oil represents less than 50% of non-electric energy production in both scenarios, while it represented 57% in 2005. After 2020, the carbon intensity keeps on decreasing in both energy sectors. In an expanding electric sector, nuclear, coal and gas CCS, wind, solar and biomass replace without-CCS coal and gas generation (which is used for less than 3% of electricity production in 2050). Due to a lower gas price (see Figure A.3), gas with CCS is more developed in the hard-cap than in the soft-cap scenario (at the detriment of coal CCS). In the non-electric sector, gas and backstop technologies (hydrogen and second-generation bio-fuels) substitute for oil and coal. In addition, electricity substitutes for non-electric energy as pre-2020 technological trajectories favor the expansion of new technologies after 2020 in the electric sector. This is not the case in the non-electric energy sector which undergoes the constraints on gas production and where the (expensive) backstop technologies are not competitive prior to 2020. This explains why, after 2020, electricity consumption grows faster than non-electric energy consumption. This evolution is particularly pronounced in the hard-cap scenario where, in 2050, there is more electricity consumed than in the soft-cap scenario (35.8 Tkwh instead of 34.9 Tkwh).

In the hard-cap deterministic scenario, the severity of the emissions target in the intermediate and long runs justifies early (pre-2060) and massive abatement efforts, especially through non-electric energy conservation and development of non-electric backstop technologies (see Figure 1.6). As a result, when banking is no longer possible, in 2060, the deployed technologies are well-adapted to the long-run emissions target, which makes possible a decreases in CO\(_2\) price as illustrated by Figure 1.3.

In the soft-cap deterministic scenario, emissions targets in the intermediate and long runs do not necessitate massive pre-2060 abatement efforts, especially regarding non-electric energy conservation and backstop technologies as shown by Figure 1.6. Therefore, when banking is no longer possible, in 2060, a reduction
in non-electric energy consumption is necessary (see Figure 1.6). This results in a high marginal abatement cost explaining the important upward disruption of CO$_2$ price in 2060 (with a price peak at almost $300 per ton in Table 1.4).

The uncertainty about the long-run emissions targets has a significant impact on the technological trajectories of the energy firms. Especially, the more probable the hard cap, the greater the accumulated stock of banked emissions permits in period 2020, as Figure 1.4 shows for the European Union. As one could expect, this higher accumulation of banked permits results from a higher expansion (contraction) of less-emitting (more-emitting) technologies prior to 2020. For instance, Figure 1.5 provides an illustration of this effect for highly-emitting coal-fired power generation (without CCS) which is less used when the hard-cap probability is high.

Let us now turn to the post-2020 periods for which the model yields non-trivial results. Let us first consider the hard-cap branches of stochastic scenarios. Since the setting of the hard cap was initially considered as a mere possibility, the stock of banked permits available in 2025 is lower than that in the deterministic hard-cap scenario. This results in a 2025 CO$_2$ price higher than in the hard-cap deterministic scenario. However, to compensate for this situation, until 2055 clean technologies expand faster in the stochastic scenarios than in the deterministic one. More specifically, Figure 1.6 shows that there are more non-electric energy conservation and a greater deployment of non-electric backstop technologies. As a consequence, in 2060, when banking is no longer possible, the CO$_2$ price is lower in the hard-cap branches of stochastic scenarios than in the deterministic hard-cap scenario. Consistently, this price increases with the probability of the hard-cap target.

Let us now consider the soft-cap branches of stochastic scenarios. In each region, when the soft cap is set at the end of 2020, a stock of banked emissions permits has been previously accumulated as a precaution against a possible hard-cap (at least, if the hard-cap probability was sufficiently high, for instance as Figure 1.4 shows for the European Union). Using this stock of banked permits results in differing the post-2020 deployment of low-emitting technologies (along with a lower CO$_2$ price until 2055 in soft-cap branches of stochastic scenarios). Especially, Figure 1.6 shows that there is more non-electric energy consumed in soft-cap branches of stochastic scenarios than in the deterministic soft-cap scenario. Consequently, when permits are banked in 2020, this results in a 2060 CO$_2$ price peak higher than that observed in the deterministic soft-cap scenario. This price peak increases with the probability of the hard-cap target.
### 1.4. ANALYSIS AND DISCUSSION OF RESULTS

#### Table 1.7: Technologies used at the world level in the deterministic and equiprobable scenarios

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<tr>
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<th>Deterministic</th>
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<th>Equiprobable</th>
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<td>HC</td>
<td>SC</td>
<td>HC</td>
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<td><strong>Electricity Production(^b)</strong></td>
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<td>11 0</td>
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<tr>
<td><strong>Total (in Tkwh)</strong></td>
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<td>23.6 35.8</td>
<td>24.03 34.84</td>
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<td><strong>Non-Electric Energy Production(^b)</strong></td>
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<td>48 37 29</td>
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<tr>
<td>gas for direct use</td>
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<tr>
<td><strong>Total (in Mtoe)</strong></td>
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<td>7186 8644</td>
<td>7835</td>
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</tbody>
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\(^a\) SC (HC) means in the soft-cap (hard-cap) branch.

\(^b\) % shares of the technologies in total electric and non-electric energy production.
Figure 1.5: Electricity production from (remaining and new) coal without CCS and from (coal and gas) CCS technologies

Figure 1.6: Total non-electric energy production and non-electric production from the backstop technologies
1.5 Conclusion

Our simulations show that the uncertainty about long-run emissions targets significantly affects the energy transition at both global and regional scales, as well as CO$_2$ and energy prices. A higher probability for the setting of the hard-cap target at the end of period 2020 leads to more abatement, and therefore more banking, until 2020. In brief, in the electric sector, prior to 2020 coal without CCS declines faster, for the benefit of nuclear and gas technologies. As a higher hard-cap probability leads to a higher stock of banked permits at the start of period 2025, fewer emissions reductions are required in the subsequent periods. More specifically, in all branches, there is less energy conservation in the non-electric sector and, in hard-cap branches, a lower penetration of non-electric backstop technologies. As a result, the technologies deployed in 2060 (when banking is no longer possible) are not fully adjusted to the long-run emissions stabilization targets. Thus, in soft-cap branches of stochastic scenarios, the initial anticipation of a probable hard-cap target results in a 2060 price peak higher than that obtained in the deterministic soft-cap scenario. In addition, since pre-2020 CO$_2$ prices are sensitive to the hard-cap probability, they reveal information about agents’ belief on this probability.

Moreover, a pre-2020 banking of emissions permits occurs for a hard-cap probability greater or equal to 0.4 (0.2) in the European Union (Pacific OECD region), while in North America banking occurs in all scenarios. In every region where such a banking takes place, the regional CO$_2$ price follows a Hotelling rule with a risk premium between 2020 and 2025. Since the long-run emissions targets have a negligible impact on regional consumptions, this risk premium is very small.

Since a pre-2020 banking occurs in all regions when the hard-cap probability is greater than 0.4, the common belief in a single world CO$_2$ price from 2025 on then leads to a convergence of CO$_2$ prices in OECD regions prior to 2020, even if inter-regional trade of emissions permits does not yet exist. For oil and gas, the observation of the Hotelling rule is hindered by constraints imposed on their production (that limit inter-temporal arbitrage in extraction decisions).

Our approach is of course subject to a given number of limitations. One of them relates to the information structure considered. In the model, agents’ belief is not assumed to evolve through time, as information is fully revealed in 2020. Taking into account a more progressive revelation of information on emissions targets would enrich the model and perhaps significantly influence its results.
Chapter 2

Energy transition under uncertain economic growth

2.1 Introduction

To face the threats of climate change, the energy system needs to be restructured towards less carbon intensity. Considerable efforts in investment on the short and medium-term are needed [European Commission, COM(2010)]. The present climate of uncertainty surrounding global economic growth and the risk of long lasting stagnation in some economies might complicate the participation of the private sector to the restructuring effort.

The recent economic and financial crises, which have particularly affected certain OECD regions, have ushered in a period of great uncertainty. Above and beyond the question of short-term business cycle, this uncertainty affects the capacity of these economies to grow at a sufficient rate in the longer term. Several institutional analyses [OECD, 2010, IMF, 2010] emphasize in particular the long-term impact of the rise in unemployment linked to the crisis1, as well as concern over the sustainability of the national-debt burden of some industrialized countries2. In the long run, this could lead to one or more decades of low growth, similar to the "lost decades" experienced by the Japanese economy since the beginning of the 1990s. This uncertainty over economic growth in industrialized countries, and more generally over global economic growth, may represent a major obstacle to the executions of the investments necessary for change in the energy mix. Thus, in developing countries with high economic growth (where elasticity of energy demand to GDP is relatively high) this un-

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1There continues to be a risk that at least part of the rise in unemployment since the crisis began will prove long-lasting". (OECD [2010], p. 40).
2"In particular, new tail-risks have arisen from the growing concerns about longer-term debt sustainability in some countries […]" (OECD [2010], p.43).
CHAPTER 2. UNCERTAIN ECONOMIC GROWTH

Certainty may slow the growth of the energy supply. In industrialized countries with moderate economic growth (and in the longer term on a global scale), this uncertainty may slow the adaptation of the energy mix to targeted reductions in CO\textsubscript{2} emissions.

This chapter studies the impact that uncertainty over economic growth may have on investment decision in the electric sector. The question is addressed by using a general hybrid multi-region dynamic general equilibrium model derived from MERGE [Manne et al., 1995]. There have been relatively few studies using dynamic general-equilibrium models under environmental constraints to determine equilibria that take into account the influence of uncertainty on agents’ behavior. Manne and Richels [1995] Manne and Olsen [1996] study the impact of the uncertainty surrounding the sensitivity of climate damages to greenhouse-gases concentrations. Bosetti et al. [2009] and Durand-Lasserve et al. [2010] study the impact of uncertainty relative to regional emissions-reduction targets. Bosetti and Tavoni [2009] consider the uncertainty over the success of R&D activities concerning a backstop technology. Cian and Tavoni [2010] evaluate the effect of uncertainty in future carbon prices and technology costs. However, none of these contributions investigates the impact that uncertainty over global economic growth may have on technological choices and resulting CO\textsubscript{2} price. Research works dealing with economic-growth uncertainty, as Scott et al. [1999] and Webster et al. [2008], generally use methods relating to Monte-Carlo simulation. Therefore, they assume that the outcomes under uncertainty are contained within some extreme deterministic outcomes. They miss the fact that not only parameters values matter, but that their uncertain nature affects agents’ behaviour (hedging).

The following section more precisely describes the stochastic economic-growth scenarios considered. The general-equilibrium model used is then described briefly, emphasizing the different forms of irreversibility taken into account. The CO\textsubscript{2} emissions targets considered for the various regions of the world are presented. Several comments on the calibration of the model form a particular subsection. We then present and interpret the results obtained, identifying the impact of the uncertainty under consideration on prices and on the global energy transition. Technological trajectories, CO\textsubscript{2} prices and electricity prices are studied in turn.

2.2 Simulation of scenarios where economic growth is stochastic

The concern about the impact of uncertainty surrounding economic recovery is clearly stated by the Energy Information Administration (DOE/EIA), for
2.2. SIMULATION OF SCENARIOS WHERE ECONOMIC GROWTH IS STOCHASTIC

which "expectations for the future rates of economic growth are a major source of uncertainty" [EIA, 2010]. To reflect this uncertainty, they presents three scenarios for global economic growth by 2035. A result put forward is the extreme sensitivity of energy demand to the economic-growth scenario.

We define stochastic scenarios for economic growth inspired by the EIA’s scenarios. The uncertainty relates to the period during which the global economy may take a path of solid growth. The climate policy considered corresponds in the medium term to the commitments announced after the 2009 Copenhagen conference, and in the long term to a reduction of 25% in global energy-related CO$_2$ emissions (with respect to 2005). Using stochastic dynamic programming, we solve a general-equilibrium model similar to that described by Durand-Lasserve et al. [2010] derived from MERGE [Manne et al., 1995]. In this multi-regional model, all agents are forward looking, in the sense that each representative household (firm) maximizes its expected sum of discounted utilities (expected present value) under rational expectations. In other words, on every date firms base their current decisions on consistent subsequent prices and outputs on every possible outcome. These decisions are influenced in particular by irreversibilities resulting from investments and technological choices. At economic equilibrium, for each variable (for instance CO$_2$, oil, gas and power prices), the model derives a stochastic scenario consistent with that assumed for economic growth.

2.2.1 Stochastic growth scenario

We consider that the global economy may experience a period of slow growth, before returning to a high growth rate. The uncertainty centres on the number of decades of low growth (i.e. of "lost decades", to borrow the expression used by Hayashi and Prescott [2002] about the Japanese economy) through which the global economy must pass before experiencing an economic recovery. More precisely, during each decade beginning in 2015, 2025 and 2035, global economic growth may, with the probability $p$, escape from the path of low growth to shift to a path of higher growth (on which it will subsequently remain). In other words, the higher the value of $p$, the more likely a rapid economic recovery$^3$.

These two possible growth paths correspond to the EIA [2010] high and low economic-growth scenarios. Each path defines specific economic-growth rates for each of the regions in the model.

$^3$Consistently, in the rest of the chapter, the term "recovery" refers to the switch from the low economic-growth path to the high economic-growth path.
CHAPTER 2. UNCERTAIN ECONOMIC GROWTH

Figure 2.1: Possible GDP growth rates in OECD and non-OECD

Figure 2.2: Structure of the stochastic scenario for each variable of the model
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On a global scale, the high-growth path implies growth rates around 1% higher than those corresponding to the low-growth path, as shown by Figure 2.2. However, this differential varies according to the region considered. Up to 2015, the economic growth is deterministic and corresponds to the EIA [2010] reference scenario. In all regions of the world, the two growth paths begin to converge from 2035. From 2060 on, all regional economies grow at the annual rate of 2%.

For each variable (price or quantity), the model will derive a stochastic scenario consistent with that considered for economic growth. This stochastic scenario may be represented by a tree with four branches, each branch defining one possible path for the variable under consideration. In the remainder of the chapter, these paths are named $R_{2015}$ (economic recovery in 2015, with probability $p$), $R_{2025}$ (economic recovery in 2025, with probability $p(1-p)$), $R_{2035}$ (economic recovery in 2035, with probability $p(1-p)^2$) and $NR$ (no economic recovery, with probability $(1-p)^3$). A new branch appears on each possible date of economic recovery, as shown in Figure 2.2.

2.2.2 Presentation of the model

Top down - bottom up structure

The general equilibrium model used, derived from MERGE [Manne et al., 1995], is essentially that described in chapter 1. The model’s horizon extends from 2005 (base year) to 2100, with 5-year time periods. The world is divided into 3 OECD regions (European Union, North America, OECD Pacific) and 8 non-OECD regions (Africa, China, India, Latin America, Middle East, non-OECD Asia, Russia, Rest of the World). The economic-growth stochastic scenario is common knowledge and all agents in the model are equally informed and have perfect foresight. In each region, a representative household maximizes the expected sum of discounted logarithmic utilities of per-capita consumption over time and states.

The good consumed by households is a composite good that includes all intermediate and consumption goods and services, as well as all the final energy needs of the economy (firms and households). It serves as a numeraire, measured in terms of units of purchasing power for the year 2005 (in the rest of the chapter, all prices are therefore expressed in 2005 dollars). This composite good can be used for final consumption (by households), investment, and intermediate consumption (in industrial sectors). This composite good is produced in each region by a final industrial sector using various equipment vintages. At any given period, the production function corresponding to a new vintage of installed equipment is described by a two-level nested Constant Elasticity
of Substitution (CES) function, using four inputs: labor, capital, electricity and non-electric energy. However, once the vintage is installed, the respective quantities of these inputs can no longer be adjusted. The resulting coexistence of different vintages in the final sector generates irreversibility, since this sector is somehow locked in the short run by previous technical choices. For instance, the choice of the energy intensity of new vintages until 2015 impacts the possible substitutions after this period between capital and energy and between electricity and non-electric energy.

Electricity and non-electric energy are supplied to the final sector by two distinct industrial sectors that use various Leontief technologies to transform fossil fuels and composite goods into energy. The technologies in the non-electric sector are: oil for direct use, gas for direct use, coal for direct use, bio-fuels, synthetic fuels, and non-electric backstop (see [Durand-Lasserve et al., 2010] for a precise description). The power generation technologies are shown in Table 2.1.

The fossil fuels are supplied by a mining firm that extracts oil, coal and gas from regional reserves. All regions are linked together by the international trade in composite good, oil and gas. An indexation of the variables [Meeraus and Rutherford, 2005] corresponding to the structure of the stochastic scenario for economic growth replaces the explicit specification of non-anticipativity constraints. Additional aspects of the calibration and numerical resolution of the model are described by [Durand-Lasserve et al., 2010].

A representation of capacity expansion

Our model explicitly considers sunk investment costs for each power generation technology, which renders irreversible the cost of a capacity increase. On this point, our model differs from that used by Durand-Lasserve et al. [2010], who, for each technology at each period, consider a total cost equal to a levelized cost multiplied by the production during that period. In [Durand-Lasserve et al., 2010], the absence of unrecoverable investment costs was compensated for by a constraint limiting the possible rate of decline in the use of the technology.

Moreover, in our model, investments are subject to time-to-build: 10 years (2 periods in the model) for nuclear technologies with CCS and non-electric backstop, 5 years (one period) for the other technologies. Considering time-to-build increases the uncertainty over energy demand and prices when investment decisions have to be made. Note that, for all technologies, installed capacity decays at an annual rate of 2%. 
### Table 2.1: Power generation technologies in the model

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment cost&lt;sup&gt;c&lt;/sup&gt; ($ per kW)</th>
<th>Efficiency (%)</th>
<th>Emission rate (TCO$_2$/MWh)</th>
<th>Load factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2050</td>
<td>2010</td>
<td>2050</td>
</tr>
<tr>
<td>Hydropower</td>
<td>2410-3210</td>
<td>3010-3330</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Remaining nuclear</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>New nuclear</td>
<td>2000-2500</td>
<td>3670-4000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Remaining oil</td>
<td>-</td>
<td>-</td>
<td>26-39</td>
<td>20-33</td>
</tr>
<tr>
<td>Remaining coal</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Remaining coal with CCS&lt;sup&gt;a&lt;/sup&gt;</td>
<td>880-1390</td>
<td>2530-2070</td>
<td>42-44</td>
<td>47</td>
</tr>
<tr>
<td>New coal</td>
<td>700-1750</td>
<td>2530-2070</td>
<td>34-36</td>
<td>39</td>
</tr>
<tr>
<td>New coal with CCS&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1510-3120</td>
<td>3140-3780</td>
<td>34-36</td>
<td>39</td>
</tr>
<tr>
<td>Remaining gas</td>
<td>-</td>
<td>-</td>
<td>36-54</td>
<td>36-54</td>
</tr>
<tr>
<td>New gas</td>
<td>600-700</td>
<td>820-900</td>
<td>55-59</td>
<td>63</td>
</tr>
<tr>
<td>New gas with CCS&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1080-1260</td>
<td>1430-1490</td>
<td>47-51</td>
<td>55</td>
</tr>
<tr>
<td>Biomass</td>
<td>2100-2480</td>
<td>2100-2220</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>1390-1730</td>
<td>1410-1520</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind offshore</td>
<td>2570-3180</td>
<td>1670-1740</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Solar photovoltaic</td>
<td>3900-4650</td>
<td>1910-2020</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electric backstop&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6140-7220</td>
<td>3090-3410</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Sources: IEA [IEA, 2010b,a, 2008b].

<sup>a</sup> A 10$/T CO2 transportation-and-storage cost is considered, in accordance with Rafaj and Kypreos (2007) and the (wide) range of estimates given by IEA [IEA, 2010a].

<sup>b</sup> Includes concentrating solar power and marine energy.

<sup>c</sup> In addition to investment costs, variable and fixed non-fuel O&M costs are also considered (along with a variable feedstock cost for nuclear and biomass power plants).
Regional technology portfolio constraints

Because of the linear structure of the energy and mining sectors submodels, constraints are imposed on the regional energy portfolios in order to limit the speed of penetration of some technologies and to rule out the possibility of having one technology with an overwhelming market share. Such constraints were already present in Chapter 1, but we give here further details, as they will play a key role in the next Chapter.

The model includes constraints on the maximum expansion of each technology. These constraints, which take the form of a maximum growth rate in technology deployment from one period to the other, reflect real-world frictions when installing new capacity. For new technologies, they also cover the inertia inherent in the emergence of a new industrial sector, an inertia which may be explained by the fact that new competing technologies face infrastructural, institutional and cultural barriers [Köhler et al., 2006]. In other words, the development and spread of any technology is in essence a gradual process, which may for example be shown by an S-shaped curve [Könnölä and Carrillo, 2008] whose take-off and acceleration phases would be mimicked by the constraints on expansion. These constraints therefore generate a path dependence - in the absence of learning curves in the model - linked to the organization of the sector, which makes adaptation of the energy system even more difficult during an economic recovery, especially if it was not properly anticipated. Note that it is very difficult to assign values to the maximum penetration rates of the technologies and that they have to be benchmarked on external projections. On the basis of the projections of the IEA World Energy Outlook 2008 [IEA, 2008b], we have chosen values ranging from 10% a year (for renewable technologies) to 1.5% a year (for new nuclear capacities outside in the OECD regions).

In each region, a single electricity demand is considered for each period. So as to consider an energy mix compatible with an averaged demand, the maximum market shares of nuclear, wind and solar technologies are limited (33% of total power generation for each). Similarly, a minimum of 10% of the total installed capacity must consist of technologies based on fossil fuels, as a complement to intermittent technologies and because of the existence of peak demands. We have to stress here that these market share definitions are highly stylized. The evaluation of the feasibility of integrating large capacities of renewable in electricity supply is an extremely complex issue, at the edge of the economic and electrical engineering literature. This issue has been investigated by Maïzi et al. [2009] and Drouineau [2011] who used a MARKAL-type model [Loulou et al., 2004] complemented by dedicated tools. However, such an approach, goes beyond the scope of this PhD dissertation. Last, we need to add that the capacities in hydropower and biomass are sub-
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ject to exogenous availability limitations that are in line with the IEA World

2.2.3 CO₂ emissions policy in the model

Table C.1 describes the gradual energy-related CO₂ emissions reductions tar-
gets \(^4\) assumed for the various regions of the world. In the long term, the
objective is to reduce global emissions by 25% between 2005 and 2050, with
all regional quotas allocated from 2050 (and up to 2100) corresponding to the
same per capita volume of emissions. Based on the demographic projections
used by EIA [2010], this per capita volume of emissions is 2.21 tons of CO₂ per
year.

To attain this objective, OECD regions, Russia, China, the Middle East and
Rest of the world will have to decrease their CO₂ emissions between 2005 and
2050. Conversely, regions where the current per capita volume of CO₂ emissions
is low may increase their emissions (±372% for Africa, +198% for India, +136%
for non-OECD Asia and +48% for Latin America). These targets of emissions
reductions for 2050 have been established within the framework of a global cap-
and-trade market for CO₂ emissions (i.e. a global market with inter-regional
trading of emissions permits) from 2025 onwards. From that date, during each
period, a quota of emissions permits is attributed to every region. The series
of quotas allocated to the various regions are set so as to converge linearly to-
wards the same per capita volume of CO₂ emissions in 2050. Unused emissions
permits can be banked, to be used during a subsequent period. By consuming
fossil fuels, the sectors supplying electricity and non-electric energy produce
CO₂ emissions. In each region, in any period, the quantity of CO₂ emitted by
these two sectors must therefore be smaller than the regional quota, increased
by the emission permits banked in previous periods, and by the purchase of
emissions permits from other regions.

In addition to this long-term objective, there are regional targets of emis-
sions reductions for 2020. These targets [WRI, 2010a,b] follow the commitments
announced after the 2009 Copenhagen conference.

\(^4\)Our model - which does not contain any modeling of the impact of GHG emissions on
climate change - implicitly considers regional CO₂ emissions permit markets.
## Table 2.2: Regional emissions-reduction targets

<table>
<thead>
<tr>
<th>Region</th>
<th>2005</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>6.88</td>
<td>-15%</td>
<td>-</td>
</tr>
<tr>
<td>European Union</td>
<td>4.10</td>
<td>-20%</td>
<td>-</td>
</tr>
<tr>
<td>OECD Pacific</td>
<td>2.19</td>
<td>-15%</td>
<td>-</td>
</tr>
<tr>
<td>China</td>
<td>5.46</td>
<td>-40%</td>
<td>-</td>
</tr>
<tr>
<td>India</td>
<td>1.23</td>
<td>-20%</td>
<td>2005</td>
</tr>
<tr>
<td>Russia</td>
<td>1.57</td>
<td>-15%</td>
<td>-</td>
</tr>
<tr>
<td>Middle East</td>
<td>1.32</td>
<td>-</td>
<td>2020**</td>
</tr>
<tr>
<td>Non-OECD Asia</td>
<td>1.50</td>
<td>-</td>
<td>2020**</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.00</td>
<td>25%</td>
<td>-</td>
</tr>
<tr>
<td>Africa</td>
<td>0.86</td>
<td>-</td>
<td>2020**</td>
</tr>
<tr>
<td>Rest-of-the-world</td>
<td>1.20</td>
<td>-20%</td>
<td>-</td>
</tr>
<tr>
<td>World</td>
<td>27.33</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:

- Reference case of IEA (2008b) in 2020. This figure only serves to define the series of quotas from 2025 to 2050.
- Latin America (Rest of the world) takes into account Brazil’s (Ukraine’s) commitments.
- Figure for the R2015 scenario.
- Figure for the non-R2015 scenarios. Sources: WRI (2010a,b), IEA (2007a, 2008b, 2010a).
OECD Regions have committed to reduce emissions by 2020: 20% for the European Union, 17% for North America and OECD Pacific (relative to 1990 levels of emissions). In the model, each of these regions implements (from 2010 to 2020) a regional cap-and-trade market (not linked to other regions) and progressively decreases the allocated quota of emissions permits (i.e., the cap) so as to converge linearly towards its 2020 emissions target. In each region, banking of permits is allowed from 2010 onwards, with the option to use the banked permits within the global emissions-permits market (from 2025 on).

China, India, Russia, Latin America and the Rest of the world are also committed to reduce emissions by 2020. Each commitment is accounted for in the model by a constraint on the emissions volume in 2020. The commitments made by China and India [WRI, 2010a] are expressed in the form of a decrease in CO₂ emissions per unit of GDP. These commitments therefore depend on the path followed by economic growth. As this is uncertain, the model takes account of the two possible objectives in 2020 for Chinese and Indian emissions.

For Africa, non-OECD Asia and Middle East (who have no commitment for 2020), the 2020 level of emissions in the IEA [2008b] reference scenario is used as a starting point for calculating regional quotas from 2025 to 2050.

2.2.4 Special issues relating to calibration on a stochastic economic-growth scenario

The exogenously specified growth in efficient labor (i.e., labor productivity\(^5\) multiplied by the population) is a key driver of economic growth in SMERGE. As a consequence, following the same procedure as Webster et al. [2008], to calibrate the model on the stochastic economic-growth scenario described by Figure 2.2, we consider the same stochastic scenario for the growth rate of efficient labor. At equilibrium, this calibration yields regional economic growth rates that are very close - but not identical - to the targeted values. As a matter of fact, the gross domestic product of a region is not equal to the production of composite goods, principally because of intermediate consumption and the added value generated by the three other industrial sectors (electricity, non-electric energy and - especially in the Middle East - mining). The economic growth rate also depends - at least to a certain extent - on the availability of energy technologies and the environmental constraints specified in the model. In the version of SMERGE used here, the parameters reflecting Autonomous

\(^5\)As emphasized by Jacoby et al. [2006], p.615, about CGE models, “it is well established that economic growth cannot be explained only by the growth of labor and accumulation of capital. A residual productivity factor always remains.”..." this phenomenon conventionally is represented in one of two ways - either a change in total factor productivity or as an increase in labor productivity".
Energy Efficiency Improvement\(^6\) (AEEI) have been calibrated on an energy-intensity scenario that is consistent with [EIA, 2010] projections.

More generally, let us stress that the joint maximization of all regional objective functions is intended to portray the market equilibrium consistent with a given (stochastic) view of the future. The choice of the corresponding parameters flows more from a descriptive than a prescriptive approach. Thus, the different regional rates of time preference for utility are chosen so as to respect economic-growth differentials between regions (corresponding to the calibration scenario). In fact, in the model, the perfect mobility of the composite good is equivalent to the perfect mobility of capital. Therefore, at equilibrium, all regional interest rates are equal. According to Ramsey rule (e.g. [Durand-Lasserve et al., 2010]), the sum of the regional rate of time preference for utility and of the rate of growth in regional \textit{per capita} consumption is therefore the same for all regions. If we consider that growth in regional \textit{per capita} consumption and regional rate of economic growth are very close\(^7\), this implies that the differential in economic growth between two regions is approximately equal to the difference between the two regional rates of time preference for utility. On this point, it is interesting to note that, in a rather unusual way, the stochastic economic-growth scenario adopted here leads us to consider regional rates of time preference for utility themselves to be stochastic (since the differentials in regional economic-growth rates depend on the branch of the stochastic scenario under consideration).

2.3 Results and interpretation

For a better understanding of the impact of the uncertainty surrounding economic recovery, the equilibrium of the model is determined for each of the following five values of the probability \(p\): 1 (deterministic scenario with \(R_{2015}\) certain), 0.8, 0.5, 0.2, 0 (deterministic scenario with \(NR_{2015}\) certain).

2.3.1 Achieved economic-growth scenarios

For the various values of \(p\) under consideration, the stochastic scenario for GDP growth obtained at equilibrium replicates relatively well the stochastic scenario of efficient labor used to calibrate the model. This is illustrated in Figure 2.3.1.

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\(^6\)All sources of non-price-induced reductions in the energy required per unit composite good are summarized in MERGE by the AEEI parameters, which operate as scaling factors on the energy input into production. As Richels and Blanford [2008] stress, these reductions may occur due to both technological progress (e.g. end-use efficiency) and structural changes in the economy (e.g. shifts away from manufactured goods towards services).

\(^7\)At the steady state of a stylised growth model in which the efficient labor grows at an exogenous rate, consumption and Gross Domestic Product both grow at this same rate (see for example Aghion and Howitt [1997] p. 22).
2.3. RESULTS AND INTERPRETATION

Figure 2.3: Efficient labor (plain lines) and achieved GDP growth (dotted lines) at equilibrium in OECD and non-OECD regions for \( p = 0.5 \).

The fact that GDP grows a little more than efficient labor during the initial periods is explained by the regional AEEIs. Energy expenditure actually rises less rapidly than the output of the final sector, even though the latter grows almost at the same rate as efficient labor. For all values of \( p \), the economic growth differential between the high and low branches nevertheless remains at around 1%, in line with the desired stochastic scenario. In concrete terms, all the agents in the model form their expectations by considering the stochastic scenario of economic growth actually achieved at equilibrium.

2.3.2 \( \text{CO}_2 \) price trajectories

Figures 2.4 to 2.6 show the \( \text{CO}_2 \) prices in the European Union - corresponding to the global-market price from 2025 onwards - in the various scenarios. The \( \text{CO}_2 \) price appears to be very sensitive to the path followed by economic growth, as well as to the agents’ initial anticipations (i.e. the value of \( p \)). In 2010, the price per ton of \( \text{CO}_2 \) ranges between $26 (\( p = 0 \)) and $29 (\( p = 1 \)). According to the scenarios and branches under consideration, the price varies between $35 (\( p = 0.5 \)) and $65 (\( p = 0.2 \)) in 2020, between $33 (\( p = 0.8 \)) and $80 (\( p = 0.2 \)) in 2030, and between $25 (\( p = 0.8 \)) and $163 (\( p = 0.2 \)) in 2045. Let us note that in the case of no recovery (the NR branch), the \( \text{CO}_2 \) price
in 2045 is extremely sensitive to initial anticipations: $78 if non-recovery was perfectly anticipated \((p = 0)\), but $25 if it was very poorly anticipated \((p = 0.8)\).

An essential difference exists between the R2015 and NR branches. In the R2015 branch, in terms of decision-making, the role of anticipations (i.e. the value of \(p\)) is limited to the 2010 and 2015 periods, since from 2020 onwards no uncertainty remains, with economic growth remaining high. On the other hand, in the NR branch, the uncertainty surrounding a possible economic recovery persists until 2035. Up to that date, during each period, the uncertainty consequently has two (opposite) effects on the CO\(_2\) price: the effect resulting from past decisions taken in anticipation of a possible rapid recovery which in the end did not take place ("past precaution effect") and the effect of current decisions taken in anticipation of a possible future recovery ("current precaution effect"). The past (current) precaution effect leads to a current CO\(_2\) price that goes lower as \(p\) gets higher (smaller).

This perspective may for example explain why, in the R2015 branch, the CO\(_2\) prices obtained in the various scenarios converge quite rapidly (from 2025 onwards) towards neighbouring values, with the past precaution effect being limited to the decisions taken in 2010 and 2015. In the same way, the figures given in the previous paragraph show that the lowest CO\(_2\) price (still drawn from the NR branch) is obtained overall for a probability that is higher the further away the date considered is. So, in 2010, the only thing that matters is the current precaution effect, which leads to less and less banking of emissions permits as the probability of a rapid recovery gets lower. The lowest price is thus obtained for \(p = 0\). However, when we move further away in time, the past precaution effect becomes more and more significant relative to the current precaution effect. In the NR branch in 2040, when there is no more uncertainty about the economic growth to come, only the past precaution effect has an impact on the CO\(_2\) price, which is therefore at its lowest ($21) when a rapid economic recovery has initially been considered highly probable (\(p = 0.8\)).

In all scenarios, emissions permits are banked right from the initial periods. This banking connects the price of an emissions permit from one period to another, so that it then follows the Hotelling rule. In 2020, each of the two possible branches of the scenario yields specific emissions-permit price and interest rate (between 2015 and 2020). As a result, the price of an emissions permit in 2015 is equal to the expected value of its price in 2020 discounted at the corresponding interest rate.

In the R2015 branch, as one might expect, the rise in the emissions permit price is higher as the value of \(p\) gets lower, i.e. the economic recovery has been poorly anticipated. When \(p=0.2\), the permits banked beforehand are used during the 2020 period to mitigate the shock on the CO\(_2\) price. The price of an emissions
2.3. RESULTS AND INTERPRETATION

Figure 2.4: CO₂ price in the European Union in deterministic and $p = 0.2$ scenarios

permit is therefore $65, compared to a price of $47 when economic recovery has been anticipated perfectly ($p=1$). This impact is nevertheless transitory, both because the energy system adapts and because of the "hot air" generated by non-OECD countries entering the global cap-and-trade market in 2025 (with Chinese and Indian emissions quotas higher in the R2015 branch). Thus, in the R2015 branch of the $p=0.2$ scenario, during the 2025 period, the European Union buys on average 287 million emissions permits per year (8.8% of its total emissions).

Conversely, the absence of economic recovery, whereas such a recovery had been considered probable, leads to a lower emissions-permit price in 2020. This pattern - impact on the permit price if the realized path (economic recovery occurring or not) was initially poorly anticipated - is repeated in 2030 and 2040. Finally, when the absence of economic recovery was anticipated perfectly ($p = 0$), the CO₂ price is lower in 2025 than in 2020, which leads to all the previously banked permits being consumed in 2020.

When the economic recovery is initially seen as fairly probable ($p = 0.5$), the European energy system prepares itself relatively well. This enables continued banking of emissions permits in 2020, with the permit price rising at the interest rate between 2020 and 2025. In fact, when $p = 0.5$, all OECD regions bank emissions permits, which, by backward induction (through the Hotelling rule) from a single global emissions-permit price in 2025, leads to a convergence of CO₂ prices in the various regional markets from 2015 onwards.
2.3.3 Technological trajectories

Figure 2.7 shows the world installed capacities for each power technology in the R2015 branch when economic recovery is either perfectly ($p = 1$), or badly ($p = 0.2$) anticipated. Figure 2.8 shows the installed capacities in the NR branch when non-recovery is perfectly ($p = 0$) or badly ($p = 0.8$) anticipated. In all cases, the development of the global electric system is fairly similar during the initial periods. The regional emissions targets are so ambitious that, regardless of anticipations on economic growth, the constraints limiting the expansion of some renewables are binding from the earliest periods (so as to enable subsequent large-scale deployment). From 2030, hydropower stagnates due to exogenous availability constraints. The share of nuclear in power generation capacity increases from 9% in 2005 to between 11% and 16% in 2045. The steep rise in gas-fired capacity between periods 2005 and 2010 is mainly explained by the substitution of gas for coal in OECD regions so as to limit their emissions. At the same time, the rise in coal-based production capacity is driven by non-OECD regions (which are not yet subject to emissions constraints). Fossil-fuel-based capacities without CCS decrease from 2015, i.e. when renewables, especially wind and biomass, have reached sufficient size to
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Figure 2.6: CO₂ price in the European Union in deterministic and $p = 0.8$ scenarios expand widely. The R2015 and NR branches diverge significantly from 2030 onwards, especially for nuclear, renewables and CCS.

The relatively low installed CCS capacity inaccurately reflects the significant role of CCS in the energy mix from 2025 onwards, because of its high load factor of 85% (especially relative to 18-40% for wind) as shown in Table 2.1. Furthermore, as illustrated by Figures 2.9 to 2.11, the deployment of CCS is highly sensitive both to the path actually followed by growth and to agents’ initial anticipations. In the scenario where recovery and non recovery in 2015 are equally probable ($p = 0.5$), the installed CCS capacity is 165 GW in 2025. This capacity is only 106 GW when non-recovery has been perfectly anticipated ($p = 0$). This sensitivity of CCS deployment to anticipations on economic growth is in particular due to its time-to-build of two periods.
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Figure 2.7: World power production capacity in the R2015 branch for \( p = 1 \) and \( p = 0.2 \).

Figure 2.8: World power production capacity in the NR branch for \( p = 0 \) and \( p = 0.8 \).
2.3. RESULTS AND INTERPRETATION

Figure 2.9: World power generation capacity with CCS in the deterministic and $p = 0.5$ scenarios

Figure 2.10: World power generation capacity with CCS in the deterministic and $p = 0.5$ scenarios
Finally, the adaptation of the energy mix results not only from investment in low-CO₂ technologies, but also from adjusting the use of existing fossil-fuel-based capacities. In the first periods, this latter mechanism is a decisive factor in the sensitivity of CO₂ prices to anticipations on economic growth. It also largely explains the electricity prices yielded by the model.

2.3.4 Marginal technologies and electricity prices

Electricity prices in the European Union are shown in Figure 2.12 for the various stochastic scenarios considered. Figure 2.12 also indicates the marginal technology in each period, i.e. the technology whose short-run marginal cost of production is equal to the price of electricity. This short-run marginal cost takes account of variable operating costs, including fuel and CO₂ emissions permits. The marginal technology is characterized by partial use of available capacity.

In some cases, this short-run marginal cost is degenerate, with a left-hand short-run marginal cost (corresponding to the technology used to produce the last kWh and whose production capacity is fully used) and a right-hand short-run marginal cost (corresponding to the technology currently not used, but which would be used to produce one additional kWh). The price of electricity given by the model therefore falls between these two marginal costs, with the
corresponding symbols being represented side by side in Figure 2.12. Agents in the model base their decisions on this price that, at equilibrium, ensures the clearing of the power market.

The sequence of marginal technologies demonstrates that the various types of CO\textsubscript{2} emitting technologies are successively abandoned as the emissions-permit price rises. In general, from 2010 to (in some branches) 2025, remaining coal-fired power plants are only partially used. Subsequently, these plants are no longer used, with remaining gas-fired plants then representing the marginal technology. After that, from 2030 (2025 in the R2015 branch of the scenario \(p=0.2\)), with remaining gas-fired plants no longer being used, electricity-production adjustment occurs through the use of new gas-fired capacities (even though this was installed after 2010). From 2040, or even 2035, the new gas-fired plants are no longer in use. Renewables and nuclear, with a low short-run marginal cost, are used at full capacity (a situation denoted by a cross and a circle side by side in Figure 2.12). In the case of an absence of economic recovery that has been correctly anticipated \((p = 0, 0.2)\), the abandonment of the technologies based on fossil fuels occurs earlier (2035 instead of 2040). This is in particular due to lower investment in the final sector leading to lower demand for electricity in 2035. The achievement of a mix of power-generation technologies emitting little or no CO\textsubscript{2} is therefore not contingent upon the realization - or the anticipation - of strong economic growth. On the contrary, strong growth may, by driving up energy demand, cause standard fossil-fuel-based capacities to be used for a longer time. As we can see from Figure 2.12, the stronger the economic growth, the higher the electricity price.
Figure 2.12: Trajectories of electricity price in the European Union in the various scenarios
Moreover, incorrect anticipations of economic growth may lead to situations of over- or under-investment, possibly with a strong impact on the electricity price. A poorly anticipated economic recovery in 2015 ($p = 0.2$ and, to a lesser extent, $p = 0.5$) leads to an abrupt rise in the price of electricity in 2020 (up to $98$ per MWh). Inadequate investment in new gas-fired plants and renewables requires the use of some old coal-fired power plants whose short-run marginal production cost is extremely high because of the CO$_2$ price. The electricity price subsequently decreases, as investments in renewables enable the further use of the old coal-fired plants to be avoided. In the $p = 0.2$ scenario, even old gas-fired plants are abandoned through the combined effect of high gas and CO$_2$ prices. In this way we move directly from a price in 2020 set by the short-run marginal cost of remaining coal-fired plants to a price in 2025 set by the short-run marginal cost of new gas-fired plants.

Conversely, a strongly-anticipated recovery that does not take place may give rise to an overinvestment situation: anticipating (wrongly) an economic recovery leads to premature investments in gas and renewables. As this recovery does not happen, the gas-fired capacities are sufficient to allow the remaining coal-fired power plants to be abandoned, as we observe in 2020 in the NR branch of the $p = 0.8$ scenario. As a result of the low CO$_2$ and gas prices in this branch (see Figures 2.4 to 2.6 and Figure 2.13), the electricity price drops to a particularly low level.

### 2.4 Conclusion

Both economic-growth path realized and agents’ initial anticipations strongly influence the CO$_2$ price. Thus, in 2040, the global price of CO$_2$ may range from
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$21 \text{ (when an initially-anticipated economic recovery never occurs)} \text{ to } $128 \text{ (in case of non-anticipated rapid economic recovery).}

A rapid and poorly-anticipated economic recovery may cause an abrupt (but transient) rise in the CO$_2$ price because of an insufficient number of banked permits and, to a lesser degree, unsuitable technologies.

The case of no economic recovery whereas a rapid upturn had been considered possible is ambiguous. The uncertainty in this case has two opposite effects on the CO$_2$ price: the existence of a stock of emissions permits previously banked in anticipation of a possible rapid economic recovery which in the end did not take place, and the need for a sufficient stock of banked permits in anticipation of a possible future recovery. As time goes by, the effect of past banking becomes preponderant, which leads in the long term to very low CO$_2$ price levels.

During the initial periods of the model, the differences in the quantities of emissions permits banked observed between the different scenarios result principally from adjustments in the use of existing fossil-fuel-based capacities. Anticipating economic recovery (and therefore higher CO$_2$ prices) as being probable speeds decommissioning, first of remaining coal-fired power plants, then of remaining gas-fired power plants, and finally of more recent gas-fired power plants. Additionally, the deployment of CCS technologies is especially sensitive to anticipations.

Beyond the role of uncertainty, an important feature of the energy transition is that the power prices tend to slightly decrease on the long run, whereas the energy mix becomes cleaner and one have to rely on renewable technologies that might be expected to be more costly. In order to explain this results, it is important to take the point of view on the investor and to wonder whether the model’s results are compatible with the usual criteria of expected VAN maximization.
Chapter 3

Endogenous generation costs

3.1 Introduction

In the previous chapter, the enforcement of the global carbon policy (a 25% emissions reduction in 2050 w.r.t. 2005) leads to a decarbonization of the electric sector, while power prices do not necessarily increase on the long run. In the case of Europe (Figure 2.12), prices tend to be slightly lower in 2050 than in 2005. In the context of a decarbonized electricity system, power is supplied by nuclear and renewable technologies, which typically have a very low short-run marginal cost and which are operated at full capacity. The price of electricity should represent the long-run marginal cost of these technologies.

However, this explanation of price formation though the long-run marginal costs is relevant only if the model represents a perfect competition equilibrium on the power market, i.e. a situation where various agents seize investment opportunities until the net marginal gain of investing in a new projet is equal to zero.

This chapter questions the consistency of the results presented in Chapter 2 with private agents behavior. In the model of Chapter 2, the power market is not perfectly competitive. Some constraints on the regional technology portfolios are used to represent a coherent evolution of the energy markets and to rule out unlikely technological trajectories. If taking the case of wind technologies, their operation and development is submitted to three constraints: (i) a maximum capacity expansion rates, (ii) market-share constraints and (iii) a required minimum of 10% of fossil-fuel based technologies in the total installed capacity.

The general equilibrium provides a first-best solution, i.e. an outcome that
maximizes regional welfare. These constraints are internalized in the welfare maximization problem and therefore they are internalized in the electric sector cost minimization problem. However, if taking a decentralized perspective where small agents compete in the power market, these constraints must be regarded both as a rationing and an externality. They represent a rationing because they limit the technology deployment. But the rationing can be relaxed as a result of other agents increasing their capacity or production. Therefore, the investment and production decisions of an agent affect the feasibility of other producer’s decisions.

In the presence of externalities, the outcome of a competitive equilibrium does not necessarily correspond to a welfare maximization. For instance, if the market share of wind is at its maximum, the development of non-wind technologies by a producer will relax the constraint on wind market share, making possible for other producers to invest in wind technologies. However, a priori, the effect on welfare of relaxing the constraints is not taken into account by the price system, and the energy mix might not correspond to the first-best solution.

A means to restore the first-best solution is to impose a system of taxes and subsidies to coordinate decentralized agents behaviors toward the welfare maximizing solution. These taxes and subsidies can be computed from the welfare maximization problem. Therefore, the model’s results can give us elements of public policies for the energy sector.

In this chapter, we focus on maximum capacity expansion rates and market-share constraints for wind technologies. Wind technologies draw our attention as they play an important part in the decarbonized energy mix obtained on the long run. The constraint about minimum fossil-fuel technology requirement is put aside for simplicity and because it is binding quite late in the model (not before 2045). We restrict the analytical approach to the deterministic cases, although, in practice we show results from stochastic scenarios. Considering the power market only, we show that the existence of constraints limiting the expansion of each power-generation technology is equivalent to rendering endogenous the price paid by the power utility for the acquisition of additional production capacity. In addition, we show how market share limitations for the renewable technologies can be interpreted in terms of additional grid connection costs.

Section 3.2 stresses that the result of a total profit maximization problem with portfolio constraints is not an equilibrium if agents are atomistic and take their investment decisions on the basis of exogenous costs (as those presented in Table 2.1). Then, section 3.3 gives a formula for computing the endogenous costs such that the equilibrium property is restored. Endogenous costs of wind technologies computed from the numerical results of Chapter 2 are presented.
3.2. EFFECT OF THE TECHNOLOGY PORTFOLIO CONSTRAINTS

and discussed in section 3.4. The last section concludes.

3.2 Effect of the technology portfolio constraints

3.2.1 Problem without portfolio constraints

We consider an electricity market where, as in Chapter 2, producers make capacity expansion and production choices. However, we put aside the maximum expansion rate and the market share constraints that are included in the model of Chapter 2.

The equilibrium on the power market can be represented as a problem of total profit maximization:

$$\max \sum_{t=1}^{T} \beta_t \left[ \sum_j (p_t - c v_{j,t}) e_{j,t} - \sum_j c_{j,t} i_{j,t-1} \right]$$

s.t: $e_{j,t} \leq k_{j,t}$ \hspace{1cm} ($\gamma_{j,t}$) \hspace{1cm} (3.1)

$k_{j,t+1} \leq i_{j,t} + k_{j,t}(1 - d)$ \hspace{1cm} ($\lambda_{j,t+1}$) \hspace{1cm} (3.2)

$k_{j,0} = \bar{k}_{j,0}$ \hspace{1cm} (3.3)

The installed capacity of technology $j$ is noted $k_j$ and the electricity generated with technology $j$ is noted $e_j$. The investment in new capacity of technology $j$ is noted $i_j$. The price of electricity is given by $p$. We note with $\beta$ the private discount factors, i.e. the discount factor based on the interest rate of the economy obtained at the general equilibrium. Parameters $c$ and $cv$ denote respectively technology-specific investment and short-run marginal costs. The investment costs have been given in Table 2.1. The short-run marginal cost includes fuel, CO$_2$ emission allowance expenditures and variable operation and maintenance costs. Note that from the point of view of a price taking firm, this short-term marginal cost is exogenous.

The capacity constraint is given by equation (3.1) and the dynamics of the capacity for a given technology is described by (3.2). Parameter $d$ represents a rate of decay. The initial capacity is specified by (3.3).

If writing the optimality conditions corresponding to the total profit maximization problem, we obtain the following mixed complementarity problem

---

$^1$Note that for simplicity we omit to precise in the equations that all the primal variables are submitted to positivity constraints
(MCP) noted $P_1$:

\[
\begin{align*}
\gamma_{j,T} - \lambda_{j,T} & \leq 0 \quad k\geq 0 \\
\gamma_{j,t} + \lambda_{j,t+1}(1-d) - \lambda_{j,t} & \leq 0 \quad k\geq 0 \quad t \leq T-1 \\
\beta_t(p_t - cv_{j,t}) - \gamma_{j,t} & \leq 0 \quad e_{j,t} \geq 0 \quad t \leq T \\
\lambda_{j,T} - \beta_{j+1}e_{j,T} & \leq 0 \quad i_{j,T-1} \geq 0 \\
\lambda_{j,t} - \beta_{t+1}c_{j,t} & \leq 0 \quad i_{j,t-1} \geq 0 \quad t \leq T-1 \\
e_{j,t} & \leq k_{j,t} \quad \gamma_{j,t} \geq 0 \\
k_{j,t+1} & \leq i_{j,t} + k_{j,t}(1-d) \quad \lambda_{j,t+1} \geq 0 
\end{align*}
\]

We consider specifically the case of a technology $j$ with a positive base-year capacity ($\bar{k}_j > 0$). Because of the geometrical scrapping, and $i_{j,t} \geq 0$, ($i_{j} \geq 0$) there is always a strictly positive capacity of technology ($k_{j,t} > 0$).

In addition, we assume that production with technology $j$ is always positive ($e_{j,t} > 0$). This assumption is particularly adapted for wind technologies, since they typically have a very low short-run marginal cost and tend to be operated as soon as they are available. With these additional assumptions, the first five conditions of the MCP problem can be rewritten as to form a subproblem $P_s(c, cv)$:

\[
\begin{align*}
\beta_t(p_t - cv_{j,t}) - \lambda_{j,T} & = 0 \\
\beta_t(p_t - cv_{j,t}) + \lambda_{j,t+1}(1-d) - \lambda_{j,t} & = 0 \quad t \leq T-1 \\
\beta_t(p_t - cv_{j,t}) & = \gamma_{j,t} \quad t \leq T \\
\lambda_{j,T} - \beta_{j+1}e_{j,T} & \leq 0 \quad i_{j,T-1} \geq 0 \\
\lambda_{j,t} - \beta_{t+1}c_{j,t} & \leq 0 \quad i_{j,t-1} \geq 0 \quad t \leq T-1 
\end{align*}
\]

From these conditions, the capacity of the technology $j$ considered increases ($i_{j,t-1} > 0$) when:

\[
\beta_t c_{j,t} = \sum_{t' \geq t} \gamma_{j,t'} \quad t \leq T-1 \quad (3.4)
\]

If taking into account the complementarity condition for $\gamma_{j,t}$ we can get a more explicit expression for condition (3.4):

\[
\text{MNPV}_{j,t}(c_j, cv_j) \equiv -c_{j,t} + \sum_{t' \geq t} \frac{\beta_{t'}}{\beta_t} (p_{t'} - cv_{j,t'})1_{\{\gamma_{j,t'} > 0\}} = 0 \quad (3.5)
\]

Condition (3.5) simply states that at equilibrium the marginal net present value MNPV$_{j,t}$ of a project must be equal to 0. The left-hand term of MNPV$_{j,t}$ is the marginal investment cost for technology $j$ at period $t$. The right-hand term is anticipated net present sum of the marginal cash flows. The discount rates
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used is the anticipated discount rate. Positive cash flows appear only when
a binding capacity constraint allows for a differential between the short-run
marginal cost and the market price of electricity.

Criteria 3.5 ensures the computed equilibrium can be decentralized. From
the point of view of an atomistic energy producer, a positive MNPV \( j,t \)
corresponds to a situation where there is an arbitrage opportunity on a project with
technology \( j \). An investment yielding with certainty a higher rate of return
than the interest rate of the economy is not realized. This situation creates an
incentive for implementing new projects with technology \( j \). Then, the projects
implementation drives down the MNPV \( j,t \), until the marginal benefit of any
new project is equal to zero. Conversely, if MNPV \( j,t \) is negative, there is an
incentive to revise the investment plan and to cancel projects for the technology
\( j \), until MNPV \( j,t \) is equal to zero.

3.2.2 Problem with portfolio constraints

The electricity submodel of Chapter 2 includes constraints on the regional energy portfolio. These constraints represent a rationing in the use of the energy technologies.

First, there are constraints about the maximum expansion rate of the generation capacity for a given technology:

\[
\frac{1}{k_{j,t} + 1} \leq \frac{k_{j,t}(1 + g_j)}{(1 + g_j)}
\]

(3.6)
The installed capacity with technology \( j \) cannot increase at an annual rate higher than \( g_j \). This constraint is used to avoid unlikely and dramatic penetration of some technologies resulting from a change in policy.

Second, the model imposes market-share constraints:

\[
e_{j,t} \leq m_s j \sum_{j'} e_{j',t}
\]

(3.7)
The share of a given power generation technology \( j \) is limited to a fraction \( m_s j \) of the total power supply. The limitation is first of all devoted to rule out a power generation portfolio where the shares of renewable technologies, in particular wind technologies, would be unmanageable for the power system. Indeed, there is a lot of uncertainty about the market share regarded as manageable. For wind, we have chosen 33%.

These constraints concern the entire energy mix. In a decentralized framework, they can be regarded as common constraints that restrict the action set
of the players of the energy market. For example, it is impossible to produce with wind capacities if the maximum market share has been reached by the production of the other agents. Therefore, these constraints, when they are binding, create externalities. Because, of the externalities, the general total profit-maximization does not correspond to the decentralized equilibrium.

The model of Chapter 2 corresponds to a situation of total profit maximization. At the optimum of social welfare in each region, the optimality conditions of the model can be interpreted as if a single power utility - acting as price taker and providing all electricity production in the region - were to maximize its value while taking into account the constraints limiting the expansion rate of each technology and the market shares constraints.

In each regions, the single power utility problem is:

\[
\begin{align*}
\text{max} & \quad \sum_{t=1}^{T} \beta_t \left[ \sum_j (p_t - cv_{j,t})e_{j,t} - \sum_j c_{j,t} \right] \\
\text{s.t.} & \quad e_{j,t} \leq k_{j,t} \\
& \quad k_{j,t+1} \leq i_{j,t} + k_{j,t}(1 - d) \\
& \quad e_{j,t} \leq \sum_{j'} s_{j} e_{j',t} \\
& \quad k_{j,t+1} \leq k_{j,t}(1 + g_j)
\end{align*}
\]

The market share and the maximum expansion constraints are internalized in the profit-maximization problem. The optimum of this problem corresponds to the optimal management of the portfolio constraints.

If writing the corresponding optimality conditions we obtain the following MCP problem noted \( P_2 \)

\[
\begin{align*}
\gamma_{j,t} - \lambda_{j,t} - \alpha_{j,t} & \leq 0 & \perp k_{j,t} \geq 0 \\
\gamma_{j,t} + \lambda_{j,t+1}(1 - d) - \lambda_{j,t} + \alpha_{j,t+1}(1 + g_j) - \alpha_{j,t} & \leq 0 & \perp k_{j,t} \geq 0 & t \leq T - 1 \\
\beta_t (p_t - cv_{j,t}) - \gamma_{j,t} - \eta_{j,t} + \sum_{j'} ms_{j} \eta_{j'} & \leq 0 & \perp e_{j,t} \geq 0 & t \leq T \\
\lambda_{j,T} - \beta_T c_{j,T} & \leq 0 & \perp i_{j,T-1} \geq 0 \\
\lambda_{j,t+1} - \beta_{t+1} c_{j,t+1} & \leq 0 & \perp i_{j,t} \geq 0 & t \leq T - 1 \\
e_{j,t} & \leq k_{j,t} & \perp \gamma_{j,t} \geq 0 & \quad (3.8) \\
k_{j,t+1} \leq i_{j,t} + k_{j,t}(1 - d) & \leq \lambda_{j,t+1} & \geq 0 & \quad (3.9) \\
e_{j,t} & \leq \sum_{j'} ms_{j} e_{j'} & \perp \eta_{j,t} \geq 0 & \quad (3.10) \\
k_{j,t+1} \leq k_{j,t}(1 + g_j) & \leq \alpha_{j,t+1} & \geq 0 & \quad (3.11)
\end{align*}
\]

Problem \( P_2 \) is a priori different from problem \( P_1 \) (no portfolio constraint). Nevertheless, as soon as the expansion rate and market share constraints are not
binding (i.e. if $\eta = \alpha = 0$), the two problems share the same optimal investment, capacity and production. But in the case of the results of Chapter 2, both of these constraints are occasionally binding. Therefore in this case, the model results do not match with $P_1$.

In particular, the marginal NPV as computed with formula 3.5 are unlikely to be equal to zero at the equilibrium in Chapter 2. The portfolio constraints lead to differences in the rate of return for the various investment projects. The results are not compatible with the marginal NPV criteria for investment decisions. The result of the profit maximization problem is not a decentralized economic equilibrium, since agents would have incentives to revise their investment decision.

### 3.3. Endogenous power-generation costs

However, it is possible to internalize the portfolio constraints in the costs of the technologies and to obtain costs such that the profit maximization problem is a decentralized equilibrium, i.e compatible with a marginal net present value equal to zero.

#### 3.3.1 Computation

To compute these new costs, we simplify the five first conditions of $P_2$ using, as in the previous section, the conditions ($k_i > 0$) and ($c_{j,t} \geq 0$). We obtain:

\[
\begin{align*}
\gamma_{j,T} - \lambda_{j,T} - \alpha_{j,T} &= 0 \\
\gamma_{j,t} + \lambda_{j,t+1}(1 - d) - \lambda_{j,t} + \alpha_{j,t+1}(1 + g_j) - \alpha_{j,t} &= 0 \\
\beta_t(p_t - cv_{j,t}) - \eta_{j,t} + \sum_{j'} ms_{j'}\eta_{j'} &= \gamma_{j,t} \quad t \leq T \\
\lambda_{j,T} - \beta_T c_{j,T} &\leq 0 \quad i_{j,T-1} \geq 0 \\
\lambda_{j,t} - \beta_t c_{j,t+1} &\leq 0 \quad i_{j,t-1} \geq 0 \quad t \leq T - 1
\end{align*}
\]
CHAPTER 3. ENDOGENOUS GENERATION COSTS

This problem can be re-written as:

\[ \beta_T (p_T - cv_{j,T}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',T} - \lambda_{j,T} = 0 \]
\[ \beta_t (p_t - cv_{j,t}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',t} + \lambda_{j,t+1} (1 - d) - \lambda_{j,t} + \alpha_{j,t+1} (1 + g_j) - \alpha_{j,t} = 0 \]
\[ \beta_T (p_T - cv_{j,T}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',T} - \lambda_{j,T} = 0 \]
\[ \beta_t (p_t - cv_{j,t}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',t} + \lambda_{j,t+1} (1 - d) - \lambda_{j,t} + \alpha_{j,t+1} (1 + g_j) - \alpha_{j,t} = 0 \]

These conditions can be re-written so as to form a subproblem \( \mathcal{P}_s(\tilde{c}, \tilde{cv}) \):

\[ \begin{align*}
\beta_t (p_t - \tilde{cv}_{j,t}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',t} + \lambda_{j,t+1} (1 - d) - \lambda_{j,t} + \alpha_{j,t+1} (1 + g_j) - \alpha_{j,t} & = 0 \\
\beta_t (p_t - \tilde{cv}_{j,t}) - \gamma_j - \eta_j + \sum_{j'} ms_{j'} \eta_{j',t} + \lambda_{j,t+1} (1 - d) - \lambda_{j,t} + \alpha_{j,t+1} (1 + g_j) - \alpha_{j,t} & = 0 \\
\lambda_{j,t} - \beta_{t+1} c_{j,t} & \leq 0 \\
\lambda_{j,t} - \beta_{t+1} c_{j,t} & \leq 0 \\
\end{align*} \]

With \( \tilde{c} \) and \( \tilde{cv} \) defined as:

\[ \tilde{c}_{j,t} = c_{j,t} + \frac{\alpha_{j,t} - (1 + g_j) \alpha_{j,t+1} + \beta_{t+1} \ell_{j,t}}{\beta_t} \] (3.12)
\[ \tilde{cv}_{t} = cv_{j,t} + \frac{\eta_{j,t} - \sum_{j'} \eta_{j',t}}{\beta_t} \] (3.13)

And \( \ell_{j,t} \) being obtained by the backward recurrence relation:

\[ \ell_{j,t} = \begin{cases} 
\frac{\alpha_t - (1 + g_j) \alpha_{j,t+1}}{\alpha_t} + (1 - d) \frac{\beta_t \ell_{j,t+1}}{\beta_t} & , t \leq T - 1 \\
\frac{\alpha_t - (1 + g_j) \alpha_{j,t+1}}{\beta_t} & , t = T
\end{cases} \] (3.14)

Using the same reasoning as in section 3.2.1, we can deduce from \( \mathcal{P}_s(\tilde{c}, \tilde{cv}) \) that:

\[ \text{MNPV}_{j,t}(\tilde{c}_j, \tilde{cv}_j) \equiv -\tilde{c}_{j,t} + \sum_{t' \geq t} \frac{\beta_{t'}}{\beta_t} (p_{t'} - \tilde{cv}_{j,t'}) 1_{\{\gamma_{j,t'} > 0\}} = 0 \] (3.15)

Using the dual variables resulting from a centralized model with portfolio constraints, we can compute with formula (3.12-3.14) costs \( (\tilde{c}, \tilde{cv}) \) that solve the decentralized equilibrium problem with no portfolio constraints. These cost are such that if they are considered by agents that make their investment decision, there is no incentive to deviate from the computed equilibrium with portfolio
3.3. ENDOGENOUS POWER-GENERATION COSTS

In practice, it is possible to use the dual variables obtained in the model of Chapter 2 to compute endogenous costs for the technologies that are compatible with private agents’ behaviors. We call these costs “endogenous”, as they differ from those used for the model calibration (see 2.1).

3.3.2 Interpretation of the endogenous costs

These portfolio constraints ration the use of the energy technologies. The endogenous costs represent the cost for the technologies such that their rationing is implemented without being enforced by specific constraints. We can be explicit by considering the wind technologies.

3.3.3 Endogenous investment costs

The endogenous investment cost $\tilde{c}_{j,t}$ may be interpreted as the price actually paid (to the equipment manufacturer) by the power utility for installing an additional unit of capacity. Equation (3.12) shows that the price is equal to the exogenous investment cost $c_{j,t}$ adjusted for the dual variables associated with the expansion constraints (Equations 3.14). This investment-cost adjustment may be interpreted as resulting from tensions between demand for additional capacity (from the power utility) and supply of new capacity (by the technological sector under consideration). From an economic point of view, the expansion constraints generate an inelasticity of supply (through bottlenecks) by the technological sector. At equilibrium, this can lead to a rise in the price paid by the power utility for the acquisition of new production capacity.

An interesting feature of the expansion rate constraints is that the level of investment rationing on a given period depends on the previous investment decisions. In particular, the welfare loss due to the impossibility of developing capacity beyond the maximum expansion rate can be offset by more investment in the previous periods. As the model maximizes welfare, it will take into account this possibility when choosing the investment capacity. In case of anticipated increase of CO$_2$ prices, it can be optimal to incur losses on the early phases of the deployment of wind technologies in order to relax the maximum expansion constraints in the following periods, when high CO$_2$ constraints require large development of wind capacities. In this case, during the early periods, the investment cost of wind technologies is lower than the exogenous cost. This can be regarded as a situation where public subsidies must be used to develop a nascent wind industry.
3.3.4 Endogenous short-run marginal costs

The endogenous short-run marginal cost may be interpreted as the price actually paid to the system operator by the power utility for providing additional quantities of wind generated power to the grid. Equation (3.13) shows that this price is equal to the exogenous short-run marginal cost adjusted for the dual variables associated with the market-share constraints. This investment-cost adjustment may be interpreted as resulting from the difficulties of keeping the meeting the grid stability requirement with a large supply of intermittent power generation. More precisely, the grid cannot be operated with more than 33% of generation from wind, and exogenous short-run marginal cost is adjusted by the system operator in order not to pass this threshold. Nowadays, indeed, the situation is the opposite in most of the grid. The renewable technology generation is encouraged, in particular through renewable portfolio standards. This situation would correspond to a minimum market share constraints. The model of Chapter 2 might yield for wind technologies an endogenous short-run marginal cost lower than the exogenous short-run marginal cost. In addition, we note that the model is run on a very long horizon. Market share constraints are reached a few decades after the base-year, when the wind capacity is massive. The question of the system cost for integrating massive power generation from renewable is still very uncertain.
3.4 Computed endogenous costs

Endogenous investment costs are computed from the model of chapter 2 on the basis of the dual variables supporting the general equilibrium optimum.

3.4.1 Computed endogenous short-run marginal costs

Figures 3.4 to 3.6 show the endogenous short-run marginal costs of wind onshore and wind offshore technologies in the European Union, North America and China. In each region and for each technology, the maximum market share of wind technologies is 33%. The cost of connection to grid is the bulk of the short-run marginal cost of the wind technology. This cost of connection intervenes as soon as the market share constraint is binding for the wind technologies. The endogenous costs have a peak at the time the market share is binding, then it decreases, as other technologies, including nuclear are more available on the grid. We see that the peaks of endogenous costs intervene earlier in European Union and North America, where medium run emission reduction policy led to early development of renewable than in China.
CHAPTER 3. ENDOGENOUS GENERATION COSTS

3.4.2 Computed endogenous investment costs

Figures 3.1 to 3.3 show the endogenous investment costs of wind onshore and wind offshore technologies in the European Union, North America and China. In each region and for each technology, the maximum annual growth rate in installed capacity is 10%. The endogenous investment cost is higher than the exogenous investment cost until 2025 in Europe and until 2030 in North America. During this lapse of time, the growth in demand for electricity, especially carbon-free electricity, comes up against bottlenecks in the supply of new capacities using these two technologies. After 2030, the expansion constraints have no further effects, because of the maturity of both technological sectors and - in a context of low growth in electricity demand - the limitation on the market share of wind power. In the European Union, where growth in demand for electricity is lower, the constraint on market share of wind becomes binding sooner than in North America. The endogenous investment cost - highly sensitive to the path followed by economic growth in North America - depends only very slightly on initial anticipations.

In China, the curves of endogenous investment costs are all bubble-shaped\(^2\) centered on 2025, a period which corresponds to this region’s entry to the global

\(^2\)By analogy, in North America and the European Union (regions subject to an emissions-permit market right from the first periods), the endogenous investment costs curves may be seen as bubbles truncated on the left.

Figure 3.3: Endogenous investment costs of wind onshore and wind offshore technologies in China in scenarios \(p = 0, 0.5, 1\).
emissions-permit market. The bottleneck in the wind equipment sectors is very significant at that date. In a context of steeply rising demand for electricity, the price of acquiring production capacity is relatively sensitive to the path of economic growth followed, and, to some extent, to agents’ initial anticipations. Interestingly, in 2015 the endogenous investment cost for wind offshore is lower than the exogenous cost. This is the result of internalizing the expansion constraints for the wind technology. The Chinese power sector anticipated the decarbonization and the bottleneck that could slowdown the diffusions of wind technologies. Therefore, a decision to invest in wind technologies is taken in order to accelerate the maturity of the offshore wind generation industry and to avoid the bottlenecks. The investment costs considered from the point of view of a power-sector planner are net of the positive effect of investments on developing the industry.

There can be alternative but equivalent interpretation, depending on the interpretation given to the centralized power market problem. If considering a market for wind offshore equipment, we can say that in the model, Chinese manufacturers therefore agree to sell below construction cost temporarily, so as to develop manufacturing capacity and produce more equipment subsequently (when the endogenous investment cost is considerably higher than the exogenous cost). Another interpretation is that, from a social point of view, the Chinese authorities should subsidize the wind offshore sector in 2015.

Finally, the model’s results suggest two elements that will successively have inflationary impact on wind generation. On the medium run the cost is driven up by the bottlenecks in the equipment industry. Then, once they have largely penetrated, the cost increase is due to the difficulty of integrating large-scale of renewable.

3.5 Conclusion

In the electricity sector, the model used in Chapter 2 internalizes the constraints limiting the expansion rate and the market share of each technology into the price paid by the power utility for purchasing additional production capacities and for connecting to the grid. This interpretation is very useful for understanding the results presented in Chapter 2. The trajectories for the electricity price in the EU can be interpreted as resulting from the penetration of renewable technologies. In a first movement, the cost of renewable is driven up by the bottleneck in the equipment industry. Once the bottleneck problem is solved and the equipment industry is mature, the issue is the cost of the grid connection. As large amounts of renewable are available, some tariff measures are taken to limit the market share of wind technologies to a manageable level.
CHAPTER 3. ENDOGENOUS GENERATION COSTS

Figure 3.4: Endogenous short-run marginal costs of wind onshore and wind offshore technologies in the European Union in scenarios $p = 0, 0.5, 1$.

Figure 3.5: Endogenous variable costs of wind onshore and wind offshore technologies in North America in scenarios $p = 0, 0.5, 1$. 
Figure 3.6: Endogenous variable costs of wind onshore and wind offshore technologies in China in scenarios $p = 0, 0.5, 1$. 

3.5. CONCLUSION
Chapter 4

Dynamic CGE calibration and benchmark scenarios

4.1 Introduction

Applied general equilibrium models are widespread tools for policy analysis. In particular, dynamic versions of these models are used to simulate the impact of environmental regulation on economic activity [Manne et al., 1995, Leimbach et al., 2010, Bosetti et al., 2006, Nordhaus and Boyer, 1999]. These models are bound to rely on univocal assumptions made during the process of their calibration. First, they contain several elasticity parameters that are not necessarily scientifically estimated. Second, they are based on the numerical specification of the several scaling factors used in the macroeconomic functions representing technologies and preferences. In this chapter and in the following we focus on the impact of the choice of scaling factors. We stress that the choice of scaling factors represents the modeler’s view on the future of the economy and influences the result of policy analysis. This view is embedded in benchmark scenarios that can be non-stationary. We will illustrate the dependence of the policy outcomes on the benchmark scenario in chapter 5 through a dynamic model of the French economy. But the construction of alternative benchmark scenarios is a real challenge and that is the reason why we decided to devote the present chapter to this topic.

For an easier analytical presentation, we consider the class of dynamic Computable General Equilibrium models (CGE) with CES production functions, logarithmic inter-temporal utility functions and non-zero prices and quantities. However, what is said in this chapter is also largely relevant for most of the dynamic Applied General Equilibrium models.
CHAPTER 4. DYNAMIC CGE CALIBRATION AND BENCHMARK SCENARIOS

To understand the role of the scaling factors in dynamic CGE, we draw a parallel with static CGE, where the scaling factors are adjusted so that a benchmark data set is replicated at equilibrium. The benchmark is typically a social accounting matrix (SAM), i.e. a collection of observed transactions representing the structure of the economy at a point in time. Counterfactual (i.e. alternative) policy simulation is then used to assess the effect of a change in policy. This effect is indeed influenced by the structure of the economy represented in the SAM.

In dynamic CGE, the procedure is equivalent, although, realized backwardly. The scaling factors are adjusted so as to generate a dynamic data set, called "benchmark scenario" (we use the latter denomination in the remainder of the chapter). Then, alternative policies are simulated to assess their impact on the economy through time. Actually, the benchmark scenario is nothing more than a dynamic SAM, i.e. a dynamic version of the static SAM. It contains not only observed transactions representing the base-year structure of the economy, but also expected future transactions, that represent the expected structure of the economy. These expectations are generated by the modeler on the basis of what he regarded as relevant, by means of scaling-factors adjustments and general equilibrium computation.

From the static case example, we can interpret the meaning of counterfactual policy analysis with dynamic CGE. The result of a counterfactual policy is influenced by the expected structure of the economy contained in the dynamic SAM. Therefore, the question of the dependence between the policy evaluation and the expectations about the future of the economy can be studied by means of various alternative dynamic SAM. Exactly as the dependence of various national economies to a policy is evaluated on the basis of the various national SAM.

As we show in this chapter, translating the assumptions about the future into an inter-temporal social accounting matrix is a real challenge. SAM construction is based on value-preserving properties of transactions that are very difficult to satisfy as soon as the scenario is not a stationary path. In addition, the formulation of relevance conditions is a difficult task. Finally, dynamic benchmark scenarios have to be generated by means of computing general equilibria based on adjustments on the model’s scaling factors.

Section 1 introduces the notion of scaling factors and shows how their calibration in dynamic models is equivalent to the static procedure. In addition, we show the difficulties of ex nihilo construction of benchmark scenarios for dynamic CGE and how the modeler’s assumptions are only partially translated into the benchmark scenario. This section concludes with an analytical repre-
4.2 Scaling factors in dynamic CGE models

We consider the class of dynamic general equilibrium models where (i) there is no inequality constraint, (ii) zero price and zero quantities are ruled out at equilibrium\(^1\), (iii) the production functions are CES and (iv) there is a representative household whose inter-temporal utility function is logarithmic.

We define \(V\) as the concatenation of variables representing quantities, prices and household revenues.

The general equilibrium conditions can be represented by a system of equations\(^2\) linking a vector \(V\) to a policy instrument vector \(\tau\) (e.g. a tax rate):

\[
H(V, \tau, a, \Sigma) = 0 \quad (4.1)
\]

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

To give a concrete view of what the scaling factors are, we consider a model with \(T\) time periods. We note \(N\) the set of production sectors (industries) and \(J\) the set of commodities and factors used as inputs.

If the technologies are CES, they can be represented as:

\[
Z_{i,t} = \left[ \sum_k a_{i,k,t} Q_{i,k,t}^{\frac{\sigma_{i,k,t}}{\sigma_{i,k,t} - 1}} \right]^{\frac{1}{\sigma_{i,k,t} - 1}}, \quad i \in N, \quad k \in J \quad (4.2)
\]

\(^1\)The model respects the Inada conditions for utility and production functions.

\(^2\)We here consider that the general equilibrium is formulated in the Mixed Complementarity Problem (MCP) form proposed by Mathiesen [1985].

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

The Mathiesen MCP formulation allows for idle capacity (zero production) and zero prices. It is therefore fit to deal with problems where constraints are occasionally binding. In our model \(V > 0\) at equilibrium, therefore the solutions of the MCP and the SNE (\(H=0\)) are equivalent.
Where $Z_{i,t}$ is sector $i$ output and $Q_{i,k,t}$ is sector $i$ input of type $k$.

If the inter-temporal utility function is logarithmic, we have:

$$W = \sum_{t=1}^{T} \beta_t \log C_t$$  \hspace{1cm} (4.3)

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

$$a = (a_{k,j,t}, \beta_t)_{i \in N, k \in J, t \leq T}$$  \hspace{1cm} (4.4)

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

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

### 4.3 Calibration procedures

The calibration procedures used for CGE models are presented in Figure 4.1. The specific CGE calibration procedure concerns the scaling factors.

The solution that seems to be "most scientific" is an econometric estimation of the elasticity parameters and scaling factors; it corresponds to the first column. But with this approach several difficulties arise. First, there can be a lack of estimates for the scaling factors as specified in the CGE model structure. Econometric studies may have been based on different functional forms and levels of sectoral or regional aggregation. In addition, even if estimates are based on the CGE model structure, econometric models are not necessarily relevant for long-run projections. In effect on the long run, some variables can loose their explanatory power and new variables can become more relevant.

Because of these difficulties, CGE models calibration is based on a "reverse" method. The elasticity parameters are chosen \textit{a priori} from the literature, or
very often by the rule of thumb. A benchmark scenario, noted \((\bar{V}, \bar{\tau})\) is set \textit{a priori} and the scaling factors are adjusted so as to match with this scenario. Therefore, they are an implicit function of the reference scenario.

\[
a = a(\bar{\tau}, \bar{V}, \Sigma)
\] (4.5)

The scaling factors are computed so that the conditional input demands in the various industrial sectors and the Marshallian demand functions of the household replicate the benchmark. From equations (4.2) and (4.3), these functions are\(^3\):

\[
Q_{i,k,t} = a_{i,k,t}^{\sigma_i} \left( \frac{\pi_{i,t}}{\pi_{k,t}} \right)^{\sigma_i} \bar{Z}_{i,t}
\] (4.6)

\[
C_t = \beta_t M / \pi_t
\] (4.7)

Where \(\pi_i\) is the price of sector \(i\) output, \(\pi_k\) is the price of input \(k\), \(M\) is the present-value sum of household’s incomes and \(\pi_c\) is the present value price of the consumption good price at period \(t\). If assigning their benchmark values to the variables, we can easily identify the scaling factors:

\[
a_{i,k,t} = \left( \frac{\bar{\pi}_{k,t} Q_{i,k,t}}{\bar{\pi}_{i,t} \bar{Z}_{i,t}} \right) \left( \frac{\bar{Z}_{i,t}}{Q_{i,k,t}} \right)^{\frac{\sigma_i - 1}{\sigma_i}}, \quad \beta_t = \frac{\bar{\pi}_{c,t} C_t}{M}
\] (4.8)

Once the scaling factors are obtained, the general equilibrium is solved and a reference equilibrium is obtained.

This procedure is the cornerstone of the static CGE case. In this case, the reference scenario taken is in general a SAM. A SAM is a collection of observed transaction data \((V_0, \tau_0)\) that meet some accountability properties, known as Walrasian flows properties\(^4\) [Wing, 2004]. The Walrasian flows properties of the SAM ensure that they are replicated at equilibrium if there is no counterfactual policy (replication check).

\[
H(\bar{V}, \bar{\tau}, a(\bar{V}, \bar{\tau}, \Sigma), \Sigma) = 0
\] (4.9)

### 4.3.1 CGE calibration on a reference path

Dynamic calibration is based on the same intention of generating and replicating a benchmark data set \((\bar{V}_t, \bar{\tau}_t)\) that represents relevant future transactions, i.e., a relevant evolution of the structure of the economy. New difficulties arise

\(^3\)See Varian [1992].

\(^4\)These conditions are that the household’s revenue is equal to the value of its factor endowments, firms’ activities yield zero profits (the value of output must be equal to the value of inputs), demand equals supply for the various commodities.
CHAPTER 4. DYNAMIC CGE CALIBRATION AND BENCHMARK SCENARIOS

<table>
<thead>
<tr>
<th>Dynamic CGE (I)</th>
<th>Static CGE</th>
<th>Dynamic CGE (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Econometrically estimated $\Sigma$ and $\Sigma'$</td>
<td>Assumed or econometrically estimated values for $\Sigma$</td>
<td>Assumed future transactions $(\bar{V}_t, \bar{\tau}<em>t)</em>{t \leq T}$</td>
</tr>
<tr>
<td>$a_0 = a_0(V_0, \bar{\tau}_0)$</td>
<td>$a_0 = a_0(V_0, \bar{\tau}_0)$</td>
<td>$a_t = a_t(\bar{V}_t, \bar{\tau}_t)$</td>
</tr>
<tr>
<td>$(V_0^*, \bar{\tau}<em>0)</em>{t \leq T}$</td>
<td>$(V_0^*, \bar{\tau}<em>0)</em>{t \leq T}$</td>
<td>$(V_t^*, \bar{\tau}<em>t)</em>{t \leq T}$</td>
</tr>
<tr>
<td>Reference equilibrium</td>
<td>Reference equilibrium</td>
<td>Reference equilibrium</td>
</tr>
<tr>
<td>Response to policy shocks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1: Calibration of CGE models

when it comes to obtain reference paths that are both relevant and replicable. If defining $SC_{REP}$ and $SC_{REL}$ as the spaces of replicable and relevant scenarios, this is equivalent to searching $(\bar{V}, \bar{\tau})$ such that:

$$(\bar{V}, \bar{\tau}) \in SC_{REP} \cap SC_{REL}$$  (4.10)

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

4.3.2 Replicability

Replicability conditions are basically the extension of static Walrasian flows properties that characterize SAM to transactions involving inter-temporal flows of commodities and values, such as lending and borrowing behaviors. In other words, a dynamic replicable scenario is an inter-temporal SAM. The more inter-temporal constraints in the model, the most difficult the dynamic SAM construction is. In addition, unlike static SAM an inter-temporal SAM, must contain not only monetary values, but it has also to specify price system to disentangle real and nominal changes through time\(^5\).

\(^5\)In static model, real and nominal values can be regarded as equivalent, by setting arbitrarily the prices to 1.
Mathematically, the set of replicable scenario \( S_{REP} \) is defined as:

\[
SC_{REP} \equiv \{(\bar{V}, \bar{\tau}) \text{ such that } (\bar{V}, \bar{\tau}, a) \text{ solves } H(V, \tau, a, \Sigma) = 0, \text{ } a \text{ is free}\} \tag{4.11}
\]

If the parameter \( a \) is free, the problem \( H(V, \tau, a, \Sigma) = 0 \) has as much equations as the general equilibrium problem (4.1), but it has as much additional variables as there are of scaling factors. If there are numerous scaling factors, the dimension of \( SC_{REP} \) is potentially high.

In addition, the set \( SC_{REP} \) is typically non convex, because (4.1) is not convex.

### 4.3.3 Relevance

The data set must contain a full time path of future, and therefore assumed, transactions between agents. It is very difficult to assess the relevance of such assumptions. In general the relevance is regarded as the similarity with external projections. Very often, the benchmark is made so as to be consistent with projections delivered by the most trustable or informed sources such as, for energy, the IEA World Energy Outlook or the EIA International Energy Outlook.

In multi-models exercises of policy simulation, such as Clarke et al. [2009] or USCCSP [2007], the benchmark is based on a common pool of assumptions. However, if there are no projections available, the modeler has to rely on more personal assumptions.

The set of relevant scenarios can be seen as:

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

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

### 4.3.4 Combining replicability and relevance

If using this definition of relevance, the computation of a replicable and relevant scenario (equation 4.11), is equivalent to searching \((\bar{V}, \bar{\tau}) \) such that:

\[
(\bar{V}, \bar{\tau}) \in SC_{REP} \tag{4.12}
\]

\[
H_{REL}(\bar{V}, \bar{\tau}, B) \leq 0 \tag{4.13}
\]

There is no guarantee that such a \((\bar{V}, \bar{\tau}) \) exists. It does not if, for example,(4.13) is over determined by constraints and bounds. However, if (4.13) is not sufficiently determined, the only scenarios solving equations (4.12) and (4.13) are
CHAPTER 4. DYNAMIC CGE CALIBRATION AND BENCHMARK SCENARIOS

Direct SAM computation

<table>
<thead>
<tr>
<th>Observed ((\bar{V}_0, \bar{\tau}_0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed or econometrically estimated (\Sigma)</td>
</tr>
<tr>
<td>Steady-state calibration of (a_t)</td>
</tr>
<tr>
<td>(a_t = a_0(\bar{V}_0, \bar{\tau}_0))</td>
</tr>
<tr>
<td>Equilibrium with constant preferences and technologies</td>
</tr>
<tr>
<td>((V^{\star}_{0,t}, \bar{\tau}_t))</td>
</tr>
<tr>
<td>Extraction of sector-specific benchmarks</td>
</tr>
<tr>
<td>Industries ((V^{\star,(i)}_{0,t}, \bar{\tau}_t)) (i \in N)</td>
</tr>
<tr>
<td>Consumption ((V^{\star,(c)}_{0,t}, \bar{\tau}_t))</td>
</tr>
<tr>
<td>Partial adjustment</td>
</tr>
<tr>
<td>(\bar{V}^{\star,(i)}<em>t = V^{\star,(i)}</em>{0,t} + \Delta^{(i)}_t)</td>
</tr>
<tr>
<td>Partial adjustment</td>
</tr>
<tr>
<td>(\bar{V}^{\star,(c)}<em>t = V^{\star,(c)}</em>{0,t} + \Delta^{(c)}_t)</td>
</tr>
<tr>
<td>Re-calibration</td>
</tr>
<tr>
<td>(a^{(i)}_t = a^{(i)}_0(\bar{V}^{\star,(i)}_t, \bar{\tau}_t))</td>
</tr>
<tr>
<td>Re-calibration</td>
</tr>
<tr>
<td>(a^{(c)}_t = a^{(c)}_t(\bar{V}^{\star,(c)}_t, \bar{\tau}_t))</td>
</tr>
<tr>
<td>non steady-state equilibrium ((V^{\star}_t, \bar{\tau}_t))</td>
</tr>
<tr>
<td>taken as benchmark scenario ((\bar{V}_t, \bar{\tau}_t) = (V^{\star}_t, \bar{\tau}_t))</td>
</tr>
</tbody>
</table>

Figure 4.2: Computation of dynamic SAM
an economically absurd scenario (e.g. extreme values). One need to have a system \((H_{REP}, B)\) sufficiently large to rule out all the "non-relevant" cases such as extreme values, or erratic variations, without the background of the theoretical properties of economic models. Therefore, the specification of \((H_{REP}, B)\) must be exhaustive. The problem \(H_{REP} \leq B\) can have more equations than \(H = 0\). In addition, the risk of over-specification increases.

### 4.3.5 Heuristic search

Another approach avoids the daunting task of specifying mathematical conditions for \(SC_{REL}\). It consists in specifying scaling factors and solving problem 4.1 to generate replicable scenario and in adjusting these factors so as to attain a relevant replicable scenario. This is the method used in practice by applied general equilibrium modelers. It is presented in Figure 4.2.

First, a scenario \((V^{\star}_{0, t}, \bar{\tau}_t)\) with constant preferences and technologies is generated by calibrating all the scaling factors on a base-year SAM. The partial benchmark scenarios, one for each industry and one for the representative consumer, are extracted from \((V^{\star}_{0, t}, \bar{\tau}_t)\). They are noted \((V^{\star,(i)}_{t}, \bar{\tau}_t)\) for industries and \((V^{\star,(c)}_{t}, \bar{\tau}_t)\) for the consumer. The partial benchmark scenarios are independently adjusted by means of user-defined shifts \((\Delta^{(i)}_t)_{t \in N}\) and \(\Delta^{(c)}_t\). They reflect the modeler’s beliefs about the changes in input intensity and consumption profiles that are not price-induced, but that are due to changes in technologies and preferences.

Scaling factors are re-computed, on the basis of the readjusted partial benchmarks, and the CGE model is solved. The general equilibrium outcome takes into account the changes in technologies preference. This equilibrium scenario can be used as a benchmark scenario. By definition, it is replicable. In addition, it conveys the modeler’s assumptions expressed into \(\Delta\). The re-adjusted sectorial benchmarks are not necessarily replicated. But appropriate choice of \(\Delta\) allows the modeler to obtain a benchmark scenario that approaches the non-stationary dynamics he desired, at least in terms of the sign of direction of changes in input intensity.

This principle, although rarely documented, is very often used by dynamic applied equilibrium modelers, where playing with sectorial benchmark data is the key for attaining a satisfactory "Business as usual" scenario.
4.4 Dependence of the policy response to the benchmark scenario

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

The general equilibrium $V$ with the counterfactual policy $\tau$ solves:

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

If the user-defined benchmark scenario is $(\bar{V}, \bar{\tau})$, it is reproduced if there is no counterfactual policy ($\tau = \bar{\tau}$):

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

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

The normalized form of the model can be written as:

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

(4.14)

By (4.14), we can see that the deviation from the benchmark $(\frac{V}{\bar{V}}, \frac{\tau}{\bar{\tau}})$ is an implicit function of the policy deviation $(\frac{\tau}{\bar{\tau}})$. If we note this implicit function $H$, and if we define it from the space of the possible deviation to the space of the possible general equilibrium outcome, we have:

$$H_{V, \tau, \Sigma}: \frac{\tau}{\bar{\tau}} \mapsto \frac{V}{\bar{V}}$$

(4.15)

This implicit function is parameterized by the benchmark scenario path and by the elasticities. Therefore the model simulates the deviation from a reference scenario responding to a deviation in the value of the policy instrument, for given (i) elasticity parameters $\Sigma$ and (ii) benchmark scenario $(\bar{V}, \bar{\tau})$. Note that if there is no counterfactual policy, there are no deviations from the reference scenario, and from equation (4.14) we have:

$$H_{V, \tau, \Sigma}(1) = 1$$
4.5 Example: a Ramsey model with energy inputs

For an illustration, we derive the specification of $H'$ for a simple variant of a Ramsey model inspired by Lau et al. [2002].

4.5.1 Assumptions

The representative household’s utility function is given by equation (4.3) The consumption good is produced using a CES production function of three inputs: capital $K$, energy $E$ and an exogenous quantity of labor $\bar{L}$. The elasticity of substitution $\sigma$ does not vary through time, but the scaling factors $a_K$, $a_L$ and $a_E$ are time-dependent.

$$Z_t = \left[a_{K,t}K_t^{\frac{\sigma-1}{\sigma}} + a_{E,t}E_t^{\frac{\sigma-1}{\sigma}} + a_{L,t}L_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma}}$$

The evolution of the capital stock given by $^6$:

$$K_t = (1-\delta)K_{t-1} + I_t, \quad K_0 = \bar{K}_0$$

Where $I$ represents investment.

Energy is produced from consumption goods $X_t$ with a Leontief technology.

$^6$Note that for simplicity, we depart on this point from Lau et al. [2002] who specified $K_t = (1-\delta)K_{t-1} + I_{t-1}$.
CHAPTER 4. DYNAMIC CGE CALIBRATION AND BENCHMARK SCENARIOS

whose efficiency, given by the scaling factor \( a_{X,t} \), is time dependent:

\[
E_t = a_{X,t}X_t
\]  

(4.19)

Finally, we have a model with a single elasticity parameter \( \sigma \). The scaling factors are \( (a_{K,t}, a_{L,t}, a_{E,t}, a_{X,t}, \beta_t) \), therefore, there are \( 5 \times T \) scaling factors in this model. In addition, we assume that there is a tax \( \tau \) on energy.

4.5.2 General equilibrium conditions \((H = 0)\)

The equilibrium values for a tax level \( \bar{\tau} \) are noted with a \(^*\), they satisfy the household income definition, the zero profit conditions, the market-clearing conditions and the household and firms’ demand specifications.

We note \( M \) the household’s revenue, \( W \) the wage rate, \( RK \) the rental rate of capital.

Household’s income:

\[
M^* = P^*_t \bar{K}_0(1 - \delta) + \sum_{t=1}^{T} (W^*_t L^*_t + \bar{\tau}_t P^*_t E^*_t) - (P^*_T - RK^*_T)K^*_T
\]

Zero-profit conditions:

\[
\begin{align*}
(P^*_t)^{1-\sigma} &= a^*_E (P^*_E t)^{1-\sigma} + a^*_K (RK^*_t)^{1-\sigma} + a^*_L (W^*_t)^{1-\sigma}
\end{align*}
\]

\[
\begin{align*}
P^*_E t &= (a_{X,t} + \bar{\tau}_t)P^*_t \\
P^*_{t-1} &= RK^*_{t-1} + (1 - \delta)P^*_t
\end{align*}
\]

Market-clearing conditions:

\[
\begin{align*}
K^*_t &= (1 - \delta)K^*_{t-1} + I^*_t, \quad K^*_0 = \bar{K}_0, \quad L^*_t = \bar{L}_t, \\
Z^*_t &= C^*_t + I^*_t + X^*_t
\end{align*}
\]

Demand functions:

\[
\begin{align*}
K^*_t &= a^*_K t (P^*_t / RK^*_t)^{1-\sigma} Z^*_t, \quad L^*_t = a^*_L t (P^*_t / L^*_t)^{1-\sigma} Z^*_t, \\
E^*_t &= a^*_E t (P^*_t / (P^*_E t)^{-\sigma} Z^*_t, \quad C^*_t = \beta t M^* / P^*_t, \quad X^*_t = E^*_t / a_{X,t}
\end{align*}
\]

We add a condition on the terminal investment in order to approximate an infinite-horizon model [Lau et al., 2002]:

\[
I^*_T / I^*_{T-1} = C^*_T / C^*_{T-1}
\]
4.5.3 Deviations resulting from a new tax policy \((H' = 0)\)

Let’s now assume a new tax level \(\tau\). If replacing the scaling factors by their expressions as function of \(V^*\), we can write the general equilibrium conditions in terms of relations between deviations\(^7\) from \(V^*\) and deviations from \(\tau\).

If we use the notation \(\bar{V} = V/V^*\) and \(\bar{\tau} = \tau/\bar{\tau}\).

Household’s income:

\[
\bar{M} = A_1 \bar{P}_1 + \sum_{t=1}^{T} \left( A_{5,t}^* \bar{W}_t + A_{3,t}^* \bar{E}_t \bar{\tau}_t \right) - A_{4,t}^* \bar{P}_T \bar{K}_T + A_{6,t}^* \bar{R} \bar{K}_T \bar{K}_T
\]

Zero-profit conditions:

\[
\begin{align*}
\bar{P}_t^{1-\sigma} &= A_{0,t}^* \bar{P}_{E,t}^{1-\sigma} + A_{7,t}^* \bar{R} \bar{K}_t^{1-\sigma} + (1 - A_{6,t}^* - A_{7,t}^*) \bar{W}_t^{1-\sigma} \\
\bar{P}_{t-1} &= A_{8,t}^* \bar{R} \bar{K}_{t-1} + (1 - A_{8,t}^*) \bar{P}_t \\
\bar{P}_{E,t} &= A_{9,t}^* \bar{P}_t + (1 - A_{9,t}^*) \bar{P}_{E,t} \bar{\tau}_t
\end{align*}
\]

Market-clearing conditions:

\[
\begin{align*}
\bar{K}_t &= A_{10,t}^* \bar{K}_{t-1} + (1 - A_{10,t}^*) \bar{I}_t, \quad \bar{K}_0 = 1, \quad \bar{L}_t = 1 \\
\bar{Z}_t &= A_{11,t}^* \bar{X}_t + A_{12,t}^* \bar{C}_t + (1 - A_{11,t}^* - A_{12,t}^*) \bar{I}_t
\end{align*}
\]

Demand functions:

\[
\begin{align*}
\bar{K}_t &= (\bar{P}_t/\bar{R} \bar{K}_t) \bar{Z}_t, \quad \bar{L}_t = (\bar{P}_t/\bar{W}_t) \bar{Z}_t, \\
\bar{E}_t &= (\bar{P}_t/\bar{P}_{E,t}) \bar{Z}_t, \quad \bar{C}_t = M/\bar{P}_t, \quad \bar{X}_t = \bar{E}_t
\end{align*}
\]

Condition for final investment

\[
\bar{I}_T/\bar{I}_{T-1} = \bar{C}_T/\bar{C}_{T-1}
\]

The parameters \(A\) are defined as:

\[
\begin{align*}
A_{11}^* &= (1 - \delta) P_{1}^* K_{0}^*/M^*, \quad A_{2}^* = L_{0}^* W_{1}^*/M^*, \\
A_{3}^* &= \pi P_{1}^* E_{1}^*/M^*, \quad A_{4}^* = P_{1}^* K_{1}^*/M^*, \\
A_{5}^* &= R K_{1}^* K_{T}^*/M^*, \quad A_{0}^* = (P_{E,t}^* E_{t}^*)/(P_{1}^* Z_{t}^*), \quad A_{7}^* = (R K_{1}^* K_{T}^*)/(P_{1}^* Z_{t}^*) \\
A_{8}^* &= R K_{1}^* /P_{t-1}^*, \quad A_{9}^* = (P_{1}^* E_{t}^*)/(P_{E,t}^* X_{t}^*), \\
A_{10}^* &= (1 - \delta) K_{1}^* /K_{t}^* \\
A_{11}^* &= X_{t}^*/Z_{t}^*, \quad A_{12}^* = C_{t}^*/Z_{t}^*
\end{align*}
\]

\(^7\)In addition, a log-linearization of the deviation system is presented in Appendix B.
4.6 Conclusion

The choice of scaling factors in dynamic CGE models amounts to building a benchmark scenario, i.e. a dynamic SAM that reflects the evolution of the economy that the modeler regards as relevant. The CGE model represents a system of deviations around this benchmark scenario that results from a policy shock. The magnitude of the deviation depends on the benchmark scenario, therefore on the assumption made by the modeler about the future. In long-run model, the future is very uncertain, and the impact of a policy on the economy is contingent to the modeler’s beliefs.
Chapter 5

Sensitivity to benchmark scenarios in a carbon leakage model

5.1 Introduction

Following UNFCCC, which acknowledged the principles of right to economic development and common but differentiated responsibility, global climate policies are based on differentiated contributions to GHG mitigation efforts. The Kyoto Protocol imposed binding emissions targets at between 2008 and 2012 for the most industrialized countries (Annex I) only. The rounds of international negotiations concerning the post-Kyoto period initiated at Copenhagen in December 2009 did not result yet in any binding emission targets at horizon 2020 for most of the non-OECD countries. In OECD countries, actions at the state, national or regional level, such as the EU Climate and Energy Package, the US Clean-Air Act, or the Australian carbon tax tend to take the lead on the UNFCCC-based negotiation scheme.

As a response to OECD mitigation policies, emissions might rise in other regions, partially offsetting the efforts to reduce emissions. This phenomenon is known as carbon leakage. Following Marschinski et al. [2009], one can identify three main canals of carbon leakage: free-riding, supply-side and specialization leakage. The free-riding leakage is due to the incentive by a region to lower provision (more emissions) for the public good (the atmospheric CO₂ concentrations) if other regions decide to reduce their emissions. The supply-side leakage relates to the negative effect of mitigation policies on fossil fuel prices that may cause a rebound of fossil fuel consumption in non-signatory
regions. The specialization linkage is due to the change in comparative advantages as an environmental policy leads to a production cost increase giving incentive to locate energy-intensive activities in the regions with no environmental policy. However, the literature about technological spillovers [Di Maria and van der Werf, 2008] puts forward, the contribution of policy induced technological changes and technology diffusion to limiting the carbon leakage.

In this chapter, the scope of the carbon-leakage problem will be narrowed from three points of view. First, we consider only the specialization leakage. Second, we put aside the emissions-induced and technological spillover externalities. Last, we regard the carbon leakage problem as the emission policy impact on the activity level of the region where it is implemented.

The potential activity loss due no non-global emission policy is a major EU concern. The EU ETS Directive (2003/87/EC) stipulates that the sectors deemed to be exposed to a significant risk of carbon leakage will receive relatively more free allowances than other sectors. A revision of the directive defines the sectors or sub-sectors "deemed to be exposed to a significant risk of carbon leakage" on the basis of sensitiveness of the production cost to the carbon prices and openness to non-EU trade\textsuperscript{1}. In addition, claims for border taxes to offset the carbon leakage have been voiced. The effects of border-tax adjustments are largely debated by economists [Lockwood and Whalley, 2010, Winchester et al., 2011] while lawyers discuss the problem of compatibility with WTO rules [Pauwelyn, 2004].

There is still a considerable debate about the magnitude of the carbon leakage problem. Several micro-funded economic models are used for this assessment. They can be cast in three groups: partial equilibrium models, recursive inter-temporal general equilibrium and dynamic inter-temporal general equilibrium models.

Partial equilibrium models focusing on specific industries have been used to evaluate the impacts of asymmetric GHG policy architectures on sectoral added-value, profits and incentive to invest [Quirion et al., 2011, Demailly and Quirion, 2008, Meunier and Ponssard, 2009, Oggioni and Sneers, 2008a,b]. In this domain work such as Lantz et al. [2011], takes into account the production process in some energy-intensive industries.

At an aggregate level, the effects on regional GDPs has to be assessed using macroeconomic models. Recursive (myopic) inter-temporal models such

\textsuperscript{1}A sector or sub-sector is "deemed to be exposed to a significant risk of carbon leakage if: The sum of additional costs induced by the implementation of this directive would lead to a substantial increase of production cost (proportion of the Gross Value Added) of at least 5%; and the Non-EU Trade intensity is above 10%." The sum of additional costs induced by the implementation of this directive would lead to a particularly high increase of production cost, of at least 30%; or if the Non-EU trade intensity is above 30%.
as IMACLIM-R [Quirion et al., 2011, Hamdi-Cherif et al., 2010], EPPA [Paltsev et al., 2005], GEMINI-E3 [Bernard and Vielle, 2009] or GEM-E3 [Proost and Van Regemorter, 2003] with a disaggregated representation of the economy can measure the effect of leakage in various industries. Therefore, they are very powerful tools for policy assessment. Nevertheless, they do not take into account policy anticipation effects and, in particular the way future GHG policies impact the value of a current portfolio and the investment choice. Dynamic inter-temporal General Equilibrium Models, as MERGE [Manne et al., 1995], REMIND [Leimbach et al., 2010], WITCH [Bosetti et al., 2006], DICE [Nordhaus and Boyer, 1999], are based on inter-temporal choice with rational expectations. They are consistent with progressive adjustment of saving behaviors and technologies to future GHG emissions regulation policies. Since these models have to be solved in one shot for the entire time horizon, computational tractability limits the number of variables that can be included at each time period. At the exception of MS-MRT [Bernstein et al., 1999], G-Cubed [McKibbin et al., 1999], and the dynamic version of EPPA [Babiker et al., 2008], the models of this family are based on a very aggregated vision of the economy.

The two families of general equilibrium models tend to give different results in terms of the cost of climate policy for the economies [Babiker et al., 2008]. Recursive models give relatively high levels of leakage, because they take into account cross-sectoral effects and because poorly anticipated policy shocks leading to high ex-post adjustment costs. In dynamic models, the cost is lower, due to anticipation of the policy and graduate ex ante adjustment that smooths the abatement cost.

However, both families of models are bound to rely on univocal assumptions made during the process of their calibration. First, they contain several elasticity parameters that are not necessarily scientifically estimated. Second, they are based on the numerical specification of the several scaling factors used in the functions representing technologies and preferences.

In this chapter, we study the importance of the assumptions about the structure of the economy on the carbon leakage yielded by a dynamic model. We specify a dynamic model of an open economy with three production sectors and four commodities. The model is calibrated on the French economy using social accounting information taken from Eurostat. The rest of the world is represented in a generic way, by specifying import supply functions and export demand functions for the various commodities [Boadway and Treuddenck, 1978]. We model asymmetric climate policy by introducing an exogenous carbon price in the model with no effect on the import supply and export demand functions. This price can be interpreted as a tax or as the market price of carbon resulting from a cap-and-trade system.
CHAPTER 5. SENSITIVITY TO BENCHMARK SCENARIOS IN A CARBON LEAKAGE MODEL

We classically simulate shocks on the carbon price and we examine the magnitude and the dynamics of the GDP response. In addition, we show that by generalizing the static or recursive inter-temporal CGE calibration procedure [Harberger, 1962], we can express the dynamic general equilibrium model as a system of deviations along a pre-defined reference scenario. This provides a framework (i) for computing response functions showing the reaction to a shock on the carbon prices and (ii) for checking for the sensitivity of these responses to the specified reference scenario. The idea is that in dynamic models, the response to the carbon price is largely driven by a priori conjectures about the future of the economy, in particular in terms of autonomous energy efficiency improvements (AEEI) and sectoral structure (weight of the energy-intensive industries.). For example, the assumption that energy-intensive industries are doomed to disappear, even in the absence of carbon price, can give way to projections where the carbon tax increase has little effect on the economy.

This exercise is not intended to contribute to the debate about the "true" effect of carbon leakage. It aims first of all at showing that the approach of policy evaluation described in Chapter 4 can be used in practice in rather complex models, with vintage production functions, Armington specification of international trade, reduced-form representation of the rest-of the world, and limited labor mobility.

We first present the model assumptions and then show how we computed alternative benchmark scenarios. Finally, we compare the responsiveness of sectorial value added and GDP to a change in carbon price for three alternative benchmark scenarios.

The variables of the model are listed in Appendix C.1. For the details of the general equilibrium conditions, the reader can refer to Appendix C.3.

5.2 Model description

We consider an economy with a representative household, four goods (indexed by $j$) and three industrial sectors (indexed by $i$). Time is indexed by $t$. The goods are fossil energy ($f$), electric energy ($e$), energy-intensive goods ($is$) and non energy-intensive goods ($ns$). The input-output structure of the economy is summarized in Table 5.1. The rows represent goods, the columns represent industrial sectors. The non-zero coefficients are in grey. There is a domestic production sector for electric energy, energy-intensive and non energy-intensive goods but not for fossil energy which is totally imported. In addition, there is international trade of the energy and non energy-intensive goods.
5.2. MODEL DESCRIPTION

Armington paradigm [Armington, 1969], the products are distinguished by their place of production. The production activities in the industrial sectors require intermediate consumption, capital and labor. The capital is sector specific. It is a mix of energy-intensive and non energy-intensive goods bundled in fixed (exogenous) proportions. The labor mobility between the sectors is limited.

5.2.1 Production functions and vintages

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

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

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

$$z_{i,t} = \left[ \sum_{j \in J_{i}} a_{(\text{prod}),i,j,t} \frac{\sigma_{i,j,t}}{\sigma_{i,t}} + a_{(\text{prod}),i,L,t} \frac{\sigma_{i,L,t}}{\sigma_{i,t}} + a_{(\text{prod}),i,K,t} \frac{\sigma_{i,K,t}}{\sigma_{i,t}} \right]^{\sigma_{i,t}} (5.1)$$

$$i = e, is, ns$$

Table 5.1: Table of resource and use in product

<table>
<thead>
<tr>
<th>Resources</th>
<th>Int. Cons.</th>
<th>Final Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported</td>
<td>Domestic</td>
<td>Cons.</td>
</tr>
<tr>
<td>e</td>
<td>is</td>
<td>Export</td>
</tr>
<tr>
<td>ns</td>
<td></td>
<td>Capital</td>
</tr>
</tbody>
</table>

93
The dynamics of input and output is:

\[ Z_{i,t+1} = Z_{i,t}(1 - \delta) + z_{i,t+1}, \]
\[ X_{i,j,t+1} = X_{i,j,t}(1 - \delta) + x_{i,j,t+1}, \]
\[ K_{i,t+1} = K_{i,t}(1 - \delta) + k_{i,t+1}, \]
\[ L_{i,t+1} = L_{i,t}(1 - \delta) + l_{i,t+1}, \]

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

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

\[ I_{i,t} = \min_{IV} \left\{ a_{(capital),i,IS,t} IV_{i,IS,t}, a_{(capital),i,NS,t} IV_{i,NS,t} \right\} \]

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

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

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

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

### 5.2.2 Foreign trade

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

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

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

The various products can be imported or exported. We use a closed-form representation of the rest-of-the-world. It intervenes in the model by means of foreign supply functions (supply for import) and foreign demand of domestic goods (demand for exports). Such specifications were introduced by Boadway and Treddenick [1978] and are discussed in Goulder et al. [1983].

The supply for imports represents the way the foreign price can be influenced by an increase in the domestic demand. The prices of imported and exported goods $PIWC_{j,t}$ and $PDWC_{j,t}$ are expressed in foreign currencies and in current values considering the following relation:

$$IM_{j,t} = a_{(im),j,t}PIWC_{j,t}^{\sigma_{IM,j}}, \ j = is, ns$$ (5.5)

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

The demand for exports (rest of the world demand for exports) is a decreasing function of the export price.

$$EX_{j,t} = a_{(ex),j,t}PDWC_{j,t}^{\sigma_{EX,j}}, \ j = is, i8$$ (5.6)

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

$$\bar{\text{DEF}}_t = \sum_{j=f,i,s,n} \text{PIWC}_{j,t} \cdot \text{IM}_{j,t} - \sum_{j=i,s,n} \text{PDWC}_{j,t} \cdot \text{EX}_{j,t} \quad (5.7)$$

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

### 5.2.3 CO₂ emissions

The CO₂ emissions ($\text{EM}$) in this economy are proportional to the total use of fossil energy (from the households and the industrial sectors). If $\varepsilon r$ is the emission rate of the fossil energy, we have:

$$\text{EM}_t = \varepsilon r \left[ \sum_i \text{X}_{i,f,t} + \text{C}_{f,t} \right]$$

The use of non-electric energy causes CO₂ emissions which are submitted to a tax $\text{TAX}_{\text{CO}_2,t}$ whose revenues are lump-sum transfers to the households. Note that the only means to decrease emissions is to decrease fossil/fuel consumption. Emissions are proportional to fossil fuel consumption and imports in the model.

### 5.2.4 Utility function

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

$$\mathcal{W} = \sum_t \beta_t \log U_t, \quad \sum_t \beta_t = 1 \quad (5.8)$$

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

$$\text{HC}_t \equiv PU_tU_t = \beta_t E \quad (5.9)$$
5.3. GENERATION OF ALTERNATIVE BENCHMARK SCENARIOS

5.2.5 Limited labor mobility

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

\[
L_{i,t+1} = (1 - \delta)L_{i,t} + l_{i,t+1}, \quad i = e, is, ns
\]  

(5.10)

The total labor \( LT \) is exogenous; therefore we directly derive the quantity of labor \( \bar{l}_t \) available at period \( t+1 \) for the new vintages:

\[
\bar{l}_{t+1} = \bar{L}_{t+1} - (1 - \delta)\bar{L}_t
\]  

(5.11)

The labor mobility among the vintages of different sectors is limited, so that among sectors, new vintages with different labor productivity coexist. As in Karp and Paul [1994], the household is endowed with an exogenous quantity of total labor \( \bar{L}_t \), but chooses the distribution of its efficient labor supply among the different industrial sectors. To represent the limited labor mobility we follow Casas [1984] and Horvath [2000] considering the household labor supply as an index of the labor supply in the different sectors. We model the limited labor mobility by means of constant elasticity of transformation (CET) functions.

\[
\bar{l}_t = \left[ \sum_i a_{(labor),i,t} \frac{\sigma_{L,i,t+1}}{\sigma_{L,t+1}} \right]^\frac{\sigma_{L}}{\sigma_{L,t+1}}
\]  

(5.12)

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

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

The general equilibrium conditions are specified in Appendix C. The problem obtained has 5801 variables and 5801 constraints. The numerical computation is done with GAMS and the CONOT3 solver.

5.3 Generation of alternative benchmark scenarios

The model contains several macroeconomic functions, therefore several scaling factors that have to be calibrated (see Table C.1). We calibrate the scaling factors on three alternative benchmark scenarios representing alternative evolutions of the French economy. In the first benchmark scenario, we assume no
technological changes or preference changes. In the second scenario the technological change improves the energy efficiency. In the last scenario, the share of energy-intensive activities in GDP decreases through time. These scenarios are generated using the partial adjustment method presented in Chapter 4. First, we construct a base year SAM and we set the elasticity parameters, then we calibrate the model on a base year. We operate shifts on the sectoral scenario reflecting the expected structural change. Finally, we recalibrate the scaling factors and obtain a reference benchmark that takes into account our assumptions.

5.3.1 Base-year data

The base-year data can be summarized in different tables. Table 5.2 shows the aggregated resource and use in products. It merely represents for each product \( j \) the accounting relationship between the value of the product available (rows "resource in products"), and the different uses as intermediate consumptions (in the rows "intermediate consumption"), final household consumption, export and use for capital accumulation (in the rows "final use in products"). This table, contains values in billions euros that were computed from very disaggregated data available on the Eurostat Website\(^2\). By definition, the Gross Domestic Product is equal to the sum of sectoral added-values (output minus intermediate consumptions). In 2007, it is equal to 1641 billion euros (1657 + 434 - 3,5 - 258 - 188).

The energy-intensive sector added value represents 18% of the GDP \((100 \times (251 + 298 - 258)/1641)\), but it weights for more that 50% of the intermediate fossil fuel consumption \((100 \times (25)/(3.5 + 25 + 21))\). The share of electricity intermediate consumption used in the is sector is 36% \((100 \times (7)/(7 + 12))\). In addition, Table 5.2 shows that the energy consumption is more balanced between firms and households for electricity energy than for fossil fuels.

The fossil fuel expenses are very limited in the electricity sector (3.5 billion euros for an electricity output of 37.22 billions euros). This is explained by the extreme predominance of nuclear in the French power production capacity (about 78% of the power production is from nuclear). Therefore, we can expect a very limited effect of CO\(_2\) tax on the power price.

In order to compute base-year quantities corresponding to the base-year expenses, we have to introduce a price system. By convention, we set the base-year price of the \( is \) and \( ns \) goods and products to 1. This is equivalent to consider a price index to compute real values from nominal values. The level of the base-year index is not important for \( is \) and \( ns \) goods and products, since

\(^2\)http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95/supply use/input tables/data/workbooks
they are macroeconomic aggregates without specific measurement units. However, for electricity and non-electric energy, which can be regarded as physical variables, it is important to preserve units, in particular as we need to relate the carbon tax to the fossil-fuel energy price. In order to match the energy data of France taken from Eurostat base, we have chosen a base-year price of 12 Euros per GJ of fossil fuels and 70 euros per MWh for power price, as shown in Table 5.3.

Base-year sectoral wage rates and labor breakdown are shown on Table 5.4. The energy intensive sector represents 11% of the labor. There are significant wage differences between the sectors. Wages are higher in the electric and energy-intensive sectors than in the non energy-intensive sector.

Assuming a 5% rate of decay and a given sectoral growth of capital, the base-year capital stocks in the various sectors can be inferred from the base-year investment in these sectors.

For simplification, we have not taken into account the CO$_2$ tax for the base year. The values assigned to the various elasticity parameters are presented in Tables 5.5.
CHAPTER 5. SENSITIVITY TO BENCHMARK SCENARIOS IN A CARBON LEAKAGE MODEL

| base-year prices |  |  |
|------------------|--|--|--|--|
| \( f \) | \( P_{1_j} \) | \( PD_{j} \) | \( P_{j} \) | \( PV_{j} \) |
| e | 12\(^a\) | 70\(^b\) | 70\(^b\) | 1 |
| is | 1 | 1 | 1 | 1 |
| ns | 1 | 1 | 1 | 1 |

Note: \(^a\) in Euro per GJ.
\(^b\) in Euro per MWh.

Table 5.3: Base-year price system

<table>
<thead>
<tr>
<th>labor market</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{i}^{a} )</td>
<td>( L_{i}^{b} )</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>67.83</td>
<td>0.118</td>
</tr>
<tr>
<td>is</td>
<td>45.47</td>
<td>2.81</td>
</tr>
<tr>
<td>ns</td>
<td>35.69</td>
<td>22.4</td>
</tr>
</tbody>
</table>

Note: \(^a\) in thousands Euro per GJ.
\(^b\) in million worker per MWh.

Table 5.4: Base-year labour force and average annual wage

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{e} )</td>
<td>0.2</td>
</tr>
<tr>
<td>( \sigma_{is} )</td>
<td>0.2</td>
</tr>
<tr>
<td>( \sigma_{ns} )</td>
<td>0.7</td>
</tr>
<tr>
<td>( \sigma_{Y,\text{is}} )</td>
<td>2</td>
</tr>
<tr>
<td>( \sigma_{Y,\text{ns}} )</td>
<td>0.8</td>
</tr>
<tr>
<td>( \sigma_{IM,\text{is}} )</td>
<td>10</td>
</tr>
<tr>
<td>( \sigma_{IM,\text{ns}} )</td>
<td>10</td>
</tr>
<tr>
<td>( \sigma_{EX,\text{is}} )</td>
<td>5</td>
</tr>
<tr>
<td>( \sigma_{EX,\text{ns}} )</td>
<td>2</td>
</tr>
<tr>
<td>( \sigma_{C} )</td>
<td>0.8</td>
</tr>
<tr>
<td>( \sigma_{L} )</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.5: Elasticity values

100
5.3.2 Three alternative benchmark scenarios

The sensitivity analysis is conducted by comparing the outcomes from 3 reference scenarios based on 3 alternative expectations. The scenarios are presented in Table 5.6. They were built with the partial adjustment method. Therefore, their content has not been fully controlled. However, with this method, it has been possible to build scenarios that represent very different possible evolutions of the structure of the economy in terms of energy prices, sector-specific AEEI, sectoral breakdown between energy-intensive and non-energy-intensive activities.

The first benchmark scenario, called "technological stagnation" (TS), represents a situation where preferences and technologies remain the same and where the growth rate of the economy is around 1.5%. The various sectors have quite similar growth rate. The oil price stagnates, and the CO$_2$ price increases by 5% per year. This benchmark is computed by assuming that the scaling factors are constant through time and equal to their base-year value. The only non-constant parameter is the carbon tax level.

We see on Table 5.6 that the benchmark scenario reproduces well the desired 1.5% GDP growth rate that remains well balanced among the various industrial sectors. The increasing carbon price involves a slowdown of fossil-fuel consumption (see Figure 5.2). But the emissions keep on increasing. Except CO$_2$ price and emissions trajectories, the relative prices and relative quantity remain almost constant.

In the second benchmark scenario, "energy efficiency" (EF), we aimed at creating a situation where AEEI leads to a better fossil-fuel efficiency in the various sectors. The CO$_2$ price is the same as in TS. But unlike TS, the fossil fuel price is not constant and increases through time at an annual 2% rate (see Table 5.6). As in the TS scenario the economy is assumed to growth at an annual rate of around 1.5%. This benchmark scenario is obtained by computing the scaling factors on values taken from TS that are then readjusted. In this readjustment the TS fossil fuel intermediate and household final consumptions are downgraded, so as to growth at a lower rate. The fossil fuels imports are also scaled down. Once the scaling factors have been re-calibrated, the general equilibrium model is solved, with a higher exogenous fossil-fuel price.

In the benchmark scenario obtained, the combination of AEEI and increasing fossil-fuel and CO$_2$ prices, lead to a decrease in fossil-fuel consumption and in emissions, as shows Figure 5.2. The GDP growth remains close to 1.5% per year and it is well balanced among the sectors (see Figure 5.1).

The last benchmark scenario, "deindustrialization" (DI), aims at represent-
CHAPTER 5. SENSITIVITY TO BENCHMARK SCENARIOS IN A CARBON LEAKAGE MODEL

<table>
<thead>
<tr>
<th>Description</th>
<th>Technological Stagnation (TS)</th>
<th>Energy Efficiency (EF)</th>
<th>De-industrialization (DI)</th>
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</thead>
<tbody>
<tr>
<td>Fossil fuel price(^a)</td>
<td>0</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>CO(_2) tax(^a)</td>
<td></td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Energy efficiency improvement</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Price induced AEEI</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Sectoral shift</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Value added (^{a,b})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>1.56</td>
<td>1.31</td>
<td>1.49</td>
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<td>is</td>
<td>1.45</td>
<td>1.31</td>
<td>0.52</td>
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<tr>
<td>ns</td>
<td>1.50</td>
<td>1.34</td>
<td>1.76</td>
</tr>
<tr>
<td>GDP(^{a,b})</td>
<td>1.49</td>
<td>1.33</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Notes: \(^a\) percent annual growth rate, \(^b\) real values.

Table 5.6: Summary description of the benchmark scenarios

...ing a situation where, as in TS, there is no AEEI, but where the GDP growth is driven to the non energy intensive sector, while the energy-intensive sector stagnates. In addition, as in the EF scenario, fossil-fuel prices and CO\(_2\) prices increase. This benchmark scenario is obtained by computing the scaling factors by readjusting the TS values. This readjustment concerns the demand for energy-intensive goods, the demand for investment and intermediate and final household consumption. On Table 5.6, we see that in the scenario obtained, the GDP growth is higher than in the other scenario. It is driven by the non-energy intensive sector growth while the growth is very low in the energy-intensive sector. Fossil fuel consumption and CO\(_2\) emissions increase, but at a slow rate, as shows Figure 5.2.

5.4 Sensitivity to the benchmark scenario

We compare the outcome of a policy shock on the model’s results for the various scenarios. We compute response functions (see section 4.4) and present them as percent deviations from the reference scenario.
5.4. SENSITIVITY TO THE BENCHMARK SCENARIO

Figure 5.1: Output growth rate in the is and ns sectors for the various reference scenarios
Figure 5.2: Electric and fossil fuel consumption growth in the various reference scenarios
5.4. SENSITIVITY TO THE BENCHMARK SCENARIO

The policy shock takes the form of a long-lasting positive shock on CO₂ prices. In the various benchmark scenarios, the real CO₂ price increases by 2% annually. Starting from 15 euros per ton in 2011, it reaches 100 euros per ton in 2050. The counterfactual policy corresponds to a long-lasting increase in CO₂ price. From 2020 on, the CO₂ price doubles compared with its benchmark value.

The effect of the tax on fossil fuel consumption/emissions is shown in Figure 5.3. The emissions decrease since the very beginning of the model’s horizon. Prior to 2020, because of anticipation about an increase in carbon prices, there is less investment in new vintages, and the installed vintages are more capital intensive and less energy intensive. The carbon tax shock in 2020 leads to a sharp drop in emissions that is largely driven by the decrease in households fossil fuel consumption, while, in the industrial sectors, the adjustment of demand is slowed-down by the vintage structure of capital. Emissions keep on diverging from the benchmarks. For the same CO₂ price, the emissions reduction realized depends on the benchmark scenario chosen. Emissions reductions are higher with technological stagnation (scenario TS). The main explanation is that unlike the TS benchmark scenario, the Energy Efficiency and Deindustrialization benchmark scenarios assume an increasing fossil fuel price (see figure 5.6). The price increase limits the share of the carbon price in the end-user fossil fuel price (that includes both fossil-fuel price and the cost of the related CO₂ emissions) and makes it less sensitive to percent deviations in CO₂ prices than with the Energy efficiency benchmark scenario.

The CO₂ tax shock leads first to a production cost increase and therefore to an increase of the prices of the French products with respect to the prices of the foreign products. This loss of price competitiveness can be observed on the upward shifts in terms of trade presented in Figure 5.3. The shift is particularly important when no technological improvement is assumed (scenario TS). It is less pronounced when autonomous energy efficiency improvements are expected (scenario EF) as the AEEI limits the exposure of the production cost to the CO₂ price. On the long run, the industries are penalized by losses of competitiveness. This lead to a disinflation process led by the negative effect of the decline of industrial activities on household’s revenues (through wages and returns on saving). As the households are "impoverishing", the domestic prices, tend to go down and the competitiveness is partly restored. This explains why the terms of trade worsen on the long run. This disinflation effect is particulary important in the cases with no AEEI (scenario TS) or no deindustrialization (DI), as the lack of energy efficiency gains lead to very costly adjustment to the carbon price.
CHAPTER 5. SENSITIVITY TO BENCHMARK SCENARIOS IN A CARBON LEAKAGE MODEL

Figure 5.3: Terms of trade, real GDP, emission and consumption response to the carbon policy shock
5.4. SENSITIVITY TO THE BENCHMARK SCENARIO

The real GDP deviations are presented on Figure 5.3. Real GDP is computed in terms of purchasing power of foreign goods. Therefore, it is adjusted by the terms of trade. On the short run, the effect on GDP is very limited. The GDP even slightly increases, because the negative effects of the tax are compensated by the improvement of the terms of trade. On the long run, the effect tends to be negative, with an exponential downward deviation from the benchmark scenario. As the economy is less competitive there are less investments in new vintages and less wealth produced in the subsequent periods. The GDP loss is more pronounced when assuming no AEEI (scenario TS). In this case, the deviation observed at the end of the model is around -2.5%. In the scenarios with AEEI (EFF) or deindustrialization (DI), the negative effect on GDP is substantially lower (around -1%). The exponential downward deviation from the baseline remains difficult to explain. In any case, it has to be related to the exponential difference between the counterfactual and the benchmark CO$_2$ tax.

The carbon tax shock leads to less use of energy input. As the energy and capital inputs were assumed to be complementary ($\sigma < 1$), this has a negative effect on the marginal productivity of capital, and on the interest rate (not presented on these graphs). As the interest rate decreases, there is more incentive to consume and less incentive to save. That is why on the short run, the carbon tax shock leads to an increase in consumption (see Figure 5.3). On the longer run, however, revenue effects are playing and consumption declines as households resources decrease. The trajectory of the decline depends on the benchmark scenario assumed. In the case where sectoral changes or AEEI limit the energy consumption, the downward shift is substantially delayed. But it is rather brutal when the benchmark scenario assumes a high energy intensity (TS scenario).

The effect of the carbon policy shock on external trade is shown on Figure 5.4. The shock leads to a decrease of exports of energy-intensive products. This decrease begins before the shock, because of the decrease in supply related to the anticipation of the shock (as explained previously). When the shock occurs, the decrease in exports is not dramatic, as it was anticipated by the industry. Then the exports decrease continuously. On the long run, the terms of trade effect is not sufficient to restore the competitiveness of the domestic energy-intensive products and exports are still worsening. The effect on energy-intensive products exports is significantly lower when the assumed AEEI (scenario EF) limits the effect of the carbon tax on prices. The difference observed between the TS and DI scenarios comes from the terms of trade adjustment. The worsening of the terms of trade is less important in the DI scenario, and therefore, the de-inflation and its positive effect on exports is less pronounced, while the neg-
Figure 5.4: Imports and export of is and ns good response to the policy shock
ative effect of the carbon tax is more important. Exports of non energy-intensive products initially decrease because of the carbon tax shock. Nevertheless, on the long run, they increase because they are not too much affected by the increase in carbon prices, and exports of these products benefit from the deterioration of the terms of trade. In other word, for these products, the terms of trade effect dominates the inflationary effect of the energy prices.

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

Figure 5.5: Sectorial value added adjustment to the policy shock

Figure 5.5 gives the evolution of sectoral output and real gross value added. By definition, the gross value added includes the taxes and therefore the cost of CO₂. The power generation sector is penalized by the carbon tax shock. But we see that it decreases slower than the fossil fuel consumption (see Figure
5.4) This expresses an increase in the electricity share in energy supply. Power generation is still less penalized when assuming AEEI (scenario EF). However, it is noticeable in this case that the increase in the share of electricity in the energy mix is less pronounced, as the decline of electricity production and fossil fuel use are closer on the long run, respectively -3% (Figure 5.3) and -7% (Figure 5.5). The gross value added in the electricity sector increases in the various scenarios, in particular in the EF scenario. It shows that the price effect outweighs the volume effect. In the scenario with energy efficiency, however, the disinflation effect of the carbon tax leads to a decrease of the electric sector value added on the long run.

In the TS scenario, output deviations in the electric and energy intensive sector are of quite similar order. These sectors have comparable initial fossil fuel intensities (because of the high share of nuclear technology in the French energy mix). The output deviation is less pronounced in the scenarios with energy efficiency as the carbon tax weights less on the domestic and international competitiveness of the energy-intensive sector. The largest effect is observed in the deindustrialization scenario, because the lack of competitiveness on the domestic market is combined with limited terms of trade adjustment. The output is far less affected in the non energy-intensive sector.

When comparing the carbon tax effect in the energy intensive and non energy intensive sectors’ gross values added, we see that they are quite similar on the long run. But indeed, the value added net of the carbon tax differs significantly (not on the graph). The non energy-intensive sector gross value added increases on the short run, because of the terms of trade effect, and also because its products are more demanded on the domestic market to compensate for the increase in energy-intensive goods prices. On the longer run, the gross value added loss is due to the effect on domestic demand of the loss of revenue induced by the decline of the energy intensive sector. The non energy-intensive sector is not very open to foreign trade and cannot compensate the decrease in domestic demand by the gains of external competitiveness induced by the degradation of the terms of trade.

5.5 Conclusion

When studying the sensitivity of the response of the French economy to a shock on carbon price for three alternative benchmark scenarios, it appears that the assumptions about AEEI and the projected weight of the energy-intensive sectors are quite important. They significantly influence the GDP response to the carbon tax shock and more generally the various effects at stake during the adjustment of the economy to the carbon price.

It seems that the sensitivity to the benchmark scenario should be more ques-
tioned in dynamic CGE models, where the sensitivity analysis is more often limited to the values of the elasticity parameters. Such analysis would cast additional risk factors and therefore more uncertainty to the policy evaluation exercises.

The derivation of benchmark scenario by partial adjustment of scaling factors that is presented in this chapter is sufficient to produce well differentiated scenarios. However, it is still rather raw. In particular, the precision in terms of translation of some sectoral assumptions into a benchmark scenario is quite limited. One could think about more elaborated methods, possibly based not only on sectoral benchmark adjustment but also on elasticity parameters adjustments.

Last, a research direction would be the use of the analytical representation of dynamic CGE models as systems of deviation around non-stationary path to estimate some elasticity parameters on the basis of de-trended macro-economic time series.
CHAPTER 5. SENSITIVITY TO BENCHMARK SCENARIOS IN A CARBON LEAKAGE MODEL
General Conclusion

What we learn from stochastic scenarios

In chapters 1 and 2 of this thesis, we studied the role of uncertainty in technology adoption in the perspective of a transition towards low-carbon economies. The main idea was that deterministic scenario analysis and Monte Carlo simulations miss the fact that, because of irreversibilities in technology choice, uncertainty influences the deployment rates of the technologies and, in turn, the energy commodity prices. The studies were based on comparisons between deterministic and stochastic trajectories simulated with general equilibrium models derived from MERGE computed by stochastic programming. The results tell us that uncertainty creates more volatile energy commodity prices and, in general, less volatile energy technology deployments. But more specific results can be singled out and further discussed.

In Chapter 1, we put forward that because of banking, simulated CO₂ prices follow a Hotelling rule in expectation adjusted for uncertainty with a risk premia. We stressed that the risk premia on CO₂ prices are very low, due to the limited impact of the emission reduction policy on consumption. Nevertheless, the results would be different if considering a feedback effect of emissions on human activities through climate damages. In addition, the risk premia computed have to be related to the value of the relative risk aversion coefficients assigned to the households. One can advocate for an analysis of the sensitivity of the risk premia to this value. Nevertheless this would change the properties of the deterministic model, as this parameter also represents the preference for intertemporal smoothing of consumption. In the models used, the representation of consistent elasticity of saving to the interest rate has been privileged to the understanding of a risk factor that would represent how society as a whole relates to risk. However, one could try to reconcile the consistency with the risk aversion by using recursive utility functions [Gollier, 2012].

Chapter 2 singled out some effects of uncertainty on CO₂ prices. On the one hand, anticipations about an economic recovery and subsequently a high
energy demand could have a positive effect on CO$_2$ prices, through banking - we called this effect "present precautionary". On the other hand, if the expected recovery is not realized, there is an important stock of previously banked permits in the economy, that depresses the CO$_2$ prices. This effect was called "past precautionary". We showed that the past precautionary effect tends to dominate the present precautionary with time, leading, when the expected recovery is not realized, to very low CO$_2$ prices.

However in Chapters 1 and 2, the stochastic scenarios do not teach us a lot about technology deployment trajectories. The sensitivity in terms of prices is not really significantly translated into the regional energy technology portfolios. A first reason relates to the use to stochastic programming and the design probabilistic trees. The results of stochastic programming can be largely influenced by the need for satisfying feasibility conditions for any of the subsequent states of the world. In our case, feasibility involves the satisfaction of the regional emissions reductions constraints (the CO$_2$ cap and trade) and the regional energy portfolio constraints such as those studied with more details in Chapter 3. Because of the emissions targets and the constraints on the technology deployment, significant emissions effort have to be achieved with limited technological options. Therefore, the optimal energy mixes tend to be quite similar in each branch of the stochastic scenarios. In other words, if we have few technological alternatives and if we need to decarbonize significantly, we have to choose one mix, no matter what can be the future energy policy or macroeconomic situation. However, one could propose more flexible alternatives to the portfolio constraints, such as penalties of quadratic costs. An extreme move in this direction would end up in a representation of electricity technologies with CES production functions.

A second reason is more specific to our choice of scenarios. Because of the curse of dimensionality arising in stochastic programming we had to limit our experiments to small stylized scenario trees (2 branches in Chapter 1, 4 branches in Chapter 2). In addition, we have chosen to represent uncertainty quite close to the model’s base year in order to be in line with some current debates: about post 2020 emissions reductions targets and about the recovery from 2008 financial crisis. Therefore, the periods when the future is uncertain are not long enough to give way to really different orientations of the regional energy mixes. This limits the risk of being locked in bad technology choice. Alternative design of the scenarios, with uncertainty over the whole model horizon might allow for combining long periods of uncertainty and uncertainty on less distant events. But the resolution for such scenarios with stochastic programming would be indeed problematic. Nevertheless, in this case, one might think about using alternative numerical methods such as Approximate Dynamics Programming methods [Webster et al., 2012].
But if alternative formulations of the technologies, richer and better designed scenarios can help retrieving more sensitivity of energy technology choices to uncertainty, some limitations will persist. They are deeply rooted in the welfare maximization nature of MERGE (and several other models) and to the representation of how firms relate to uncertainty. The results of Chapter 1 and 2 tell us that in a micro-founded model like MERGE, uncertainty on prices is not necessarily translated into investment decisions. These results are not in line with the view that rational forward-looking agents’ investments are influenced by their view on possible future prices. But they can be explained by the fact that even if MERGE is micro-founded, it is not an agent-based model. In chapter 3, we stressed that the constraints on the regional energy technology portfolio generate externalities. Consequently, the results of the model, computed by welfare maximization, are not consistent with the behavior of separate small agents that base their investments on expected market prices. What the model gives us is a welfare maximizing outcome. But it also gives indirectly, on the basis of dual variables associated with the portfolio constraints and using the formula of Chapter 3, the taxes and subsidies to implement this outcome in a decentralized setting. When the portfolio constraints are binding, the uncertainty is passed to the dual variables associated with the portfolio constraints. Therefore, by construction, we have models where the policies adjust optimally so that the firm’s cash flows are secured.

Actually, one can doubt that policy compensate uncertainty. On the contrary, policies can increase the uncertainty faced by the energy firms. To study such situations, one must shift the modeling approach away from welfare maximization to represent exogenous policies about the energy mix. This would be possible with agent-based energy submodels. In terms of mathematical programming, one could use a Mixed Complementarity Problem (MCP) formulation of the general equilibrium model. Such a formulation might be inspired by the work done in Chapter 5, where a top-down model, derived from MERGE has been solved using a MCP format.

Another missing element that is fundamental for risk analysis and that could make the use of stochastic scenarios more interesting is a better representation of the way private firms deal with risk. In the simulations proposed, the agents based their action on maximization of expected criteria (utility or profits). A alternative representation of the way firms behave under uncertainty might be complemented by using risk functions that represent their aversion to the less favorable outcome. Such risk function, for instance Conditional Value at Risk (CVaR), have been already used in partial equilibrium power capacity expansion models [Ehrenmann and Smeers, 2011]. Using risk functions for the firms might give a better view of the way they react and adjust their invest-
ments in an uncertain world. This might create important risk premia on the rate of return of the projects developed. But this approach requires an explicit representation of the cash flows in the model and therefore a MCP formulation.

What we learn about benchmark scenarios in general equilibrium models

Chapter 5 was devoted to studying the impact of the choice of a benchmark scenario on counterfactual policy analysis. The sensitivity of the French economy to an asymmetric shock on carbon price is compared for alternative benchmarks that represent alternative views on the future of the French economy. The benchmarks are contrasted in terms of intra-sectorial energy efficiency gains and shares of energy-intensive activities in the French economy. The results illustrate the dependency of the response to the choice of the benchmark scenario. In particular, the dependency of the GDP contraction to assumptions about energy efficiency gains and reshuffling of industrial activity. In addition, we put forward some effects of the benchmark scenario choice on the policy analysis that are conveyed by terms-of-trade adjustments.

But for such a policy analysis, the biggest challenge was the building of alternative non-stationary benchmark scenarios that represent contrasted views of the future. The building process was presented in Chapter 4. In this chapter, we showed that benchmark scenarios need to satisfy two conditions. The first condition that we called relevance is the consistency with the modeler’s views on the future. It can be seen as distance criteria with some external projection the modeler refers to. Alternatively, if projections are not available, the definition of relevance might require the daunting task of specifying a full set of conditions on the prices, quantities and revenues contained in the model. The second condition is replicability: the benchmark scenario has to be replicable with the general equilibrium model. Equivalently, the scenarios have to be Walrasian, i.e., the flows represented have to fulfill some value-preservation properties. In a static setting, these properties are those on which Social Accounting Matrices are built. In a dynamic model the Walrasian flow property requires not only intra-temporal, but also inter-temporal value preservation. For non-stationary scenarios, the set of Walrasian scenarios is non-convex. The non-convexity adds up to the problems related to the specification of relevant scenarios and makes the direct computation of benchmark scenarios with mathematical programming very difficult. The only solution to obtain relevant and replicable scenarios is backward engineering. The backward engineering procedure is based on the computation of general equilibrium models, starting from a stationary calibration. The outcome represents Walrasian flows. Then, from the stationary outcomes, some
elements are adjusted so as to obtain a non-stationary path that matches the modeler’s view of the future. However, the control over the computed benchmark remains loose.

The efforts for a better computation of benchmark scenario should be continued. The heuristic method proposed in Chapter 4 is quite rough yet. It remains very difficult with such an approach to get a precise representation of some beliefs about the future of the economy. But the calibration problem might be stated in mathematical programming in a different way. If one manage to find a benchmark scenario, it is possible to minimize the distance between this scenario and the benchmark under the replicability constraints. As these replicability constraints represent equilibrium conditions one might think about using a formulation of the calibration problem in terms of Mathematical Programming with Equilibrium Constraints (MPEC) and about using the related literature. This type of approach should be experienced first on models far more stylized than the one in Chapter 5.
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<table>
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<td>European Union CO\textsubscript{2} price</td>
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<td>Expected 2020-2025 CO\textsubscript{2} price increase and stock of banked emissions permits in 2020 in the European Union, with respect to the hard-cap probability</td>
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<td>Structure of the stochastic scenario for each variable of the model</td>
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<td>Efficient labor (plain lines) and achieved GDP growth (dotted lines) at equilibrium in OECD and non-OECD regions for ( p = 0.5 )</td>
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<td>CO\textsubscript{2} price in the European Union in deterministic and ( p = 0.5 ) scenarios</td>
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<td>CO\textsubcript{2} price in the European Union in deterministic and ( p = 0.8 ) scenarios</td>
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<td>World power production capacity in the R2015 branch for ( p = 1 ) and ( p = 0.2 )</td>
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<td>World power production capacity in the NR branch for ( p = 0 ) and ( p = 0.8 )</td>
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<td>World power generation capacity with CCS in the deterministic and ( p = 0.5 ) scenarios</td>
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APPENDIX
Appendix A

Complements to Chapter 1

A.1 simulated energy consumption and prices

Figure A.1: World coal consumption
APPENDIX

Figure A.2: World oil price and consumption

Figure A.3: Gas price in the European Union and world gas consumption
Figure A.4: Total electric consumption in OECD and non-OECD regions and power prices in the European Union and China
A.2 Technologies used in the deterministic and equiprobable scenarios
### Table A.1: Technologies used in the European Union for the deterministic and equiprobable scenarios

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<sup>a</sup> SC (HC) means in the soft-cap (hard-cap) branch.

<sup>b</sup> % shares of the technologies in total electric and non-electric energy production.
## Table A.2: Technologies used in North America for the deterministic and equiprobable scenarios

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\(^a\) SC (HC) means in the soft-cap (hard-cap) branch.

\(^b\) % shares of the technologies in total electric and non-electric energy production.
### Table A.3: Technologies used in China for the deterministic and equiprobable scenarios

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<td></td>
<td></td>
</tr>
<tr>
<td>gas for direct use</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Total (in Mtoe)</strong></td>
<td>786</td>
<td>1522</td>
<td>1956</td>
<td>1511</td>
<td>1805</td>
<td>1518</td>
<td>1978</td>
<td>1788</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> SC (HC) means in the soft-cap (hard-cap) branch.

<sup>b</sup> % shares of the technologies in total electric and non-electric energy production.
Appendix B

Log-linearization

For small deviations of $\tau$ from $\bar{\tau}$, we can log-linearize the system and expressed it as a linear system linking $\hat{\tau}$ and $\hat{V}$, with $\hat{\tau} \equiv (\tau - \bar{\tau})/\bar{\tau}$ and $\hat{V} \equiv (V - V^*)/V^*$. Household's income:

$$\hat{M} = A_1 \hat{P}_t + \sum_{t=1}^{T} \left( A_{5,t}^* \hat{W}_t + A_{5,t}^* (\hat{E}_t + \hat{P}_t + \hat{\tau}_t) \right) - A_{6,t}^* (\hat{P}_T + \hat{K}_T) + A_{5,t}^* (R K_T + \hat{K}_T)$$

Zero-profit conditions:

$$\hat{P}_t = A_{6,t}^* R K_t + A_{7,t}^* \hat{W}_t + A_{8,t}^* \hat{P}_{E,t}$$
$$\hat{P}_{t-1} = A_{9,t}^* R K_{t-1} + A_{10,t}^* \hat{P}_t$$
$$\hat{P}_{E,t} = A_{11,t}^* \hat{P}_t + A_{12,t}^* \hat{P}_{E,t}$$

Market-clearing conditions:

$$\hat{K}_t = A_{13,t}^* \hat{K}_{t-1} + A_{14,t}^* \hat{I}_t, \quad \hat{K}_0 = 0, \quad \hat{L}_t = 0$$
$$\hat{Z}_t = A_{15,t}^* \hat{C}_t + A_{16,t}^* \hat{I}_t + A_{17,t}^* \hat{X}_t$$

Demand functions:

$$\hat{K}_t - \hat{Z}_t = \sigma (\hat{P}_t - R K_t), \quad \hat{L}_t - \hat{Z}_t = \sigma (\hat{P}_t - \hat{W}_t),$$
$$\hat{E}_t - \hat{Z}_t = \sigma (\hat{P}_t - \hat{P}_{E,t}), \quad \hat{C}_t = \hat{M} - \hat{P}_t, \quad \hat{X}_t = \hat{E}_t$$

Condition for final investment

$$\hat{I}_T - \hat{I}_{T-1} = \hat{C}_T - \hat{C}_{T-1}$$
The parameters $A$ are defined as:

\[
\begin{align*}
A_1^t &= (1 - \delta)P_t^* K_t^*/M^*, \quad A_{2,t} = L_t^* W_t^*/M^*, \quad A_{3,t} = \bar{\tau} P_t^* E_t^*/M^*, \\
A_{4,t}^* &= P_t^* K_t^*/M^*, \quad A_{5,t}^* = R K_t^* - K_t^*/M^*, \quad A_{6,t}^* = (R K_t^* K_t^*)/(P_t^* Z_t^*), \\
A_{7,t}^* &= (L_t^* W_t^*)/(P_t^* Z_t^*), \quad A_{8,t}^* = (P_t^* E_t^*)/(P_t^* Z_t^*), \quad A_{9,t}^* = R K_{t-1}^*/P_{t-1}^*, \\
A_{10,t}^* &= (1 - \delta) P_t^*/P_{t-1}^* \quad A_{11,t}^* = (P_t^* E_t^*)/(P_{E,t}^* X_t^*), \quad A_{12,t}^* = \bar{\tau} P_t^*/P_{E,t}^*, \\
A_{13,t}^* &= (1 - \delta) K_t^*/K_{t-1}^*, \quad A_{14,t}^* = I_t^*/K_t^*, \quad A_{15,t}^* = C_t^*/Z_t^*, \\
A_{16,t}^* &= I_t^*/Z_t^* \quad A_{17,t}^* = X_t^*/Z_t^*.
\end{align*}
\]
Appendix C

MCP formulation of the carbon leakage model

C.1 Notations

The variables in the model:

- $C_{j,t}$: Quantity of goods $j$ consumed by the household at time $t$
- $DEF_t$: Trade deficit / foreign savings at period $t$, expressed in current foreign currency.
- $E$: is the sum of discounted household’s consumption expenditures
- $EM_t$: Total regional CO$_2$ emissions
- $EX_{j,t}$: Quantity of goods $j$ exported at time $t$
- $EXR_t$: Exchange rate in the economy (value of the foreign currency in Euros)
- $I_{i,t}$: Investment in industry $i$ at time $t$
- $IM_{j,t}$: Quantity of goods $j$ imported at time $t$
- $IV_{i,j,t}$: Quantity of good $j$ used to create capital at period $t$
- $K_{i,t}$: Stock of capital is sector $i$ at time $t$
- $k_{i,t}$: Stock of capital required by vintage $t$ sector $i$ at time $t$
- $L_{i,t}$: Quantity of labour used in sector $i$ at time $t$
- $l_{i,t}$: Quantity of labour used by the new vintage in sector $i$ at period $t$
- $LT_t$: Overall quantity of labour at time $t$
- $lt_t$: Overall quantity of labour used in new vintages period $t$
- $P_{j,t}$: Price of good $j$ at time $t$
- $PD_{j,t}$: Price of the domestic good $j$ at time $t$
- $PDW_{j,t}$: Present value of the international price of the domestic product $j$ at time $t$
- $PDWC_{j,t}$: Current value of the international price of the domestic product $j$ at time $t$
C.2 Technologies and labor supply with putty-clay functions and exponential decay

C.2.1 Production with vintage: zero-profit condition and conditional factor demand

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

\[
\min_{X_i, K_i, L_i} \sum_t \left[ \sum_{j \in J_i} P_{j,t} x_{i,j,t} + RK_{i,t} k_{i,t} + W_{i,t} l_{i,t} \right]
\]

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

\[
X_{i,j,t+1} = x_{i,j,t} + (1 - \delta) X_{i,j,t}
\]

\[
K_{i,t+1} = k_{i,t} + (1 - \delta) K_{i,t}
\]

\[
L_{i,t+1} = l_{i,t} + (1 - \delta) L_{i,t}
\]

\[
F_t(x_{i,1,t}, \ldots, x_{i,J,t}, k_{i,t}, l_{i,t}) = z_{i,t} \quad (\lambda_t)
\]

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

\[
\min_{X_i, K_i, L_i} \sum_t m_t \left[ \sum_{j \in J_i} \sum_{n \geq 0} P_{j,t} x_{i,j,t} - n (1 - \delta)^n + \sum_{n \geq 0} RK_{i,t} k_{i,t} - n (1 - \delta)^n + \sum_{n \geq 0} W_{i,t} l_{i,t} - n (1 - \delta)^n \right]
\]

\[
F_t(x_{i,1,t}, \ldots, x_{i,J,t}, k_{i,t}, l_{i,t}) = z_{i,t} \quad (PD_{i,t})
\]

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

\[
\min_{x_{i,k}, l} \sum_t \left[ \sum_{j \in J_i} P'_{j,t} x_{i,j,t} + RK'_{i,t} k_{i,t} + W'_{i,t} l_{i,t} \right]
\]

\[
F_t(x_{i,1,t}, \ldots, x_{i,J,t}, k_{i,t}, l_{i,t}) = z_{i,t} \quad (PD'_{i,t})
\]

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

\[
\min_{x_{i,k}, l} \sum_{j \in J_i} P'_{j,t} x_{i,j,t} + RK'_{i,t} k_{i,t} + W'_{i,t} l_{i,t}
\]

\[
F_t(x_{i,1,t}, \ldots, x_{i,J,t}, k_{i,t}, l_{i,t}) = z_{i,t} \quad (PD'_{i,t})
\]
The prices noted with ′ are indexes of future prices defined as:

\[ P'_j,t = \sum_{m=0,...,T-t-1} (1-\delta)^m P_{j,t+m} + P_{j,T} P_{j,T-1}/(P_{j,T-1} - P_{j,T}(1-\delta)) \]

\[ PD'_i,t = \sum_{m=0,...,T-t-1} (1-\delta)^m PD_{i,t+m} + PD_{i,T} PD_{i,T-1}/(PD_{i,T-1} - PD_{i,T}(1-\delta)) \]

\[ RK'_i,t = \sum_{m=0,...,T-t-1} (1-\delta)^m RK_{i,t+m} + RK_{i,T} RK_{i,T-1}/(RK_{i,T-1} - RK_{i,T}(1-\delta)) \]

\[ W'_i,t = \sum_{m=0,...,T-t-1} (1-\delta)^m W_{i,t+m} + W_{i,T} W_{i,T-1}/(W_{i,T-1} - W_{i,T}(1-\delta)) \]

(C.5)

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

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

Finally, the decision of the final good producer with the putty-clay production function can be seen as a set of independent static production decisions with the CES technology corresponding and indexes of future prices. This allows us to cast the vintage problem in the textbook formulation of producer behavior with flexible technologies. If the production function is CES, the analytical computation of conditional factor demands can be directly derived from the many existing textbook examples that deal with flexible technologies. In particular, in the case of the production function defined in (5.1), at each period, the conditional factor demand can be derived from Varian [1992]:

\[ X_{i,j,t+1} = X_{i,j,t}(1-\delta) + a_{i,j,t+1} \left( \frac{PD'_{i,t+1}}{PD_{i,t+1}} \right)^{\sigma_i} z_{i,t+1}, \quad j \in J_i \]

\[ K_{i,t+1} = K_{i,t}(1-\delta) + a_{i,K,t+1} \left( \frac{PD'_{i,t+1}}{RK_{i,t+1}} \right)^{\sigma_i} z_{i,t+1} \quad (C.6) \]

\[ L_{i,j,t+1} = L_{i,j,t}(1-\delta) + a_{i,L,t+1} \left( \frac{PD'_{i,t+1}}{W'_{i,t+1}} \right)^{\sigma_i} z_{i,t+1} \]
And the zero profit condition is:

\[ PD_{i,t}^{1-\sigma_i} = \sum_{j \in J_i} a_{(prod),i,j,t}^{\sigma_i} + a_{(prod),i,K,t}^{\sigma_i} RK_{i,t}^{1-\sigma_i} + a_{(prod),i,L,t}^{\sigma_i} W_{i,t}^{1-\sigma_i}, t \geq 1 \]

**C.2.2 Household Labor supply**

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

\[ \max_{t \geq 1} W_{i,t} L_{i,t} \]

\[ \hat{L}_{t+1} = \hat{L}_t(1 - \delta) + \hat{l}_{t+1}, \quad t < T \]

\[ L_{i,t+1} = L_{i,t}(1 - \delta) + l_{i,t+1} \quad (C.7) \]

\[ \hat{l}_{t} = \left[ \sum_{i} a_{(labor),i,t}^{\frac{\sigma_{L} + 1}{\sigma_{L} + 1}} \right]^{\frac{\sigma_{L} + 1}{\sigma_{L} + 1}} (\lambda_{(l)t}) \]

At equilibrium, the dual variable \( \lambda_{(l)t} \) is equal respectively to the value of the wage aggregate \( WT_{i} \).

Similarly to the cost-minimizing problem of the producer with vintages (equation C.1), this problem of labor supply can solved as \( t \) independent problems of the form:

\[ \max_{t \geq 1} W_{i,t}' L_{i,t} \]

\[ \hat{L}_{t} = \left[ \sum_{i} a_{(labor),i,t}^{\frac{\sigma_{L} + 1}{\sigma_{L} + 1}} \right]^{\frac{\sigma_{L} + 1}{\sigma_{L} + 1}} (WT_{i}') \quad (C.8) \]

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

\[ L_{i,t+1} = (1 - \delta)L_{i,t} + a_{(prod),i,L,t}^{\sigma_i} W_{i,t}^{1-\sigma_i} PD_{i,t}^{1-\sigma_i} z_{i,t+1} \quad i = e, is, ns \]

And the zero profit condition for labor supply:

\[ WT_{i,t}^{1+\sigma_L} = \sum_{i} a_{(labor),i,t}^{\sigma_L} W_{i,t}^{1+\sigma_L}, \quad t \geq 1 \]

With \( WT_{i}' \) the index of total wage, defined as:

\[ WT_{i,t}' = \sum_{m=0,...,T-t-1} (1 - \delta)^m WT_{i,t+m} + WT_{i,T}WT_{i,T-1}/(WT_{i,T-1} - WT_{i,T}(1 - \delta)) \]

\[ (C.9) \]
C.3 The model’s equations

C.3.1 Household’ budget balance

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

$$HC_t + S_t = \sum_i RK_{i,t}K_{i,t} + \sum_i W_{i,t}L_{i,t} + DEF_tER_t + \text{er} \cdot IM_{f,t} \cdot PU_{t} \cdot TAX_{\text{co}_2,t} + PR_t$$

Profits less carbon tax are:

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

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

C.3.2 Zero profit conditions

On the composition of the consumption basket:

$$PU_{t}^{1-\sigma_C} = \sum_j a^{\sigma_C}_{(\text{cons}),j,t} P_{j,t}^{1-\sigma_C} \quad t \geq 1$$

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

$$PD_{i,t}^{1-\sigma_i} = \sum_{j \in J_i} a^{\sigma_i}_{(\text{prod}),j,t} P_{j,t}^{1-\sigma_i} + a^{\sigma_i}_{(\text{prod}),i,K,t} RK_{i,t}^{1-\sigma_i} + a^{\sigma_i}_{(\text{prod}),i,L,t} W_{i,t}^{1-\sigma_i} \quad t \geq 1$$

On the labor composite:

$$W_{t}^{1-\sigma_L} = \sum_i a^{\sigma_L}_{(\text{labor}),i,t} W_{i,t}^{1+\sigma_L} \quad t \geq 1$$

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

\[ P_{f,t} = ER_t \cdot PIW_{f,t} + e_r \cdot PU_t \cdot TAX_{co2,t}, \quad t \geq 1 \]
\[ P_{c,t} = PD_{c,t} \]

On the production of capital goods:

\[ PV_{i,t} = a_{(capital),i,\text{i,s},t} P_{\text{i,s},t} + a_{(capital),i,\text{n,s},t} P_{\text{n,s},t}, \quad i = e, \text{i,s}, \text{n,s}, \quad t \geq 1 \]

On the composition of the Armington good:

\[ P_{1}^{1-\sigma Y,i}j_{i,t} = a_{\text{dom},i,t}^{\sigma Y,i} P_{D1}^{1-\sigma Y,i} + a_{\text{for},i,t}^{\sigma Y,i} P_{1}^{1-\sigma Y,i} \quad i = \text{i,s}, \text{n,s}, \quad t \geq 1 \]

On the inter-temporal transfer of investment goods:

\[ PV_{i,t} = RK_{i,t} + PV_{i,t+1}(1-\delta), \quad i = e, \text{i,s}, \text{n,s}, \quad t \geq 1 \]

On the inter temporal transfer of consumption:

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

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

\[ PI_{j,t} = EXR_t \cdot PIW_{j,t}, \quad j = f, \text{i,s}, \text{n,s} \]
\[ PD_{j,t} = EXR_t \cdot PDW_{j,t}, \quad j = \text{i,s}, \text{n,s} \]

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

\[ PIW_{j,t} = PU_t \cdot PIWC_{j,t}, \quad j = f, \text{i,s}, \text{n,s} \]
\[ PDW_{j,t} = PU_t \cdot PDWC_{j,t}, \quad j = \text{i,s}, \text{n,s} \]

C.3.3 Conditional demand conditions

As written in Equation (5.9), the period \( t \) present-value consumption expenditure of a household represents a fraction \( \beta_t \) of its total present value expenditures.

\[ \beta_t E = HC_t, \quad t \geq 1 \]

At a period \( t \), the household’s Marshallian demand of good \( j \) is:

\[ C_{j,t} = a_{(cons),j,t}^{\sigma_{C}} P_{j,t}^{-\sigma_C} PU_t^{\sigma_C-1} HC_t, \quad t \geq 1 \]
The conditional labor supply by the households derived is computed in Appendix C.2.2 as:

\[ L_{i,t} = (1 - \delta)L_{i,t} + a_{(labor),i,t+1}^{\sigma_L} W_{i,t+1}^{\sigma_L} W_{t+1}^{\sigma_L} \]

The conditional demand for intermediate consumption is computed in Appendix C.2.1 as:

\[ L_{i,t+1} = (1 - \delta)L_{i,t} + a_{prod}^{\sigma_i} \sigma_i^{(prod)} i,t,PD_{i,t}^{\sigma_i} P_{i,t}^{\sigma_i} \]
\[ K_{i,t+1} = (1 - \delta)K_{i,t} + a_{prod}^{\sigma_i} \sigma_i^{(prod)} K_{i,t}^{\sigma_i} PD_{i,t}^{\sigma_i} P_{i,t}^{\sigma_i} \]
\[ X_{i,j,t+1} = (1 - \delta)X_{i,j,t} + a_{prod}^{\sigma_i} \sigma_i^{(prod)} X_{i,j,t}^{\sigma_i} PD_{i,t}^{\sigma_i} P_{i,t}^{\sigma_i} \]

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

\[ IV_{i,j} = a_{(capital),i,j,t} I_{i,t} \]

The conditional demand for domestic and foreign goods are:

\[ ZD_{j,t} = a_{(dom),j,t}^{\sigma_Y} PD_{j,t}^{\sigma_Y} Y_{j,t} \]
\[ IM_{j,t} = a_{(for),j,t}^{\sigma_Y} PD_{j,t}^{\sigma_Y} Y_{j,t} \]

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

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

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

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

Foreign supply function (supply for import) and foreign demand of domestic goods (demand for exports) were given by equations (5.5 and 5.6).

C.3.4 Market clearing conditions

The import of fossil fuels is equal to fossil fuel use (households’ and intermediate consumption).

\[ IM_{f,t} = C_{f,t} + \sum_{i=e,is,ns} X_{i,f,t} \]

150
Electricity production is equal to electricity use (household’s and intermediate consumption).

\[ Z_{c,t} = C_{c,t} + \sum_{i=i,s,ns} X_{i,c,t}, \quad t \geq 1 \]

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

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

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

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

C.3.5 Initial conditions

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

C.3.6 Model closure and the Walras law

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

\[ S_t + PU_1 \cdot EXR_t \cdot DEF_t = \sum_i PV_{i,t} I_{i,t} \]

If all the market-clearing conditions of section hold and if the other general equilibrium conditions are met, the last market, which is the market for foreign capital clears. The trade deficit is financed by the flow of foreign capital, i.e. equation (5.7) is satisfied.

C.4 Computation of the scaling factors from a benchmark scenario
### Scaling factors (a)

<table>
<thead>
<tr>
<th>Scaling factor formula</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{(prod),i,j,t} )</td>
<td>( \frac{P_{i,t} z_{i,j,t}}{P_{D,i,t} z_{i,j,t}} )</td>
</tr>
<tr>
<td>( a_{(prod),i,K,t} )</td>
<td>( \frac{BK_{i,t} z_{i,t}}{P_{D,i,t} z_{i,t}} )</td>
</tr>
<tr>
<td>( a_{(prod),i,L,t} )</td>
<td>( \frac{W_{i,t} l_{i,t}}{P_{D,i,t} z_{i,t}} )</td>
</tr>
<tr>
<td>( a_{(cap),i,is,t} )</td>
<td>( \frac{I_{i,is,t}}{IV_{i,t}} )</td>
</tr>
<tr>
<td>( a_{(cap),i,ns,t} )</td>
<td>( \frac{I_{i,ns,t}}{IV_{i,t}} )</td>
</tr>
<tr>
<td>( a_{(dom),j,t} )</td>
<td>( \frac{PD_{i,t} Z_{D,i,t} \left( \frac{Y_{i,t} - \sigma_{Y,i}}{\sigma_{Y,i}} \right)^{\sigma_{Y,i} - 1}}{PD_{i,t} Z_{D,i,t} \left( \frac{Y_{i,t} - \sigma_{Y,i}}{\sigma_{Y,i}} \right)^{\sigma_{Y,i} - 1}} )</td>
</tr>
<tr>
<td>( a_{(far),j,t} )</td>
<td>( \frac{P_{i,t} Y_{i,t} \left( \frac{Y_{i,t} - \sigma_{Y,i}}{\sigma_{Y,i}} \right)^{\sigma_{Y,i} - 1}}{P_{i,t} Y_{i,t} \left( \frac{Y_{i,t} - \sigma_{Y,i}}{\sigma_{Y,i}} \right)^{\sigma_{Y,i} - 1}} )</td>
</tr>
<tr>
<td>( a_{(im),j,t} )</td>
<td>( \frac{IM_{j,t}}{PI_{j,t}} )</td>
</tr>
<tr>
<td>( a_{(ex),j,t} )</td>
<td>( \frac{EX_{j,t}}{PDWC_{j,t}} )</td>
</tr>
<tr>
<td>( \beta_t )</td>
<td>( \frac{HC_t}{E} )</td>
</tr>
<tr>
<td>( a_{(cons),j,t} )</td>
<td>( \left( \frac{C_{j,t}}{HC_t} \right)^{1/\sigma_{C,j}} \frac{1^{1-\sigma_{C,j}}}{P_{i,t}} )</td>
</tr>
<tr>
<td>( a_{(labor),i,t} )</td>
<td>( \frac{W_{i,t} l_{i,t}}{W_{T,i,t}} )</td>
</tr>
</tbody>
</table>

Table C.1: Formulas to compute the scaling factors from a benchmark scenario