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REGIONAL IMPACTS OF THE GLOBAL CARBON STAKES: LONG-TERM PROSPECTIVE WITH THE TIMES INTEGRATED ASSESSMENT MODEL (TIAM)

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Abstract

The aim of this study is to discuss the Copenhagen commitments, using the modelling tool TIAM-FR, and to propose some keys to understanding long-term climate policy. More precisely, we investigate different coordination schemes for regions that have pledged to reach CO_2 mitigation targets during the period 2005-2050. Using regional carbon constraint scenarios, we show what these possible futures represent for different regions committed to the Copenhagen Agreement. Our analysis mainly focuses on the effects of these environmental constraints on several indicators such as, global and regional CO_2 emissions, the cost of the climate policy, the carbon marginal costs, the progress of primary energy consumption and the energy mix. This paper compares global efforts on CO_2 mitigation with the marginal cost of carbon for a variety of climate policies and focuses on the evolution of the energy mix. Lastly, it discusses the plausibility of developing CO_2 storage technologies to satisfy the carbon constraints.

JEL

O21, Q29, Q4, Q54, Q58

Keywords

Global energy system, CO_2 mitigation targets, ETSAP/TIAM-FR, Long-term modelling, International agreements, Carbon Capture and Storage (CCS)

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1. INTRODUCTION

In late January 2010, some countries pledged their commitment to the United Nations Framework Convention on Climate Change (UNFCCC) as part of the Copenhagen Agreement to mitigate CO_2 emissions in line with various targets. Although this international agreement did not meet up to expectations, it laid the first foundations of the post-Kyoto global fight against climate change, which was not an easy task. It is worth taking a look at the context of its creation.

1.1. International framework

Over recent years, the climate change debate has not only seen increased scientific evidence published in the fourth IPCC assessment report, but also a number of major political events: the approval of the EU climate package by the EU parliament in December 2008, a shift in the US, with greener positions expressed by the new administration, and the high participation of developed and developing countries at the Copenhagen Climate Change Conference (COP 15), in December 2009. The international agreement made at COP 15 was to be the last step in the two-year negotiation process determined at the 2007 Bali conference. The Kyoto Protocol was signed ten years earlier in 1997 and aimed to address climate change, and more precisely a 5% reduction in GHG emissions over the period 2008-2012 for the industrialized countries included in Annex I.

For the post-Kyoto period, i.e. beyond 2012, no international agreement had been planned, and this was the aim of COP 15. In the event of a failure in negotiations at Copenhagen, no process would be in place. It was therefore essential to ensure the signing of a global agreement at the Copenhagen conference, including all major industrialized countries (and primarily the United States, which had not ratified the Kyoto Protocol), and for the first time, the fastest developing countries whose economic activities and demographic prospects constitute real challenges for the coming decades. This was a major issue for 2009, both for Europe and for all other countries that are resolutely committed to fighting climate change.

1.2. Current context of the pledges

For the long term, a noticeable convergence existed between the views expressed by the European Union and the Obama-Biden new energy plan for America. However, the deal on medium-term targets was far from sealed. On the one hand, the European Union pledged to reduce its carbon dioxide (CO_2) emissions by 20% compared to its 1990s level by 2020, and was prepared to commit to additional efforts ratified by international agreements. This would involve a 30% reduction in emissions by 2020. On the other hand, the current medium-term target for the USA was a 17% reduction on 2005 levels by 2020. While this represents a significant step, it roughly leads to a mere stabilization at 1990 levels by 2020. At the same time, the USA also stressed a need for mitigation efforts from fast-growing transition countries such as China and India.

A crucial factor to finding global agreement in 2009 was whether industrialized countries would keep their promises of aiding developing countries so that they could adapt to the impacts of climate change. After many years of discussion, the Poznan conference in December 2008 finally allowed a better utilization of funds allocated to adaptation. Although still highly inadequate, consensus concerning their utilization had proved difficult to reach. This commitment had to be confirmed in 2009 to provide tools and resources for meeting arising challenges. Without these, developing countries, which are vulnerable and highly affected by the climate change, would not commit to reducing their own greenhouse gas (GHG) emissions.

It was imperative that such mitigation policies be promptly considered by these countries, primarily China, India, and Brazil, which will represent a majority share of global emissions in the near future. For example, in 2008 China surpassed Germany in terms of economic wealth, and the United States in terms of CO_2 emissions. Naturally, such positions left ample room for negotiations and one rule of the Copenhagen game was: what involvement is acceptable from others to define our own commitment level? The European Union was thus waiting for signs from other developed countries and in particular the US, who were in turn waiting for positive signs from China.

1.3. What is at stake now and for the future?

Even though negotiations during COP 15 failed to reach a global agreement on post-Kyoto greenhouse gas emission reductions, the stakes are no less crucial and the pledges announced at the beginning of 2010 consolidate this position.

The aim of this paper is to analyze the outcomes of different coordination schemes for intermediate mitigation targets. Using scenario analysis based on the ETSAP/TIAM-FR modelling tool, we assess for the period 2005-2050 the evolution of primary energy consumption, global and regional emission levels, and the global and regional costs of the climate policy. Section 2 presents the model we use for our investigation. Section 3 specifies the pledges for different regions. Various results are presented in section 4 before concluding in section 5.

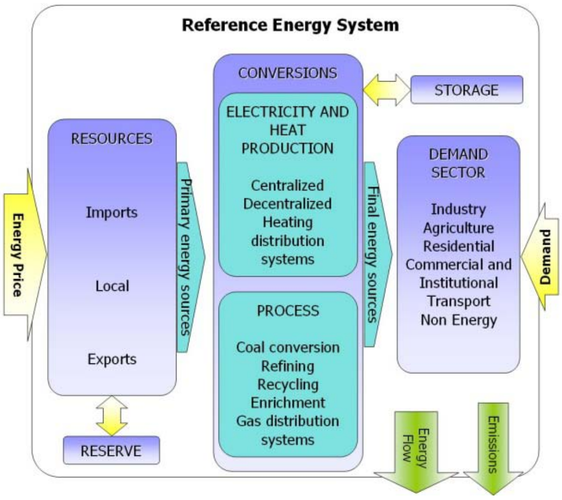
2. METHODS

Two types of model are commonly used to assess the implications of climate change mitigation: top-down general equilibrium macroeconomic models, which assess the whole economy but with a limited description of the energy system, and bottom-up models, which focus on the energy system, thus providing increased accuracy on this portion of the economic system. The analyses carried out in this paper are based on the ETSAP/TIAM-FR (the French version of the TIMES Integrated Assessment Model) bottom-up model developed under the Energy Technology Systems Analysis Programme (ETSAP) under the aegis of IEA (International Energy Agency).

2.1. Overview of the energy system with TIAM-FR

TIAM-FR is a technology-rich, bottom-up energy system model. It depicts the world energy system with a detailed description of different energy forms, resources, processes/technologies and end-uses. The link between the commodities and the technologies is described via a Reference Energy System (RES). Figure 1 gives a synthetic description of the RES covering the whole energy chain.

Figure 1: Synthetic view of the reference energy system



Source: Maïzi, Assoumou, Bordier, Guerassimoff, Mazauric, 2006

More precisely, the RES is a network of interlinked technologies (anything that produces and/or consumes commodities) and commodities (an energy form, an emission, a material, or an energy service). TIAM-FR includes several thousand technologies in all sectors of the energy system (energy procurement, conversion, processing, transmission, and end-uses). The system includes the extraction, transformation, distribution, end-uses, and trade of various energy forms and materials. Each economic sector is described by means of technologies, each characterized by its economic and technological parameters.

End-use demands (i.e. energy services) are based on socio-economic assumptions and are specified exogenously by the user in physical units (number of houses, commercial area, industrial production, vehicle-kilometers, etc.) over the planning horizon. However, contrary to traditional bottom-up models, TIAM acknowledges that demands are elastic to their own prices. This feature insures the endogenous variation of the demands in constrained runs (on emission or concentrations), thus capturing the vast majority of the macroeconomic feedback of the energy system. Thereby, the energy consumption in TIAM-FR is based on external projections of the growth of regional GDP as well as population and the volume of various economic sectors (transport, residential, industry, etc.).

These drivers and IEA statistics for a given base year, in this case 2000, are the basis for future projections of the consumption of different types of energy, such as road passenger transportation, steel demand and residential heating. In order to satisfy the demands, energy sources are extracted and in a number of steps, transformed into end-use demand commodities. The model contains a vast number of technology descriptions for energy production, transformation and end-use demands. The description of the technologies includes data on investment and operation costs, efficiency levels and, sometimes, market potential. The model also includes a number of other elements, such as user-defined constraints and international trade links.

2.2. Main features of TIAM-FR

TIAM-FR is the global multiregional version of the TIMES model generator, a linear programming model that estimates an inter-temporal partial economic equilibrium on integrated energy markets. The model assumes perfect markets and unlimited foresight for the calculation period, the described economic sectors, and commodities. In other words, the model minimizes, under environmental and technical constraints, the total discounted cost of the energy system over the entire model horizon [2000-2100]. The cost of the energy system includes investment costs, operation and maintenance costs, costs of imported fuels, incomes of exported fuels, the residual value of technologies at the end of the horizon, and welfare loss due to endogenous reductions in demand.

The model computes both the flows of commodities (energy forms, materials, and environmental), and their prices. The prices of the commodities are computed in such a way that, at the prices computed by the model, energy suppliers produce exactly the amounts that the consumers are willing to buy. The equilibrium feature is present at every stage of the energy system: primary energy forms, secondary energy forms, and energy services. TIAM-FR aims to supply energy services at minimum global cost by simultaneously making decisions on equipment investment, equipment operation, primary energy supply, and energy trade.

The main outputs of the model are future investments and activities of technologies for each time period. Furthermore, the structure of the energy system is given as an output, i.e. type and capacity of the energy technologies, energy consumption by fuel, emissions, energy trade flows between regions, transport capacities, detailed energy system costs, and marginal costs of environmental measures such as GHG reduction targets. The model tracks emissions of CO_2, CH_4, and N_2O from fuel combustion and processes. Emission reduction is brought about by endogenous reductions in demand, technology and fuel substitutions (leading to efficiency improvements and process changes in all sectors) and carbon sequestration (including CO_2 capture at the power plant and hydrogen plant level, sequestration by forests, and storage in oil/gas fields, oceans, aquifers, etc.). An additional output of the model is the implicit price, or opportunity cost (shadow price), of each energy form, material and emission.

2.3. Geographical representation

TIAM-FR is a global multiregional model. It is geographically integrated and offers a representation of the global energy system in 15 regions covering the entire world: Africa (*AFR*), Australia-New Zealand (*AUS*), Canada (*CAN*), China (includes Hong Kong, excludes Chinese Taipei; *CHI*), Central and South America (*CSA*), Eastern Europe (*EEU*), Former Soviet Union (includes the Baltic states, *FSU*), India (*IND*), Japan (*JPN*), Mexico (*MEX*), Middle-East (includes Turkey; *MEA*), Other Developing Asia (includes Chinese Taipei and Pacific Islands; *ODA*), South Korea (*SKO*), the United States of America (*USA*) and Western Europe (EU-15, Iceland, Malta, Norway and Switzerland; *WEU*). TIAM-FR describes the entire energy system of each region with regard to all essential current technologies from the primary energy supply (through the processing, conversion, transport and distribution of energy carriers) to the end-use sectors, as well as energy demands. The regions are linked by energy, material, and emission permit trading variables, if desired. The trade variables transform the set of regional modules into a single multiregional (possibly global) energy model, where actions taken in one region may affect all other regions. This feature is essential when global as well as regional energy and emission policies are simulated.

3. Scenario specification

To analyze possible alternative development paths of the system, we investigated a variety of environmental target scenarios on different regions of the world over the period 2005-2050. A baseline business as usual (BAU) scenario without any emission constraints was calculated first. In the reference scenario, no climate policy, and thus no post-Kyoto policy, is assumed. The BAU scenario outlined some key patterns in the evolution of the energy system, and served as the starting point for the analysis. Carbon constraint scenarios allowed us to investigate the changes induced by a strong environmental policy. Thus, the BAU scenario was compared to the emission mitigation scenarios to assess its implications on the future development of the energy system and formulate policy recommendations.

3.1. The four scenarios specified

In total, four scenarios were defined according to different long-term paths of carbon mitigation: **LowLow, LowUp, UpLow and UpUp**. These scenarios represent the CO_2 mitigation targets for post-Kyoto commitments expressed to UNFCCC for the Copenhagen Agreement in January 2010 by Western Europe, the United States of America, Australia, Canada, Japan, China and India.

Table 1: Scenarios specification

2050 TARGETS 2020	Optimistic	Pessimistic
Optimistic	Scenario **UpUp**	Scenario **UpLow**
Pessimistic	Scenario **LowUp**	Scenario **LowLow**

For the 2020 target, we consider the fixed pledges and the more or less important announced pledges following the optimistic or pessimistic scenario. The international community appears to converge on these long-term objectives. We also present environmental long-term targets devised for analyzing more or less ambitious future developments. The following table presents the various international coordination schemes analyzed.

Table 2: Scenarios specification

Regions	Reference year	Target level	Emission reduction		Reduction type	
			2020	2050	2020	2050
Western Europe	1990	Low	20%	60%	Emission reduction	
		Up	30%	80%		
USA*	2005	Fix	17%	83%	Emission reduction	
Australia	2000	Low	5%	60%	Emission reduction	
		Up	25%	80%		
Canada*	2005	Fix	17%	83%	Emission reduction	
Japan	1990	Fix	25%		Emission reduction	
		Low		60%		
		Up		80%		
China	2005	Low	40%	90%	Carbon intensity	Carbon intensity
		Up	45%	10%		Emission reduction
India	2005	Low	20%	60%	Carbon intensity	Carbon intensity
		Up	25%	10%		Emission reduction

*Intermediate targets are also introduced for the USA and Canada regarding their pledges to UNFCCC: 30% for 2025 and 42% for 2030

Note that for China and India, the commitment does not relate to emission levels but to carbon intensity (except for the optimistic 2050 target, i.e. scenarios LowUp and UpUp). This means that Indian and Chinese GDPs will continue to rise but their carbon emissions will have to increase at a lower rate due to greater energy efficiency and investment in greener technologies.

An important and well-known observation to note concerns the choice of reference year. Indeed, while Western Europe and Japan pledge for a CO_2 emission mitigation target up to 2020 compared to 1990 levels, other regions take 2005 (or 2000 for Australia) as the reference year. This naturally has a significant impact on targets. More precisely, what happens if we translate these pledges to the same reference year and follow the same type of reduction, i.e. emission mitigation?

3.2. Understanding the targets

The following table expresses commitments based on the same reference year, i.e. either 1990 or 2005, and the same reduction type (emission reduction) for each region considered.

Table 3: Understanding the targets

Regions	On 1990 scale (+/-)		On 2005 scale (+/-)	
	2020	2050	2020	2050
Western Europe	-20% to -30%	-60% to -80%	-44.9% to -51.8%	-72.5% to -86.2%
USA	-0.3%	-79.6%	-17%	-83%
Australia	+4.3% to -17%	-56.1% to -78%	-16.5% to -34.3%	-65% to -82.5%
Canada	+3.2%	-78.6%	-17%	-83%
Japan	-25%	-60% to -80%	-32.4%	-63.9% to -82%
China	+295.6% to +262.7%	+194.9 to +111.2%	+68.6% to +54.5%	+25.6% to -10%
India	+423.2% to +390.5%	+1318.7% to +85.6%	+153.8% to +137.9%	+588.1% to -10%

For example, in the case of China, by reducing carbon intensity by 40% by 2020 (*90% by 2050*) compared to 2005 is equivalent to limiting the increase of its CO_2 emissions by 295% in 2020 (*195% in 2050*) compared to 1990. This is immediately clear that we are not in the same context of commitment, whether for political, economic or technological reasons. For the **LowUp** and **UpUp** scenarios, in which China pledges to reduce its CO_2 emission levels by 10% by 2050 compared to 2005 levels, this is equal to limiting the increase of its CO_2 emissions to 111% in 2050 compared to 1990 levels. Therefore, due to wide variations in GDP projections, it is obvious that China cannot reasonably pledge a reduction in emissions with 1990 as a base year. Indeed, the annual average growth rate of China's GDP for the period 2000-2050 is 6.37%, and it totaled US$30 000 billion in 2050.

For the United States, a 17% reduction in its CO_2 emission levels by 2020 (*83% by 2050*) compared to 2005 levels, is, in all four scenarios, equivalent to a 0.3% reduction by 2020 (*79.6% by 2050*) compared to 1990 levels. It clearly emerges that the United States is committed to making less effort in the medium term, notably compared to Western Europe, even though the US has emitted a larger share of CO_2 emissions. In the long term, CO_2 emission mitigation in 2050 compared to 2005 is more comparable than optimistic targets of industrialized countries by 2050 compared to 1990.

Therefore, through the different targets, we can already note the levels of commitment announced by the regions, particularly the weaker medium-term targets of China and the United States. We wonder what these targets represent and involve for the different regions. Now we can move on to analyze the impact of these environmental measures on the cost of this policy and on the energy system for each region.

4. RESULTS

The previous scenarios are analyzed to compare the effects of international coordination on the main environmental and economic indicators. The impacts of different commitment levels under post-Kyoto policies can thereby be discussed. In the first part, an analysis of the optimization results focuses on the effects of climate policy on CO_2 emissions at global and regional level. In the second part, we discuss the total cost of the policy, the regional costs of avoided CO_2 (carbon marginal cost) associated with the different CO_2 mitigation targets and finally, the level of ambition of the CO_2 reduction targets. In the third part, the model shows the impact of international climate change strategies on the energy system. Analyses are performed to investigate the long-term development of CCS technologies in response to the constraint that influences the energy mix.

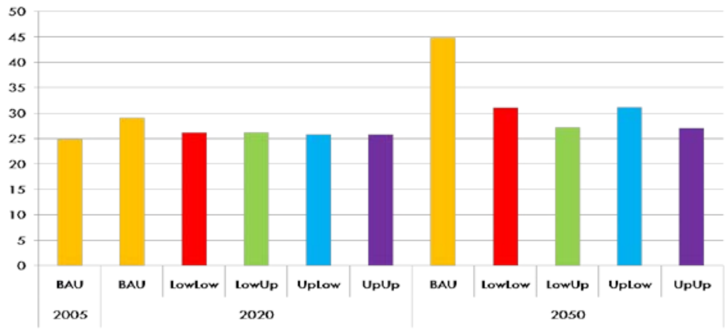
4.1. Global CO_2 stakes and regional ambitions

In this section, we present the major impacts of these climate targets in terms of CO_2 emissions. In the long term, the impact of the climate policies is more noticeable in terms of global CO_2 emissions, whether the scenario is optimistic or pessimistic, even though the effects of the ambitious target for 2050 are more significant compared to the BAU scenario. Then, in 2050, carbon constraints involve a decrease in emissions of more or less 15 Gt CO_2 (following optimistic or pessimistic targets for that year) in comparison with BAU.

In the medium term, the situation is different, with a less marked effect for all carbon constrained scenarios in 2020. For this target year, the level of CO_2 emissions for all climate policy scenarios is lower than for the BAU, yet there are similarities between them, and the level of global CO_2 emissions is only slightly lower than for the BAU. The level of global CO_2 emissions decreases by about 5 Gt in 2020 in comparison with the BAU scenario.

Figure 2 presents global CO_2 emissions according to the BAU scenario and the scenarios with different mitigation constraints.

Figure 2: Global CO_2 emissions (Gt CO_2)



Furthermore, the effect of the climate policies developed regarding COP 15 pledges are for the most part expected in the long term(by 2050), even for pessimistic targets. In the medium term (by 2020), the carbon constraint leads to a less noticeable decrease in CO_2 emissions. An interesting medium-term result is that the level of ambition of a climate policy does not really impact on global CO_2 mitigation.

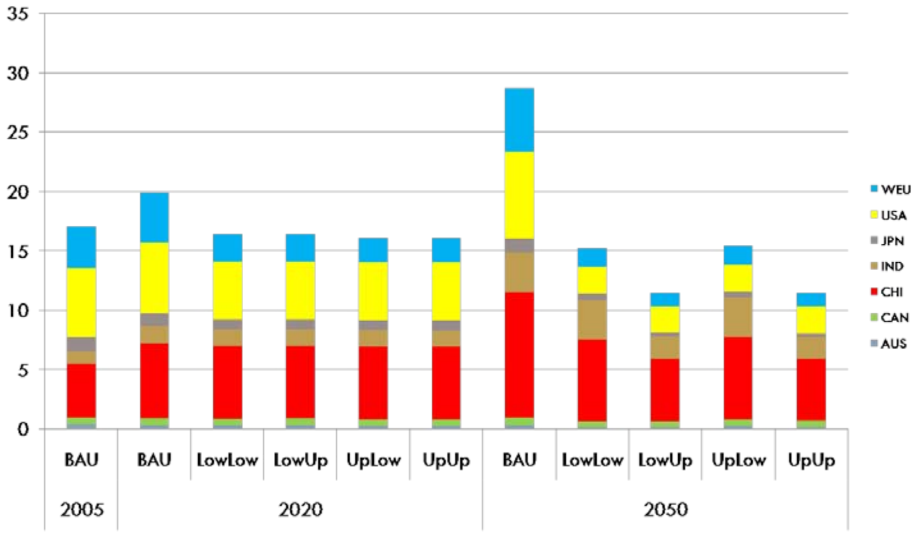
While environmental stakes involve global action, a more interesting observation concerns the impact of these various targets at regional scale. Indeed, the level of ambition of CO_2 mitigation from developed countries (especially the USA) and developing countries (particularly fast developing countries like China and India) is a determining factor in the post-Kyoto international agreement to establish a course of action for climate change. Global impact of the international agreement is the result of regional policies expressed in terms of CO_2 emission mitigation targets over the medium and long term. As seen above, these targets express more or less ambitious participation from various regions in the fight against climate change.

More precisely, the European Union, which before COP 15 was alone in committing to a Post-Kyoto international agreement, had pledged a 20% reduction in CO_2 emissions by 2020 compared to 1990 levels, and is prepared to commit to additional efforts in case of international agreements, i.e. to increase its pledge from 20% to 30%. Another point concerns the commitment of fast growing transition countries and particularly China and India. Indeed, while the European Union was waiting for signs from other developed countries and in particular the USA, the USA stressed the need for some mitigation efforts from China, and to a lesser extent India. China and India have pledged and committed themselves to the international agreement but only to marginal measurements. Equally, the USA's commitment and its implications are far from ambitious and satisfying in the medium term. Conversely, the impact of USA policy is clearly more noticeable in the long term. This point should be taken into account in the final target decided by the European Union.

In the international agreement investigated in this analysis, it appears important to distinguish between medium- and long-term targets. By 2020, the European Union, together with Japan, has pledged the biggest effort in combating climate change. This point is apparent in figure 3 showing regional CO_2 emissions according to the different scenarios.

The following graph expresses the CO_2 emissions of the constrained regions. The appendix includes those of the other countries. This graph obviously highlights how strong the European targets are for the medium and long term, for all carbon constraint scenarios. Western European CO_2 emissions in 2020 decrease from 4.2 Gt in the BAU scenario to 2 Gt in the carbon mitigation scenarios. In 2050, CO_2 emissions decrease from 5.3 Gt to 1.1 Gt, or 1.6 Gt for optimistic and pessimistic targets. The effect of the Japanese policy is stronger in the long term than in the medium term. Thus, if we compare the results of the climate scenarios with those of the BAU scenario, CO_2 emissions decrease from 1.1 Gt to 0.8 Gt in 2020. But, in 2050, CO_2 emissions reach 1.2 Gt in the BAU scenario against 0.5 Gt in the "Low" constraint scenarios and 0.3 Gt in the "Up" constraint scenario.

Figure 3: Regional CO_2 emissions (Gt CO_2)



For Australia, the effect of climate policy essentially appears in 2050, when CO_2 emissions decrease from 0.35 Gt to 0.20 Gt in the more optimistic scenario (for 2020, the best impact represents a decrease of 0.05 Gt in CO_2 emissions). The impact of Canadian targets is similar, in as much as in 2020, CO_2 emissions decrease from 0.58 Gt to 0.54 Gt and in 2050, from 0.67 Gt to 0.51 Gt. The Canadian government has committed to the same climate targets as the USA. Carbon mitigation targets pledged by the USA involve a more significant decrease in CO_2 emissions in the long term than the medium term. In 2050, carbon constraint scenarios ensure that the USA reduces its CO_2 emissions by more than two thirds in comparison with the BAU. More precisely, CO_2 emissions in 2020 reach 4.9 Gt in climate policy scenarios, against 6 Gt in the BAU scenario. In 2050, CO_2 emissions represent 2.2 Gt in carbon constraint scenarios, against 7.3 Gt in the BAU scenario.

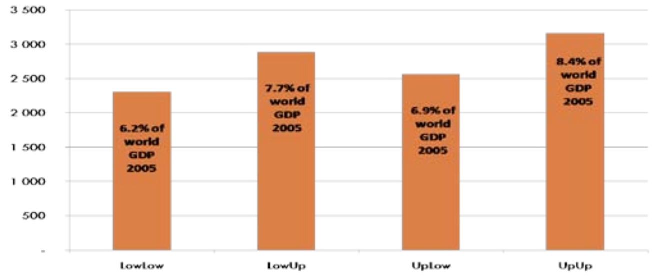
Results for China and India appear to be telltale signs of the effort that the Chinese and Indian governments are willing to make in the climate change context coupled with an economic context of fast growth, as their CO_2 mitigation target on carbon intensity leads us to suppose. Thus, for China, in 2020, CO_2 emissions represent 6.3 Gt in the BAU scenario and around 6.1 Gt in the climate scenario. In 2050, they represent 10.5 Gt in the BAU scenario and respectively 6.9 Gt and 5.2 Gt in the Low and Up climate scenarios. For India, in 2020, CO_2 emissions represent 1.4 Gt in the BAU scenario and are at the same level in the climate scenario. In 2050, CO_2 emissions reach 3.4 Gt in the BAU scenario and respectively 3.3 Gt and 1.8 Gt in the Low and Up climate scenarios. Considering these results, the impact of the climate target expressed in carbon constraint scenarios on the CO_2 emissions pathway is hardly noticeable. The weak impact of Chinese and the Indian climate commitments emerges clearly in the medium term. But for 2050, where there is no official position on their ambitions, 10% of mitigation based on the level of CO_2 emissions involves not only an effective impact, but also ambitious and concrete participation in the fight against climate change. One question could be: At what cost? This is the object of the following sub-section.

4.2. The cost of regional ambition

We studied the cost implications of these regional climate policies. First of all, scenario analysis provides the total discounted cost on the energy system and energy services market. This cost represents the global additional cost of CO_2 emissions mitigation constraints in comparison with the BAU scenario. Figure 4 expressed this additional cost incurred by climate policy. As we can see, the cost increases with the stringency of the carbon target, reaching 8.4% of world GDP (2005) with the most optimistic scenario (UpUp), wherein China and India are notably constrained in their CO_2

emissions level. In the most pessimistic scenario (LowLow), the discounted cost of the climate policy reaches USD 2,307 billion in 2005, which represents 6.2% of world GDP in the same year.

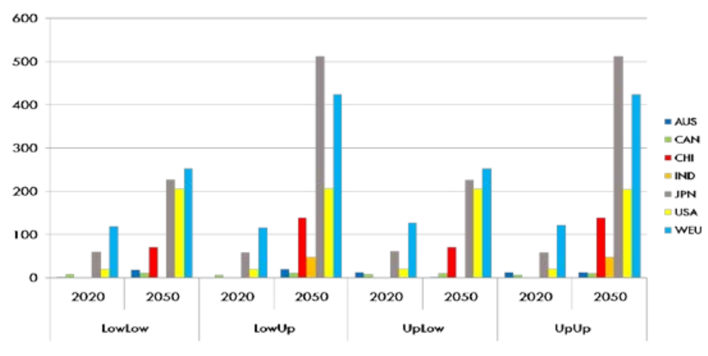
Figure 4: Global CO_2 mitigation target costs (USD billion 2005)



It is worth asking how this cost can be distributed between the different committed regions. Is climate policy through associated targets weighed in the same manner for all regions? To answer this question, we analyze the carbon marginal cost for the different regions and express the cost of one ton of avoided CO_2. Following this, the cost increase resulting from the stronger global constraints is also reflected in the carbon marginal costs of the various regions. This is particularly true for China. Indeed, China's CO_2 mitigation target by 2020 (a 40% or 45% reduction in carbon intensity), because it does not really impact on its level of CO_2 emissions, does not put pressure on the carbon marginal cost under the GDP growth effect, which minimizes the mitigation effort. The pressure appears in 2050. In the long term, the carbon target imposed on China sharply increases carbon marginal costs for this region, particularly in the optimistic scenario (a reduction of 10% of CO_2 emissions), where it reaches $140/t$CO_2$. The marginal cost of carbon reaches $71/t$CO_2$ in 2050 in the pessimistic scenario (a 90%reduction in carbon intensity).

This factor raises the question of the extent to which China is capable of supporting more ambitious targets. It is important to put regional CO_2 emission mitigation in perspective with the cost borne. In this analysis, the marginal cost of CO_2 reduction constitutes an indicator of what each region needs to manage to reach its commitment and also, indirectly, an indicator of the level of effort needed to achieve the various targets. The regional carbon marginal costs according to the various scenarios are given in the Figure 5. We note that India presents the same phenomenon as regards its carbon marginal cost; even though to a lesser extent expressing the least restrictive target it has pledged to. Null in 2020 whatever the scenario, the Indian marginal cost of CO_2 reaches $49/t$CO_2$ in 2050, but only for its optimistic target, i.e. when India pledges to reduce its carbon emissions by 10% by 2020 compared to 2005.

Figure 5: Regional carbon marginal costs ($/t$CO_2$)



This question of marginal cost also applies to Japan and Western Europe. The cost is a good reflection of the effort agreed to by the region to fight climate change. These burdens appear high for the four scenarios and especially for Japan with the optimistic target by 2050. More precisely, Japanese carbon marginal costs reach respectively \$512/tCO_2 and \$227/tCO_2 in 2050 for the optimistic and pessimistic targets (against around \$160/tCO_2 in 2020). For Western Europe, carbon marginal costs reach respectively \$425/tCO_2 and \$223/tCO_2 in 2050 following optimistic or pessimistic ambition levels (against between \$118/tCO_2 and \$128/tCO_2 in 2020).

Concerning the USA, their target medium-term induces a carbon marginal cost in 2020 of only \$21/tCO_2, which is low compared to those of Japan and Western Europe. In 2050, conversely, the average carbon marginal cost reaches \$206/tCO_2. This higher marginal cost in 2050 reflects the long-term deferment of CO_2 mitigation actions. Moreover, in their commitment to the Copenhagen Agreement, the USA have already pledged to the 2050 target, indicating intermediate targets (for 2025 and 2030) to guide the CO_2 mitigation pathway of their policy up to this long-term target. The USA is constrained by political barriers, which limit medium-term possibilities for the new government, despite its greener position. This pledge could be a way of expressing its ambition to act against climate change and to position the USA at the forefront of this global combat.

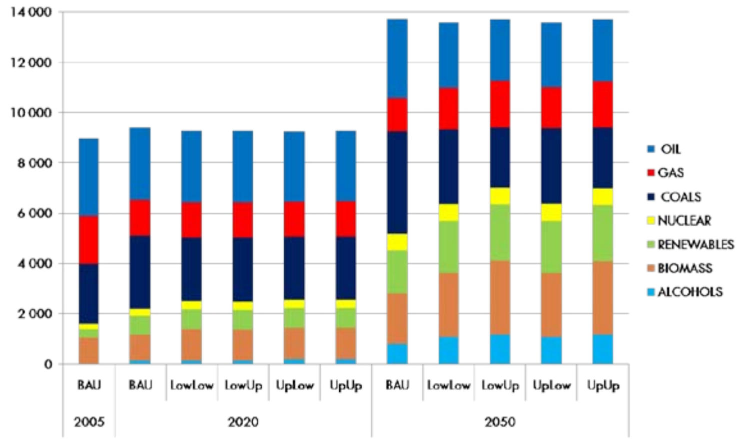
4.3. Policy implications on the energy system

Additional constraints imposed on the energy system involve variations in energy and technology choices. Here, climate policy with carbon emission mitigation influences the structure of the energy mix. However, impact is weak on the total volume of primary energy consumption, which noticeably increases, especially in 2050 and for all the scenarios. In the BAU scenario, primary energy consumption represents 8,998 Mtoe in 2005 and reaches 13,715 Mtoe in 2050, which represents an increase of more than 52%. The volume is similar for the four climate policy scenarios, both for 2020 and 2050. More precisely, carbon constraints have a weak effect on primary energy consumption, which decreases respectively to 1.55% and 0.6% on average in 2020 and 2050 by comparison with BAU levels.

4.3.1. Impact of climate policies on the energy mix

In 2005, in the BAU scenario, the world energy mix relied on 34.7% oil, 26.6% coal, 20.9% gas, 15.4% renewables and 2.4% nuclear. In 2020, the market is still dominated by fossil fuels but the share of renewables increases and surpasses gas. More precisely, in 2020, in the BAU scenario, the world energy mix relies on 30.8% coal, 30.7% oil, 20% renewables, 15% gas and 3% nuclear. We also note that coal takes over from oil as the most consumed primary energy. Figure 6 highlights the evolution of the primary energy supply mix in 2020 and 2050 according to all scenarios, and table 4 presents fuel shares in the energy mix.

Figure 6: Total Primary Energy Supply (mtoe)



If we compare the BAU and climate scenarios in 2020, carbon constraints lead to an increase of other renewables and biomass and to a lesser extent, nuclear. Gas is not really influenced by CO_2 mitigation actions, and the impact of climate policy on oil consumption is low in 2020 by comparison with the BAU scenario. Also, environmental targets lead to reduced coal supplies compared with the reference scenario. Moreover, coal supplies in carbon constraint scenarios in 2020 are only slightly greater than the 2005 level.

Table 4: Fuel shares in the energy mix (%)

Year	Scenario	Oil	Gas	Coals	Nuclear	RNW	Bio	Alcohols
2005	BAU	34.7	20.9	26.6	2.4	3.9	11.5	0.03
2020	BAU	30.7	15.1	30.8	3.2	7.9	10.9	1.4
	LowLow	30.6	15.2	27.0	3.7	8.5	13.5	1.4
	LowUp	30.6	15.4	27.1	3.7	8.5	13.3	1.4
	UpLow	30.1	15.2	26.9	3.8	8.5	13.5	2.0
	UpUp	30.2	15.3	26.9	3.7	8.5	13.4	2.0
2050	BAU	23.0	9.6	29.6	4.9	12.4	14.6	5.9
	LowLow	19.1	12.2	21.8	5.0	15.3	18.8	7.9
	LowUp	17.8	13.5	17.6	5.0	16.3	21.3	8.6
	UpLow	19.1	12.0	21.9	5.0	15.3	18.8	7.9
	UpUp	17.8	13.5	17.7	5.0	16.3	21.2	8.6

In 2050, in all scenarios, but to a larger extent in the carbon constraint scenarios, there is a further decline of the oil share, which reaches respectively 19.1% and 17.8% in “Low” and “Up” carbon constraints scenarios (and 23% in the BAU scenario).

Moreover, apparent differences occur in 2050. The environmental constraints lead to an increase of renewables to shares of 41.2% and 46.2%, depending on more or less ambitious scenarios for 2050, against 32.9% in the BAU scenario (with an marked increase essentially for biomass).

We note that nuclear progresses, but not to a great extent, and is not really impacted by climate constraints. The nuclear share reaches 4.9% in the BAU scenario and 5% in CO_2 mitigation scenarios.

Interestingly, in 2050, fossil fuels represent the major share of the energy mix. First of all, in the BAU scenario, the energy mix is still dominated by fossil fuels, but clearly to a lesser extent due to the large progression of renewables, reaching 33% against 62% for fossil fuels.

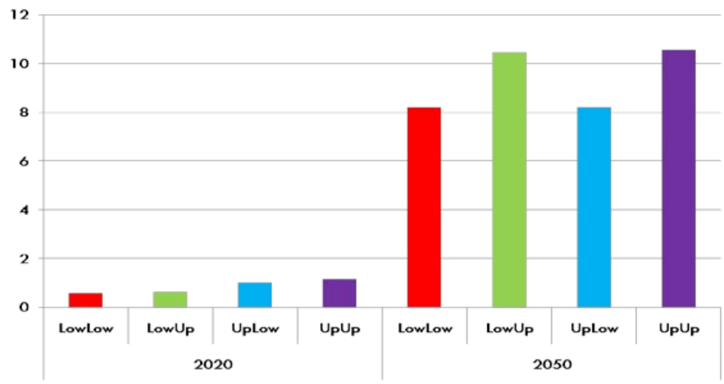
Then, in the less ambitious climate policy scenarios for the long term (LowLow and UpLow), renewables represent 42% and fossil fuels 53%. We can already see the change in the energy landscape. Finally, in the more ambitious scenarios for 2050 (LowUp and UpUp), while fossil fuels remain the dominant fuels, their share only represents 49% of energy, with renewables reaching 46%.

The consumption of all fossil fuels decreases in 2020 and 2050, whatever the climate scenario, if we compare with the BAU scenario. The share of coal remains high, despite carbon constraints. This could be explained by the development of carbon capture and storage (CCS) technologies.

4.3.2. Carbon Capture and Storage development

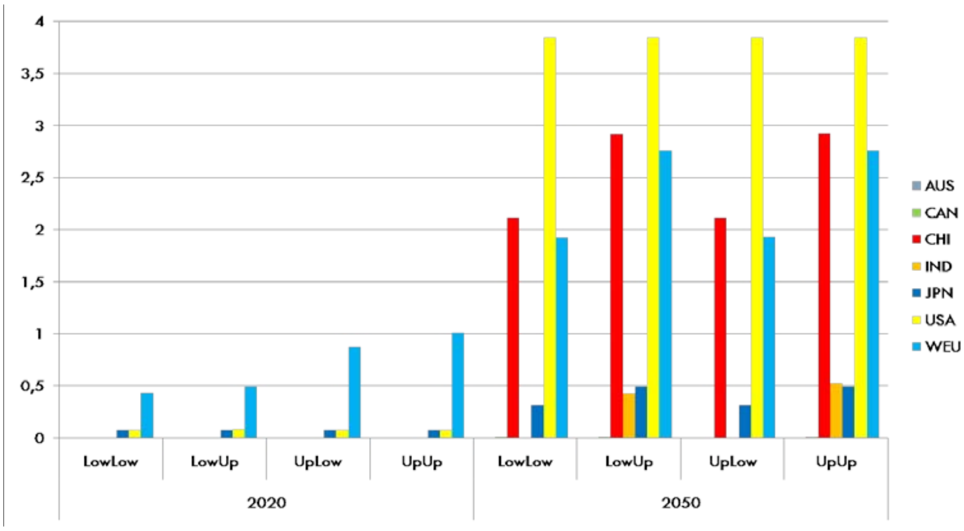
In addition, we can suppose that the choice between gas and coal is influenced by this CCS development, to the detriment of gas. Indeed, as is presented in the figure 7, environmental constraints lead to the development of CCS technologies.

Figure 7: CO_2 storage (Gt)



In 2050, between 8 and 12 Gt of CO_2 should be sequestrated to reach the carbon emission mitigation target, depending on the stringency of the climate target. Note that the stringency of the various climate policies expressed in the scenarios investigated here is reflected in CCS development, and particularly if we consider regional developments in this technology, given in figure 8.

Figure 8: Regional CO_2 storage (Gt)



Regarding China, the level of CO_2 emissions and costs have shown the weak impact, not to say the complete lack of effect, of the Chinese targets in 2020. We also have noted that the carbon constraint imposed on China by 2050 weighs in term of carbon cost (especially when the reduction type is CO_2 emissions and not the carbon intensity), even if the target seems weaker by comparison with other countries. This contrast between medium- and long-term Chinese targets and their participation in the fight against climate change is reflected by their investments in CCS technologies.

In 2050, the stronger constraint imposed on China directly leads this country to develop CCS technologies. The more ambitious China's target, the higher the amounts of sequestrated CO_2 in China. This CCS is necessary to satisfy the carbon constraint representing 2.9 Gt of sequestrated CO_2 when the target is a reduction of 10% by 2050 compared to 2005 of CO_2 emissions (and 2.1 Gt of sequestrated CO_2 when the target is a 90% reduction in carbon intensity by 2050 compared to 2005).

In the same manner, strong long-term constraints on the USA involve a significant growth in CO_2 sequestration. To reach their climate objectives, the USA needs to sequestrate 3.8 Gt of CO_2 by CCS technologies.

Thus, in addition to the development of renewables, the use of CCS technologies appears to be a solution for CO_2 mitigation targets. The same is true for Western Europe and Japan (for the long term). In 2050, Western Europe sequestrates between 1.9 and 2.7 Gt of CO_2 to fulfil its commitment, depending on its stringency, and Japan between 0.3 and 0.5 Gt. In the medium term, CCS investment is more limited, but still reaches 1 Gt of sequestrated CO_2 for Western Europe, reflecting its stringency target. Despite the relatively high Japanese carbon marginal cost in 2020, we note that Japan does not respond to its constraint investing so highly in CCS technology in comparison with other countries.

5. CONCLUSION

In this paper, we have analyzed different paths of CO_2 emission mitigation targets and focused on their impact on costs, total energy consumption, and the energy mix. A key feature of the Copenhagen agreement is the participation of the United States of America and non-Annex I countries, especially China, as they represent a large share of global CO_2 emissions. China and the USA are largest emitters of CO_2 globally and without their participation in a climate agreement, the latter cannot really ensure achieving stabilized CO_2 concentration and global temperatures.

But this scenario analysis shows that the impact of these countries' CO_2 mitigation targets on global CO_2 emissions is essentially long term. Moreover, the relatively high CO_2 marginal cost that China has to bear to ensure its 2050 pledge shows that is important for each region to evaluate the costs of its CO_2 emission targets and the scope they have to make a concrete commitment in the climate change context.

The question of technological plausibility is also a critical factor for post-Kyoto international climate policy. Indeed, the carbon constraint response in these scenario analyses is investments in CCS technologies in order to reach targets of different levels. However, the feasibility of avoiding 8 or 12 Gt of CO_2 emissions by investing in CCS technologies is questionable. Could the potential use of these technologies be enough to satisfy this need?

This question of plausibility also concerns renewables. In the total primary energy supply, the shares of renewables, biomass, and alcohols appear high. Their importance might increase significantly with a more stringent target, but this depends on the cost and efficiency of renewables technologies, and their comparability with fossil fuels. Their future technological development is still an uncertain variable that should be taken into account.

This study also shows that no country can mitigate climate change on its own. International cooperation is needed to face the energy-climate problem. However, it is not only countries that must act, but technological progress must also find an adequate response to countries' ambitions to expand the pool of available (or not) technologies and their mitigation potential. This not only concerns CCS technologies, but also non-fossil energies, like wind, solar, biomass, etc.

This study is not yet a final analysis. However, it shows the way forward for further development. In particular, it might be worthwhile investigating new scenarios with limited CCS technologies expressing optimistic or pessimistic views of their future development. The model used to make the analyses in this paper, TIAM-FR, allows us to act on the deployment of CCS technologies and distinguish the different technologies.

Also, the potential development of renewables could be discussed further in the same perspective of optimistic or pessimistic deployment and efficiency. Another further development is that non-CO_2 gases and CO_2 permits could be included to be considered in the analyses.

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7. APPENDIX

This figure represents the regional CO_2 emissions shares for all world regions:

- The CO_2 constrained regions: Western Europe (WEU), the USA (USA), Japan (JPN), China (CHI), India (IND), Canada (CAN) and Australia and New Zealand (AUS):
- The other countries (OC): Africa (AFR), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MEA), Other Developing Asia (ODA) and South Korea (SKO).

Figure 9: Regional CO_2 emissions (Gt)