Joint Research Project « *Carbon-constrained scenarios* »

FONDDRI
Fondation pour le développement durable et les relations internationales

Final Report

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Introduction

This report provides the results of the study entitled '*Carbon-Constrained Scenarios'* that was funded by FONDDRI from 2004 to 2008. The study was achieved in four steps:

(i) Investigating the stakes of a strong carbon constraint for the industries participating in the study, not only looking at the internal decarbonisation potential of each industry but also exploring the potential shifts of the demand for industrial products.

(ii) Developing an hybrid modelling platform based on a tight dialog between the sectoral energy model POLES and the macroeconomic model IMACLIM-R, in order to achieve a consistent assessment of the consequences of an economy-wide carbon constraint on energy-intensive industrial sectors, while taking into account technical constraints, barriers to the deployment of new technologies and general economic equilibrium effects.

(iii) Producing several scenarios up to 2050 with different sets of hypotheses concerning the driving factors for emissions – in particular the development styles.

(iv) Establishing an iterative dialog between researchers and industry representatives on the results of the scenarios so as to improve them, but also to facilitate the understanding and the appropriate use of these results by the industrial partners.

This report provides the results of the different scenarios computed in the course of the project. It is a partial synthesis of the work that has been accomplished and of the numerous exchanges that this study has induced between modellers and stakeholders.

The first part was written in April 2007 and describes the first reference scenario and the first mitigation scenario designed to achieve stabilization at 450 ppm CO_2 at the end of the 21st century. This scenario has been called "mimetic" because it has been build on the assumption that the ambitious climate policy would coexist with a progressive convergence of development paths toward the current paradigm of industrialized countries: urban sprawl, general reliance on road transportation, centralized power systems, etc. It is no surprise that with such an assumption, the absolute decoupling of growth and CO_2 emissions demands a rapidly increasing value of carbon in the economy.
After many fruitful discussions between industry representatives and researchers, these scenarios have been corrected and finalized in September 2007. A brief explanation of the adjustments introduced is included in the report.

The second part of the report was written in September 2008. After the first two scenarios, it was agreed to investigate the simulation of a "non-mimetic" scenario, which would take into consideration significant shifts or mutations in the development styles and in land planning..
In this scenario, the two models involved have been forced by exogenous assumptions on development bifurcations made by ENERDATA.
Discussions within the steering committee made clear that two assumptions were critical to the plausibility of the two mitigation scenarios:

(i) Timely acceptance and massive deployment of certain technologies such as carbon capture and storage and nuclear power;

(ii) No-delay adoption of ambitious climate policies by all emerging and developing countries (before 2020).

In order to challenge these two assumptions, two additional sensitivity scenarios were produced: the first one built on the assumption that carbon capture and storage would not be available before 2030, the second delaying the efforts of non-Annex B countries to 2025.

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FIRST PART:

A Reference scenario
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1 Reference Scenario

Compared to the range of long term world projections in the literature, our reference scenario stands as a **median demographic and economic story**: world population increases at an average rate of 0.8 % per year (SRES[1] trajectories were between 0.7 % and 1.2 %), and average per capita GDP (PPP) meanly increases at 1.3 % per year (the interval was 1 % to 3 %, but it was measured in money exchange terms and not in purchasing power parity[2]). Concerning emissions this scenario remains **mainly based on fossil energies,** which leads to a moderate reduction (-0.7 % per year) in the GDP carbon intensity (in SRES the interval ranges from -0.8 % to -2.5 % per year).

1.1 Economic Growth

In the Imaclim-R model economic growth is endogenous. It results both from exogenous driving forces – demography and labor productivity improvements – for each region and from the conditions under which the real growth can be achieved, such as conditions for international trade of goods and capital, energy prices, investment availability.

1.1.1 Assumptions

Population

Population assumptions are derived from the UN2006 median scenario. They assume a world population of 7.5 billions in 2020 then 9 billions in 2050, with 84 % of the total be located in ‘current’ developing countries.

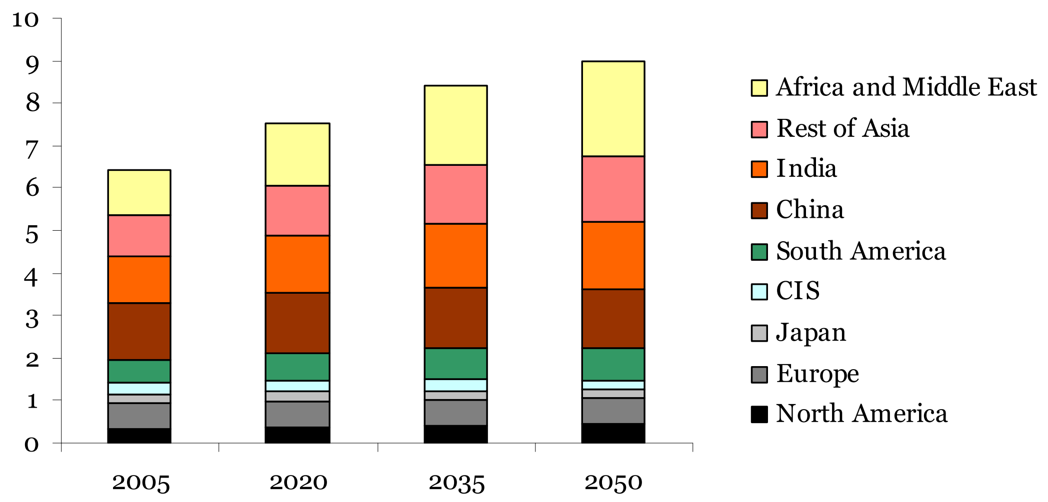

Figure 1: Total population (billions)

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[1] Special Report on Emission Scenarios, IPCC, 2001. The upper limit of the population range has been lowered in all recent forecasts – Census Bureau, UN, IIASA.

[2] Using purchasing power parity reduces the spread of per capita GDP between developed and developing countries, and, in a general way, leads to a reduction in average growth rates for identical paths

There is a significant difference between countries with a growing population (US, all developing countries except China) and others (China, CIS, OECD except US) where the average rate of growth remains below 1‰.

In countries with a weak growth, the ageing of the population implies a continuous decline of the activity ratio (ratio of working population[3]* over total population). On the contrary, countries with a dynamic demographic growth experience activity ratios lower at the beginning of the period but increasing at least until 2040. USA also suffers from an important aging trend but its dynamic demography growth allows the activity ratio to remain above 60 %.

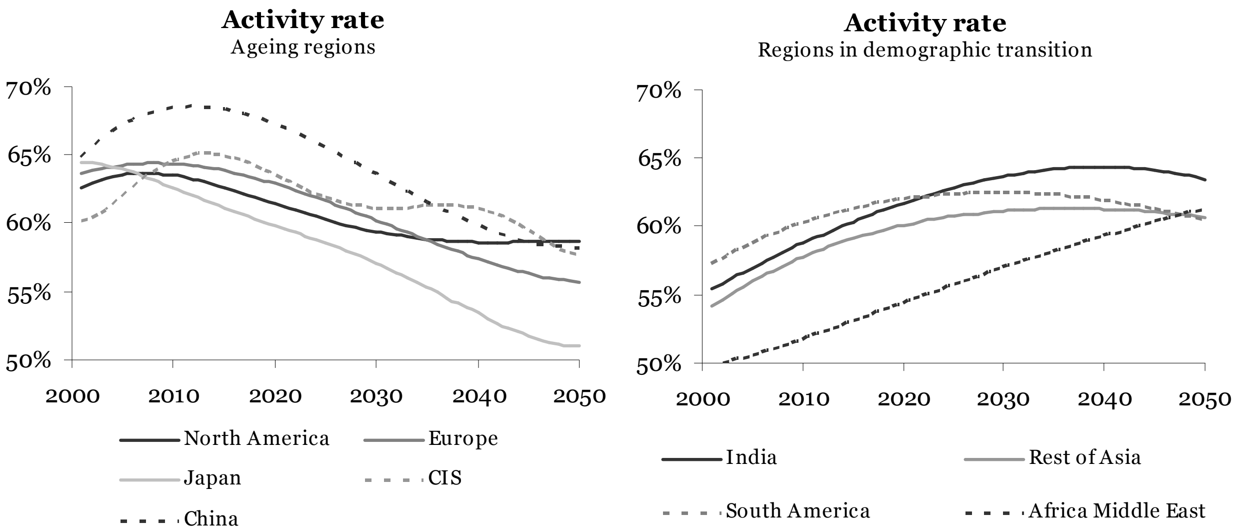

Figure 2 : Ratio of active population over total population

	Total Population	Active Population
North America	**6.2 ‰**	**4.4 ‰**
Europe	0.3 ‰	-2.9 ‰
Japan	-0.6 ‰	-5.6 ‰
CIS	-3.3 ‰	-4.9 ‰
South America	**7.4 ‰**	**8.0 ‰**
India	**8.1 ‰**	**10.6 ‰**
China	1.2 ‰	-2.0 ‰
Rest of Asia	**10.0 ‰**	**11.8 ‰**
Africa and Middle East	**16.6 ‰**	**20.9 ‰**

Table 1 : Mean annual growth rate of total and active population between 2005 and 2050

[3] Active population really means the population whose age would allow it to work: Between 18 and 65 years in developed countries and 15-65 in developing countries (available data).

Labor Productivity

Labor productivity growth relies on two assumptions :

(i) USA remains the world leader with a current stabilized growth of 2 % per year. OECD countries and CIS follow this leader and the ratios converge near 2050.

(ii) Developing countries progressively catch-up the productivity gap : China and India catch up most vigorously, followed by the Rest of Asia, Brazil and the rest of Latin America. Africa and the Middle East do not experience such a take off but keep a continuous growth of 2 % per year.

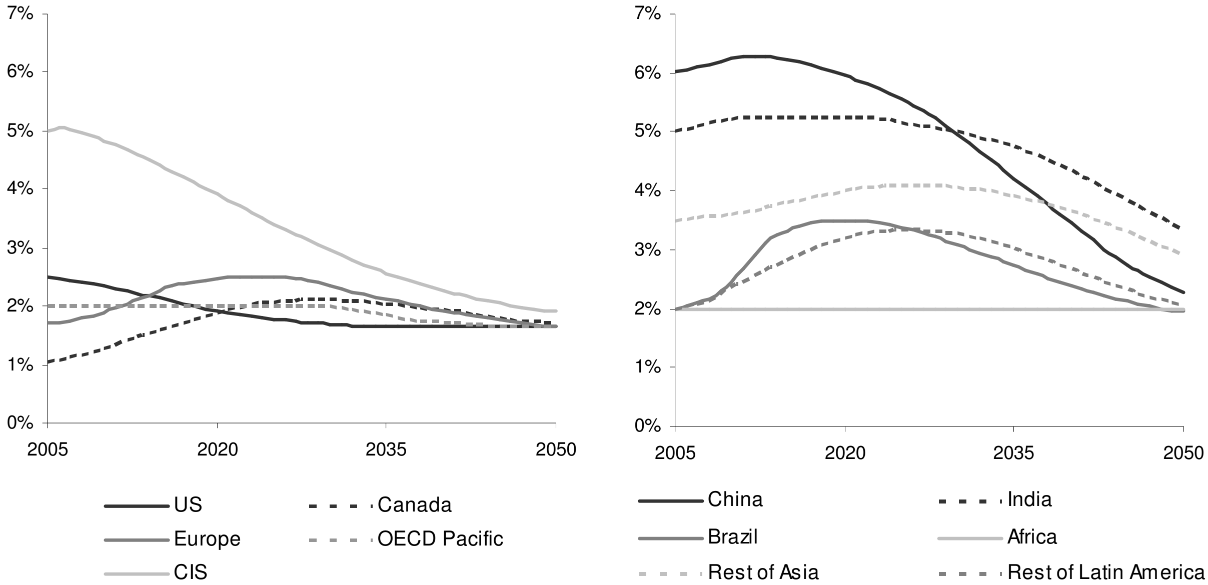

Figure 3: Labor productivity growth trends

Savings

In Imaclim-R the savings rate follows an exogenous trajectory. For the purpose of these simulations the savings rate has been kept at the level of 2001 for all regions except China in which it decreases from 44 % in 2001 to 14 % in 2050.

USA	9 %	**CIS**	24 %	**Middle East**	20 %
Canada	18 %	**China**	44 %	**Africa**	10 %
Europe	13 %	**India**	18 %	**Rest of Asia**	22 %
Japan OECD Pacific	19 %	**Brazil**	12 %	**Rest of Latin America**	11 %

Table 2 : Regional saving rates

International Regime

The reference scenario is a scenario of ongoing globalization. International trade parameters translate a permanent international competition. Capital flows progressively adjust so that capital accounts converge toward the equilibrium. This is a strong but common assumption in long term scenarios, especially because very few information is available to model long run disequilibrium of capital flows. To achieve a robust representation of permanent capital flow imbalances, it would be necessary to take into account the external debt of the regions, which is one of the future developments of Imaclim-R, but will not be taken into consideration in this study.

1.1.2 RESULTS

Economic growth

As regards to the assumptions concerning the growth engine of each region and the stable international context in which this growth occurs, there is nothing surprising in the effective growth computed by the model:

- OECD regions remain world leaders in terms of per capita income, essentially due to higher per capita productivity levels;
- Emerging and developing countries experience a steep growth, coming from both their dynamic demography and their partial productivity catch-up. China and India are the most dynamic in the beginning of the period, enjoying a 7 % per year average growth rate of total GDP. This growth slows down significantly after 2025 because these two growth engines become weaker. CIS achieves a somewhat similar growth path with high productivity gains, in spite of the lack of demographic dynamism. The rest of developing countries have growth rates superior to the OECD average, with the catching-up of the productivity gap taking a little more time than for Asia and India, but with a strong population growth.

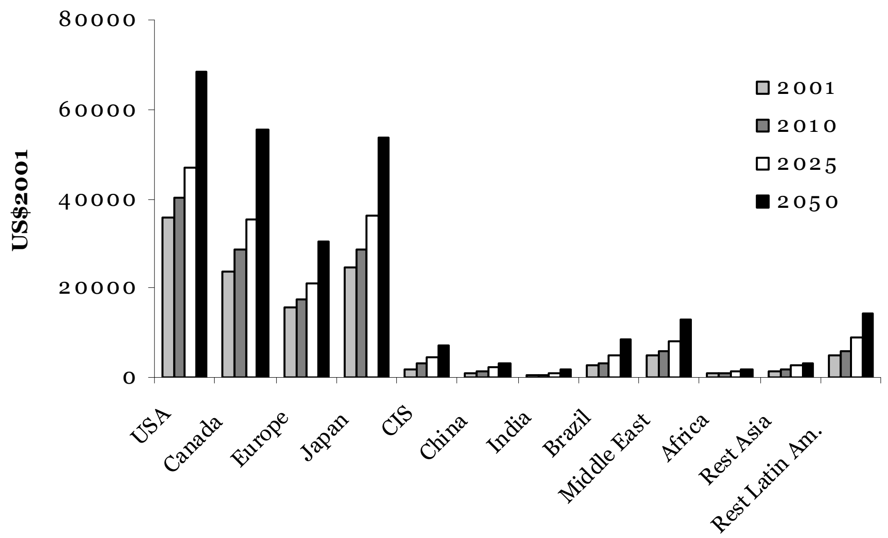

Figure 4 : Per capita GDP (Market exchange rates, constant US$2001)

	2005-2010	2010-2025	2025-2050
USA	2.6%	2.4%	2.4%
Canada	3.2%	2.2%	2.4%
Europe	2.2%	1.9%	1.5%
Japan	1.8%	1.7%	1.2%
CIS	6.0%	2.3%	1.6%
China	7.0%	4.3%	1.5%
India	7.0%	6.2%	2.6%
Brazil	5.2%	4.2%	2.5%
Middle East	4.8%	3.7%	3.3%
Africa	4.8%	4.5%	3.7%
Rest of Asia	5.7%	4.8%	2.5%
Rest of Latin America	4.9%	4.5%	2.8%
World	4.1%	3.2%	2.1%

Table 3 : Mean annual growth rate of GDP

International trade

In line with the assumptions concerning the fluidity of trade and the competition level on international markets, international trade keeps growing at a higher rate than the world GDP (average annual rate of 2.1 %). The value share of energy in international trade increases continuously, mostly as a consequence of an increase in the price of fossil resources[4]: it rises from 11 % of total international trade flows in 2005 to 18 % in 2030 and 20 % in 2050.

	2005-2020	2020-2035	2035-2050
All international trade flows	3.6%	2.7%	2.1%
Energy trade flows	5.8%	4.4%	2.4%

Table 4 : Mean annual growth rates of international trade (constant dollars)

Regional shares in total exports change progressively, mostly because of the changes in energy flows:

- OECD and China market shares all decrease of about a few points, except Canada where increasing exports of non conventional fuels improve its trade balance in the second half of the period ;
- the largest energy exporting countries – CIS and Middle East in the front row - show the most important increase.

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4 See paragraph 1.3.2 for fossil energy prices.

	2005	2030	2050
USA	18.4%	17.3%	16.8%
Canada	5.7%	5.4%	5.7%
Europe	21.0%	18.4%	17.7%
Japan	13.4%	12.1%	11.9%
CIS	3.1%	4.4%	5.3%
China	8.1%	7.1%	7.0%
India	1.3%	1.4%	1.4%
Brazil	1.5%	1.5%	1.5%
Middle-East	5.2%	7.9%	8.4%
Africa	3.5%	4.8%	4.6%
Rest of Asia	12.0%	12.2%	12.1%
Rest of Latin America	6.8%	7.6%	7.6%

Table 5: Regional shares in international trade

1.2 Development patterns

1.2.1 QUALITATIVE ASSUMPTIONS

In this scenario the development pattern of the OECD countries[5] is progressively adopted by the developing world in a "mimetic" way, which means large urbanization and rural exodus, exponential transports development, first targeted to road, railway, and then air. Infrastructure policy is assumed to follow the evolution of transportation services demand, as opposed to a policy that would explicitly try and induce modal shifts. The share of agricultural goods in final demand decrease progressively with per capita GDP increasing and with the simultaneous industrialization of developing countries

1.2.2 RESULTS

Housing

Dwelling surfaces per capita are supposed to increase in all regions of the world. It is a moderate but significant increase for OECD countries where the level is already high: among these countries there is a clear difference between the North American model with a level close to 80 m^2 per capita and Europe and Japan where per capita dwelling surfaces are half that level in 2050. For developing countries the rate of growth is higher but with lower starting levels.

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[5] Here we assume that there is a 'mean' development style in the OECD, as a paradigm of urban and spatial planning that induce much mobility, space, energy and materials. Obviously it neglects that there are many discrepancies in development styles within OECD countries, for example between West Europe, Japan or United States.

	2005	2030	2050
USA	60	62	67
Canada	48	62	79
Europe	33	36	39
Japan	29	32	34
CIS	27	36	41
China	20	23	28
India	8	12	19
Brazil	11	16	23
Middle East	20	27	39
Africa	11	15	22
Rest of Asia	18	23	31
Rest of Latin America	12	16	24

Table 6: Average dwelling surfaces (square meters per inhabitant)

Due to the strong demographic growth in developing countries and as the surface per capita increases, the residential building construction requirements are huge, not only for China which is often given as an example, but also for other developing regions (India, Africa, rest of Asia).

	2005-2015	2015-2025	2025-2035	2035-2045
USA	4.4	4.8	5.3	5.8
Canada	0.6	0.7	0.8	1.0
Europe	4.4	4.2	4.0	3.9
Japan	1.3	1.2	1.1	1.0
CIS	2.8	1.8	1.6	1.6
China	6.6	7.2	7.9	8.6
India	4.3	5.7	7.5	10.0
Brazil	0.9	1.1	1.4	1.7
Middle East	1.9	2.5	3.3	4.5
Africa	5.4	7.5	10.2	14.0
Rest of Asia	7.3	9.0	11.2	14.0
Rest of Latin America	1.8	2.3	3.0	3.8

Table 7: New built residential surface (Billions of m^2 per year, including the replacement of 1,5% per year)

Transportation: Vehicles stock and Modal shares

The household equipment level in terms of private cars is the another critical indicator of the development pattern, since it is directly related to the road traffic expansion, provided there is a sufficient development of necessary infrastructures. The assumption is that the equipment level increases in all regions (except in the USA, where it is already close to the saturation level) as for the residential housing. For emerging and developing countries the increase of the vehicles' stock is striking. It means that these countries would choose a development path without any real road traffic constraint.

This may seem contradictory with a vigorously rising oil price during the whole period, with a regular rise of 2.5 % per year in constant dollars, reaching 120 dollars per barrel in 2050 (see infra, Figure 13). However the effect of any increase of the crude oil price on the gasoline price is considerably softened by the fiscal system in place in most countries; in the European context for instance, the increase of oil price from 60 $/bl today to 120 $/bl in 2050 only induces a 34 % increase in gasoline price (1.28 to 1.71 €/l).

Considering these conditions, household car equipment levels increase in all regions of the world. The increase is clearly more important in the developing regions. In 2050 car equipment for all developing regions is in the range of 100 to 300 vehicles per 1000 inhabitants except Africa (90 per 1000), while this level stands around 500 vehicles per 1000 inhabitants in the industrialized countries, except the United States (700 per 1000) (see Table 8).

	2005	2030	2050
USA	0.73	0.77	0.79
Canada	0.48	0.52	0.56
Europe	0.38	0.43	0.48
Japan	0.43	0.46	0.48
CIS	0.12	0.21	0.27
China	0.01	0.07	0.12
India	0.01	0.09	0.20
Brazil	0.10	0.22	0.31
Middle East	0.07	0.13	0.23
Africa	0.02	0.04	0.09
Rest of Asia	0.04	0.09	0.14
Rest of Latin America	0.08	0.20	0.30

Table 8: Households' equipment in personal vehicles (per capita)

The world stock of cars climbs from 675 millions in 2000 to 1.89 billion in 2050. In 2050 the structure of the world inventory is fundamentally changed: industrialized countries (including CIS) would only account for 50% of the world car stock in 2030 and 37% in 2050 against 80% today (Table 9). In 2050 vehicles stocks for India and China together would amount to 485 millions cars. In 2050 the world would count nearly three times more cars than today.

	2005	2030	2050
USA	212185	260561	278452
Canada	15285	20171	23593
Europe	224864	256103	269593
Japan	54510	54841	51110
CIS	32990	58969	75199
China	10525	99947	181360
India	9865	131535	304131
Brazil	17358	49845	74971
Middle East	12121	36590	80235
Africa	15117	62934	164628
Rest of Asia	38690	125562	226964
Rest of Latin America	30634	96694	164669

Table 9: Vehicles' stocks (thousands)

In the reference scenario (without any strong climate policy) conventional cars remain predominant and account for 1.2 of the 1.9 billion. However alternative vehicles such as hybrids, 100 % electric, or hydrogen vehicles are already developed under the pressure of the growing scarcity of oil (Table 10). Within our set of assumptions, fuel cells do not reach the competitive threshold before 2050 and their development remains clearly marginal.

	2005	2030	2050
Conventional	673323	1153758	1196463
Gas Fuel Cell	0	0	16
H2 Fuel Cell	0	1	25
Hybrid	130	34510	269261
Electric	616	54779	222923
H2 conventional	73	10703	206216

Table 10: Technology shares of vehicles (thousands)

In fact, mobility by car evolves largely in the developing regions during the next fifty years but remains relatively stable in the industrialized regions where road traffic rises only slightly. The strongest increases take place in India, China and Africa, where the traffic is multiplied by more than ten between 2005 and 2050 (Table 11). At the world level, car traffic is multiplied by 2.4 between today and the end of the projection.

	2005	2030	2050	2050/2005
USA	3872	4675	4952	1,3
Canada	290	314	316	1,1
Europe	3710	3821	3836	1,0
Japan	868	860	793	0,9
CIS	456	803	1017	2,2
China	138	1292	2334	16,9
India	111	1465	3368	30,3
Brazil	223	689	1075	4,8
Middle East	202	597	1290	6,4
Africa	223	904	2328	10,4
Rest of Asia	611	1952	3508	5,7
Rest of Latin America	449	1396	2361	5,3

Table 11: Road Traffic (millions of Vehicles. kilometers)

Structural Change of Final Consumption

Under the assumption of 'mimetic' development patterns, structural changes are only moderate, no significant breakdown are observed:

Energy: in OECD countries, a progressive limited decoupling with the energy share decreasing from 5.5 % to 4.4 % of final consumption is observed, a stronger one in CIS where it decreases from 16 % to 9 %. Conversely, in developing countries the growth in end-use equipments and a better access to energy increases the energy budget share from 3.7 % to 6.5 % in China, and from 7.8 % to 12.3 % in the Middle East.

Transport: in the OECD countries the share of transportation in final consumption increases from 5.2 % to 6.5 % while remaining stable in the developing countries. It still means a large volume increase as the revenue per capita sharply increases everywhere.

Energy intensive industries and construction: the share of these sectors (16 %) remains stable inside OECD and globally decreases in all developing countries, mostly after 2030 (from 23 % to 21 % in China, and 21 % to 19 % in Latin America).

1.3 Energy Content

1.3.1 ASSUMPTIONS

Regarding the energy partial equilibrium model POLES, energy scenarios are based on four large sets of exogenous assumptions:

1. Demography and economic growth in consistency with the assumptions and the results of the IMACLIM-R model;
2. Availability of fossil energy resources that might be constrained around 2050 (oil and gas)

3. Emission constraints induced by an endogeneous carbon value considered as a variable proxy of the whole set of established policies (Policies and Measures, quotas, and/or taxes);
4. Technologies adopted because of i) their cost and their performance for the production and the conversion of energy ii) the manufacturing of structural materials iii) low and very low energy end-use equipments.

Fossil reserves

Scenarios are ruled by the oil and gas availability issue. Combining the representation of the finding and the production of oil resources with the simulation of the technical progress concerning the recovery process - which increases the volume of resources along the way – the POLES model computes an endogenous evolution of the available reserve estimates. Figure 4 shows the estimate of resources in 2001. On the whole the dynamic assumptions of the model lead to a production increase that could reach 25 % more than today, with stabilization of conventional production around 2030.

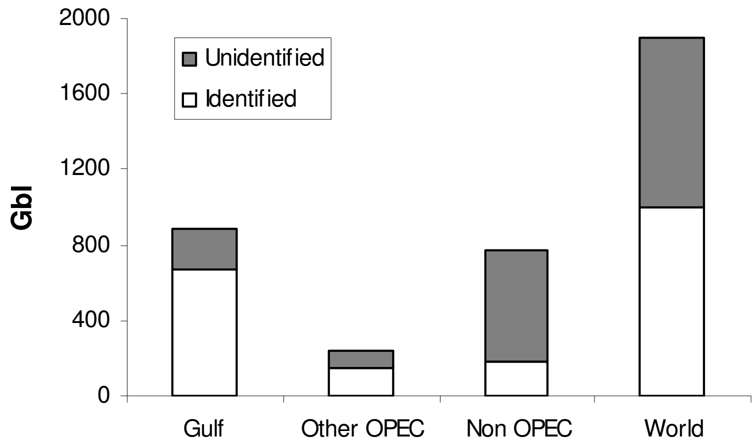

Figure 5 : Estimated oil supply (2001)

Carbon value

Carbon value is an exogenous variable for the model, as it represents the intensity of climate policies implemented in different regions. In the reference scenario these climate policies remain quite modest. A moderate policy is assumed for Europe represented by a 10 €/tCO_2 in 2010 increasing up to 30 €/ tCO_2 in 2050.

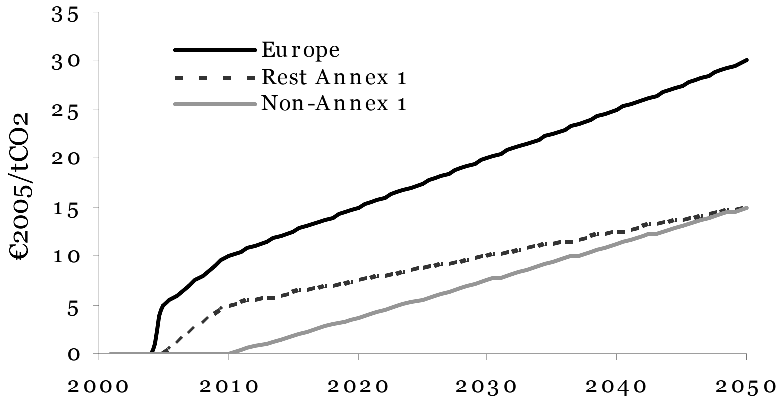

Figure 6: Carbon value – reference scenario

Technical progress and efficiency gains

In the POLES model, autonomous energy efficiency improvements are taken into account at the level of each sector. Their combination of those with the effects induced by the rise in energy prices leads to significant efficiency gains in the reference, so that the primary energy consumption only increases at half the rate of GDP: the energy intensity of the world GDP decreases from 200 to 120 toe per million dollars.

Nuclear

Based on the assumptions of the TECHPOL database concerning the improvement of the technology cost of the 3rd generation nuclear plants, combined with the price increase of all fossil energies throughout the period of this scenario, nuclear energy competitive position increases. Under these conditions new capacities are built in Europe after 2030.

Renewable energies

Renewable energies also achieve rapid growth based on established incentives, especially advantageous feed-in tariffs in Europe – even with limited technical potential of intermittent energies in the electricity production. The TECHNOL database supplies a unified framework on costs and performances of renewable energy technologies at different time horizons.

1.3.2 RESULTS

Energy final demand

As shown on Figure 6, the world energy consumption increase is both modest and significant: *modest* as it only amounts to a doubling of the final consumption over 50 years, which seems slight as regards to current great unsatisfied needs; *significant* if one takes into account implied development of production, transport and distribution capacities.

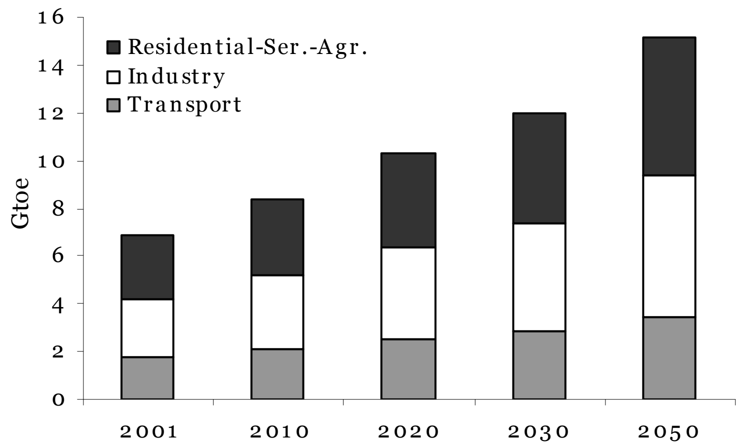

Figure 7: Final Energy Consumption - World

Final energy demand is multiplied by 2.2 in 50 years, growing from 6.9 Gtoe to 15.1 Gtoe. The most dynamic increase concerns the demand from industry (2.45 multiplication factor) compared to transportation demand only multiplied by 1.93 thanks to large efficiency progresses. As noticed above, the automobile stock is multiplied by 2.8, and the road traffic by 2.4. Adding transportation of goods there is indeed a large increase in the world vehicles stock, but both a slightly less utilization rate and a higher efficiency somewhat limit the increase in fuel consumption.

The European final demand increases by 30 % in 50 years (from 1.35 Gtoe to 1.8 Gtoe) but the main part of this raise comes from the residential/services/agriculture sectors with a growth of the demand of 50 %, while transportation demand only rises by 5 %. Thus, assuming a decoupling of the consumption of transports - the first fruits of which already appear in some countries like France - is confirmed by the model projection.

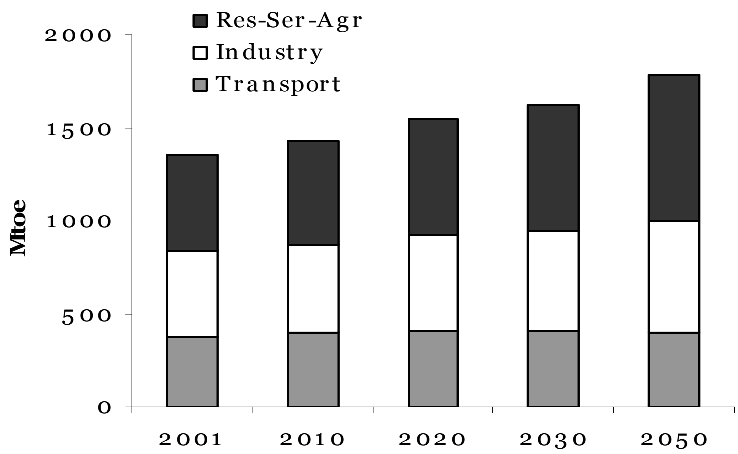

Figure 8: Final energy consumption – Europe

Primary energy

World primary energy consumption reaches 24 Gtoe in 2050. The whole energy perspective is dominated by the progressive stabilization of conventional oil and gas production beyond 2030. Production of non-conventional hydrocarbons and coal increases rapidly throughout the period as they are the only two fossil resources remaining relatively abundant in the middle of the century. Non fossil energies, renewables and nuke encounter a significant development which, even in this reference scenario, brings them close to their maximum development limits.

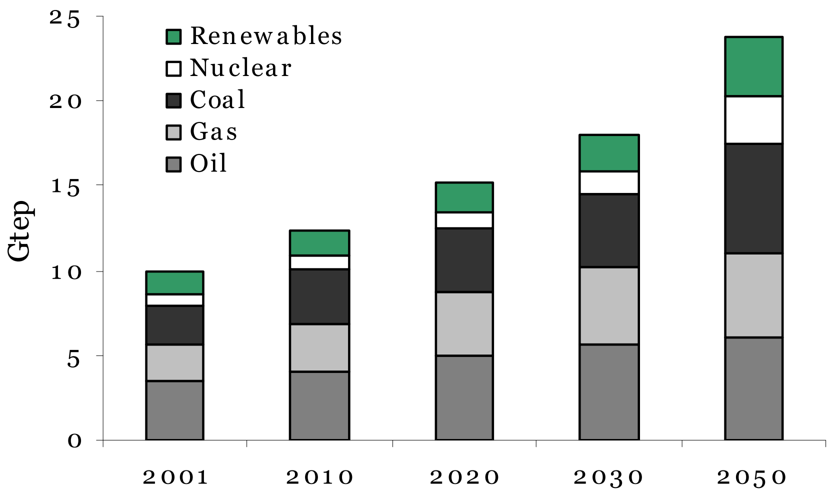

Figure 9: Primary energy production - World

Splitting consumption between regions shows that the essential part of the growth happens in developing countries, especially in Asia. In OECD countries the consumption increases only slowly (6 to 8 Gtoe between 2000 and 2050), while it is multiplied by 4 (from 4 to 16 Gtoe) in the developing and emerging world over the same period.

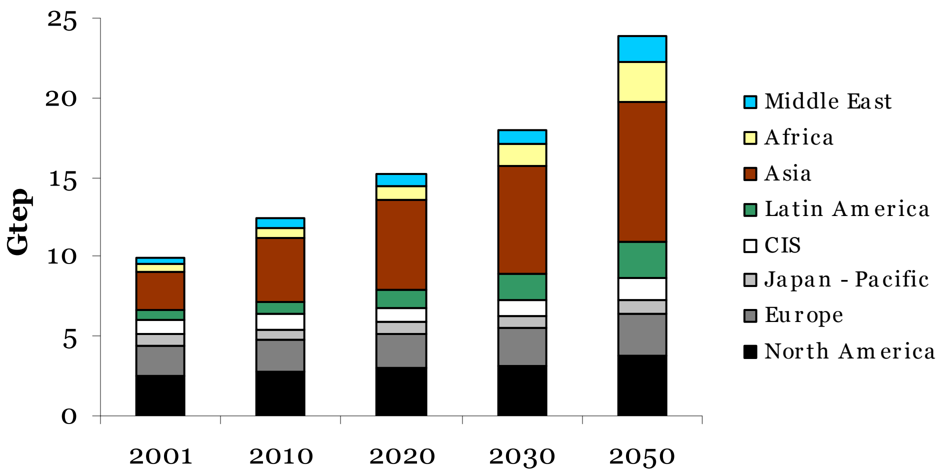

Figure 10: Primary energy demand per region

In Europe (inc. Turkey), primary energy consumption increases from 2 to 2.7 Gtoe, especially because of the growing demand from Eastern countries. Oil decreases, both in share and in absolute level during the whole period, while gas first increases, stabilizes around 2020 and decreases beyond 2020. Then Coal comes back significantly. After 2030 nuclear energy grows largely, as a consequence of the nuclear programs renewal, while renewables experiment a sustained grow over the whole period.

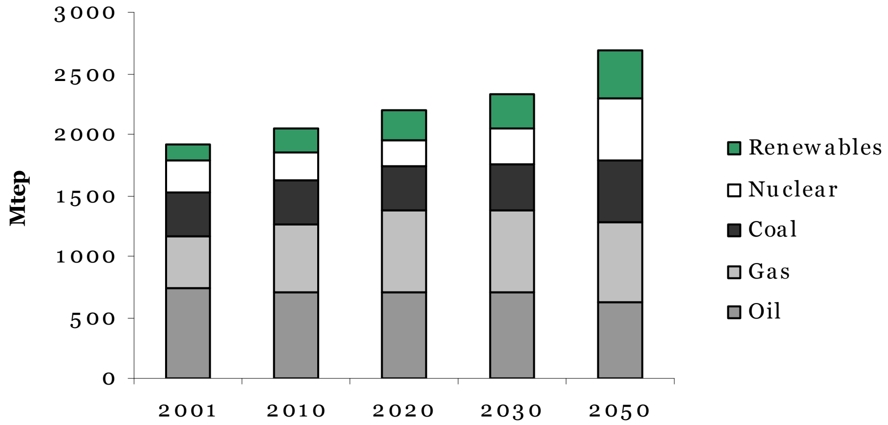

Figure 11: Primary energy consumption - Europe

Electricity production technologies mix

World electricity consumption increases fourfold during this period. This means that the elasticity between electricity demand and GDP remains close to 1 over the next half century. This can be explained both by the size of the unsatisfied needs in the developing countries, and because electricity remains an energy vector in progress. The production mix changes in a significant way, with first a strong increase in coal and, after 2030, of the renewables and nuclear energy.

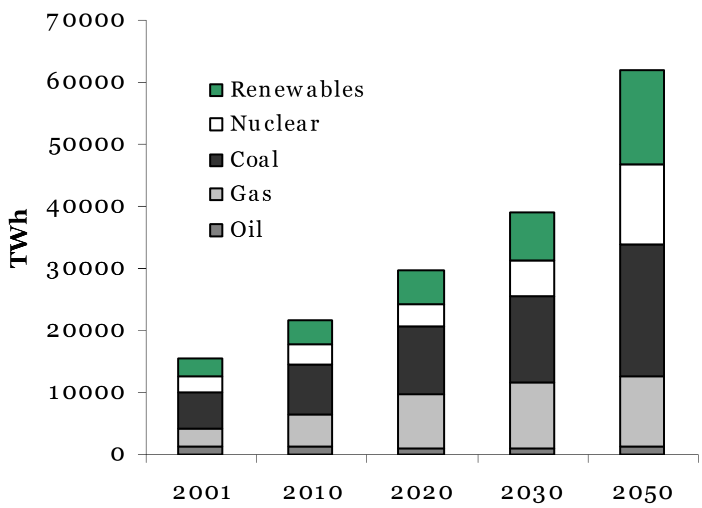

Figure 12: Electricity mix production – World

While the demand increases less in Europe, comparable evolutions exist for the production mix with nuclear and renewables being developed in comparable proportions. In 2050, 60 % of the electricity is produced by these two sources together.

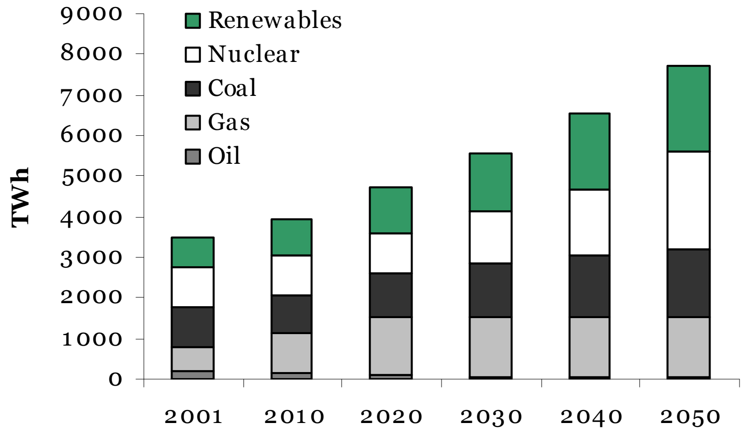

Figure 13: Electricity mix production– Europe

Fossil resources scarcity drives price dynamics and physical production

The growing tension on the oil market feeds a structural price increase after a short lull around 2010. Oil price reaches 120 $/bl in 2050. This is a structural price level which does not take into account crises, accidents, ups and downs which would certainly have an impact on the evolution of the markets over this period: in a way, it is the "climate tendency" of the oil market, not its "weather forecast".

Expected gas evolutions are quite comparable. They do not derive from a systematic indexation of the gas price on the oil price but simply from the fact that, in terms of price mechanisms and in terms of length of available resources, the fundamentals are quite similar for natural gas and for oil.

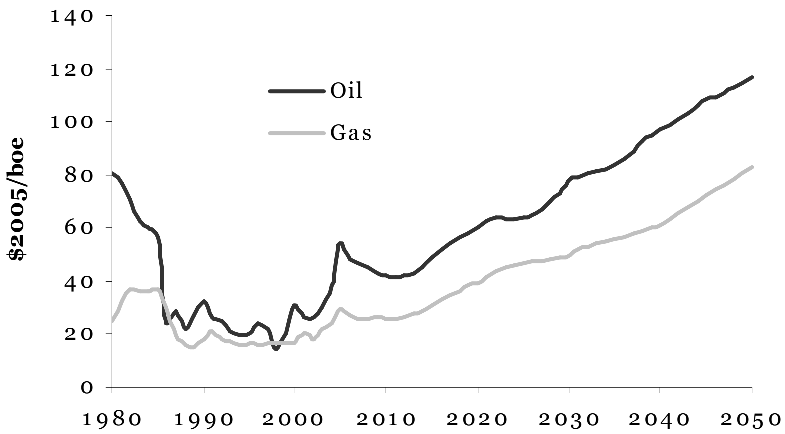

Figure 14: International prices crude oil and natural gas

The world oil production does not show any steep peak as forecasted by some experts, but more likely a progressive stabilization slightly above 100 Mbl/day before 2040, followed by a very progressive decline. In this context a large part of the supplementary supply relies on non conventional oil resources such as heavy shales from Venezuela or asphalt sands from Canada.

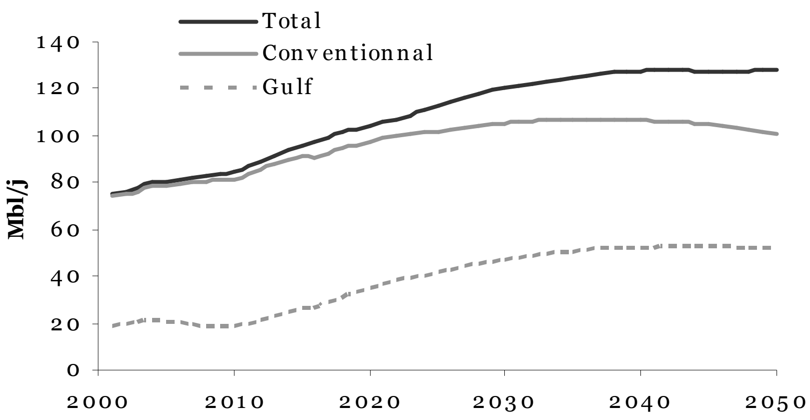

Figure 15: Total oil production

However these evolutions do not offer any margin on the supply side: despite oil recovery improvements, oil fields discoveries follow a curve of diminishing returns and reserves decline significantly.

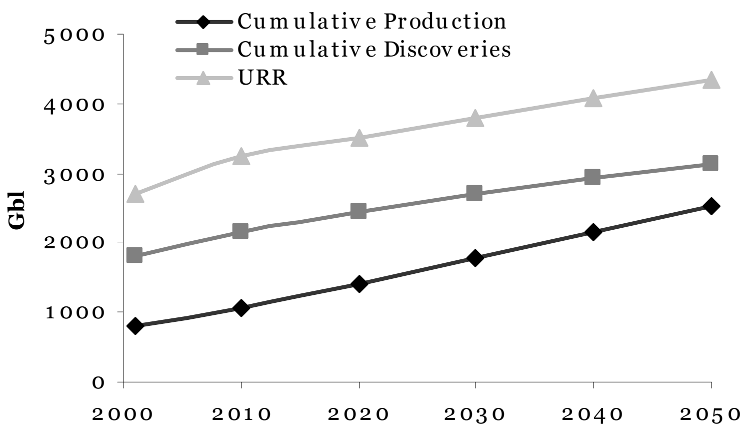

Figure 16: Resources of conventional oil– World
URR : Ultimate Recoverable Resources

Under these circumstances non conventional oil production must increase very substantially. In a first phase, until 2030, only ultra heavy and asphalt sands are developed, with similar shares. When the price of oil exceeds 100 $/bl after 2040, bituminous schist are exploited in large quantities by 2050, especially in the US. At this date non conventional oil represents 35 Mbl per day, more than the OPEP production at the present time.

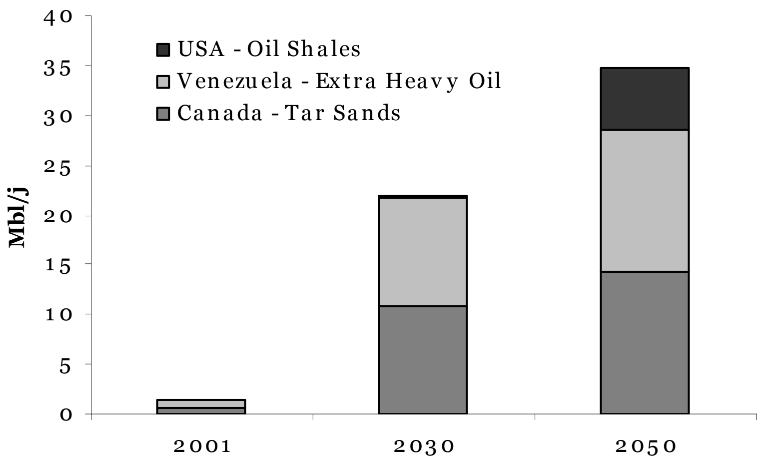

Figure 17: Non conventional oil production

Carbon capture and storage

The reference scenario is based on a "business as usual" approach without any vigorous climate change mitigation policy, but it is assumed that there is some weak climate-friendly actions, raising an explicit or implicit carbon value which is sufficient to trigger investments in the carbon capture and storage of CO2 after 2030. Thus, already 8 % of total emissions in 2050 are processed with this technology.

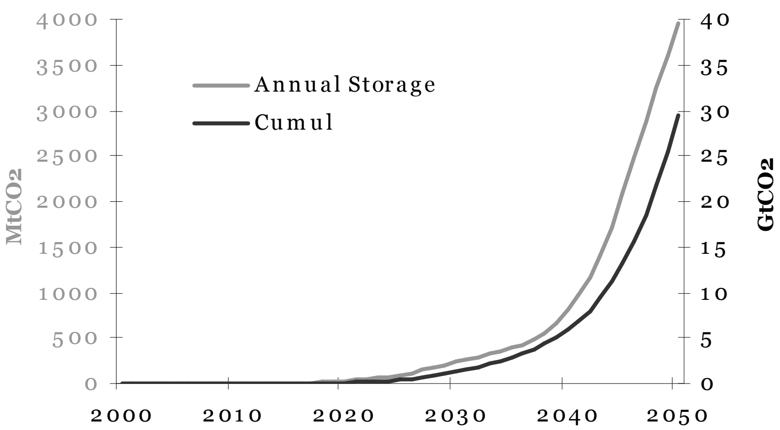

Figure 18: Development of carbon sequestration

Energy bill

The evolution of the households' energy bill depends on the change affecting their final energy demand, which itself depends on: structural changes, energy efficiency progress, the rise of the cost of fossil energies and the increase of per capita income:

- for OECD countries the energy share in households' budget remains somewhat constant or decreases (mostly because eastern countries joining Europe and CIS enjoy important efficiency progresses and a shift towards services);

- for China and India, the first part of the period corresponds to an increase of the bill, linked to an equipment phase and a growth in energy consumption, while in the second part of the period, efficiency progresses become dominant.
- for other developing regions, the energy bill is nearly stable (South America, Africa and Middle East) or growing (rest of Asia).

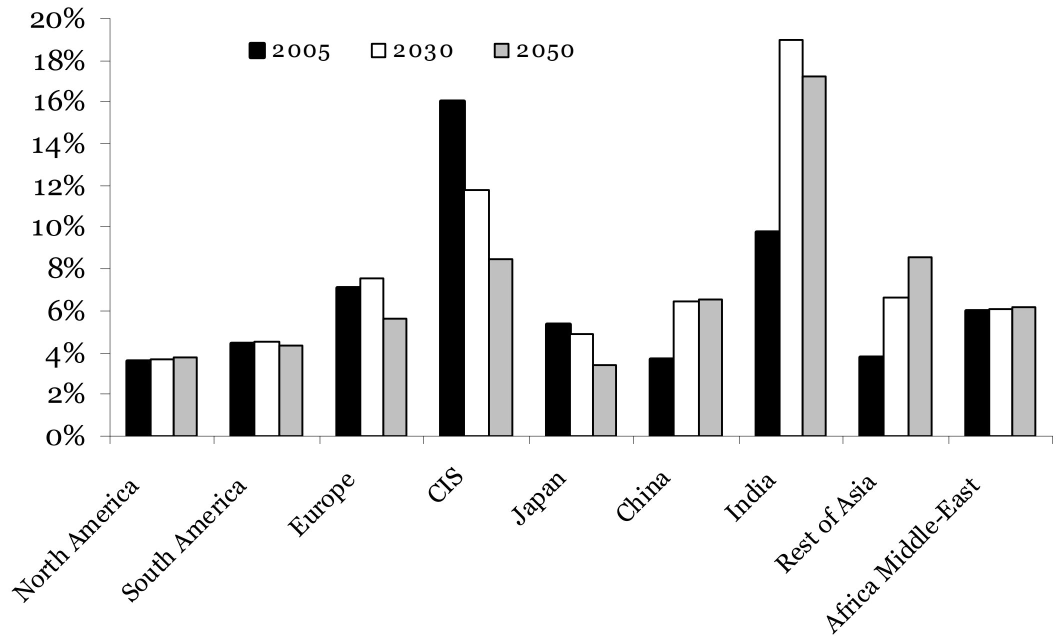

Figure 19: Households' energy bills (ratio of energy expenses over total consumption)

The ratio between energy imports and exports and the GDP is another main indicator of the weight of energy in regional economies. For fossil energy exporters this ratio is positive : in 2050 it reaches 35 % for CIS, 25 % for OPEP and remains lower than 5 % for South America (with however some country ratios which could be higher, for instance Brazil and Venezuela).

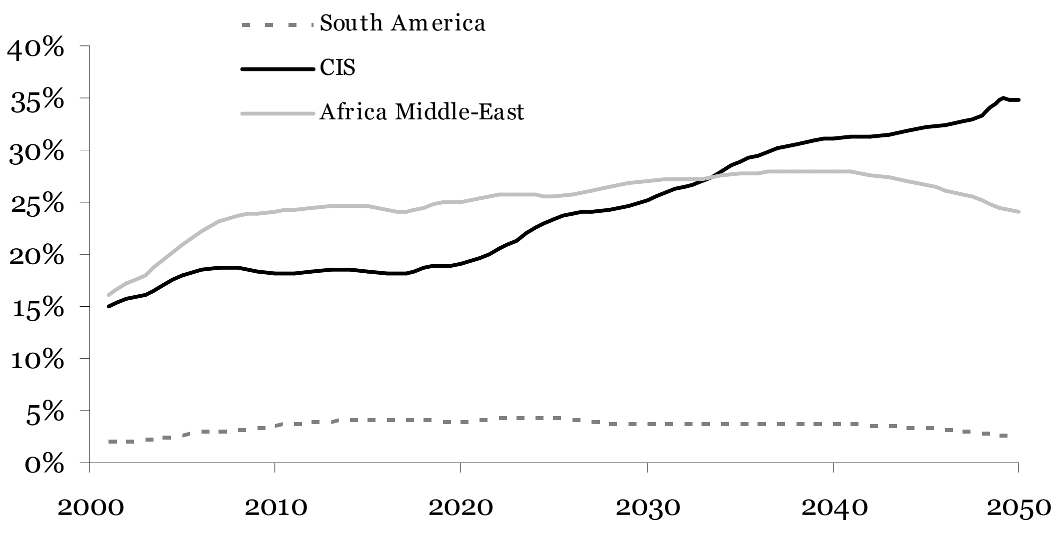

Figure 20: Ratio trade balance over GDP– exporting countries

For importers this ratio is negative and in general increases in value over the next half century. OECD countries remain under 5 %, but China, India and the rest of Asia respectively reach -7 %, -14 % and -6 %.

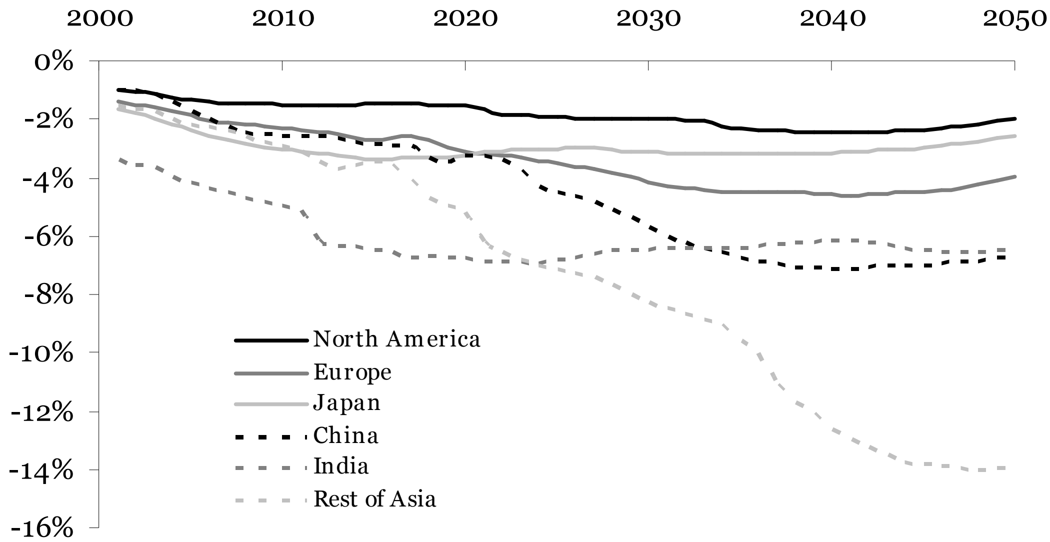

Figure 21: Ratio trade balance over GDP– importing countries

1.4 Industrial sector

1.4.1 ASSUMPTIONS

This study mainly focuses on the evolution of four main energy-intensive industries producing steel, cement, aluminium and glass. Submodel dedicated to each industry covers both the supply side – in particular the description of the main production technologies – and the demand side – with the representation of the activities using these materials and of their material intensity.

Technologies

The data on costs and performances of the main production technologies for these materials have been aggregated in the TECHNOL database. The purpose of this database is to provide reliable data on costs and performances of the technologies for energy supply and demand, especially in order to feed the energy system POLES[6]. These data allows to compute the discounted production costs with a standard process that can be applied identically to all technologies.

[6] This database now includes an extension for new technologies with very low emissions: new energy vectors (hydrogen), new production technologies (CO2 capture, 4th generation nuclear ,…) or concerning energy demand (fuel cells for stationary uses, new engines,...).

For **steel** production, eleven technologies have been taken into account, two of which with enhanced performances (advanced technologies) related to evolutions of current processes:

- Open Hearth Furnace
- Blast Oxygen Furnace
- BOF advanced
- Blast Oxygen Furnace with CO2 capture
- Smelting Reduction Process
- Smelting Reduction Process, H2 based
- Smelting Reduction Process with CO2 capture
- Electric Arc Furnace
- EAF Advanced
- Direct Reduction Process
- Direct Reduction Process, H2 based

For **cement**, besides the shaft kiln, the dry process and the wet process are the main existing technological families with different options for pre-heating or pre-burning which can reduce energy consumption:

- Wet process / Rotary kiln
- Semi wet process / Rotary kiln
- Semi dry process / Rotary kiln
- Dry process / Long rotary kiln
- Dry process / Rotary kiln with pre-heater
- Dry process / Rotary kiln with pre-heater and pre-burner
- Shaft kiln

For **aluminium** production, the main available process is the Hall-Heroult electrolytic process, but with different anode types and alumina feeding systems:

- Point Feeder Prebake
- Center Work Prebake
- Side Work Prebake
- Horizontal furnace Stud Söderberg
- Vertical furnace Stud Söderberg
- Secondary aluminium

Material intensities and materials-intensive activity indicators

Available data do not allow to record and analyze in detail the demand for the main materials that are studied here. Usually it is linked to GDP with an exogenous trend for the aggregate material intensity. In the POLES and IMACLIM-R models, demand has been disaggregated so that consumption of materials for buildings, transports, and the rest of other uses (machinery, equipments, packaging) can appear. For the first two uses, consumptions are linked with endogenous indicators in the models, such as dwelling surfaces or automobile stocks.

1.4.2 RESULTS

Materials demand: steel, cement, aluminium

In our reference scenario world steel demand doubles in the next half century. This happens even with a continuous trend toward dematerialization of the economy, similar in proportion to what is happening for energy. This world demand can be split between a demand for buildings which is rather stable during this period, while the demand for transports and for other uses experiment sustainable increase.

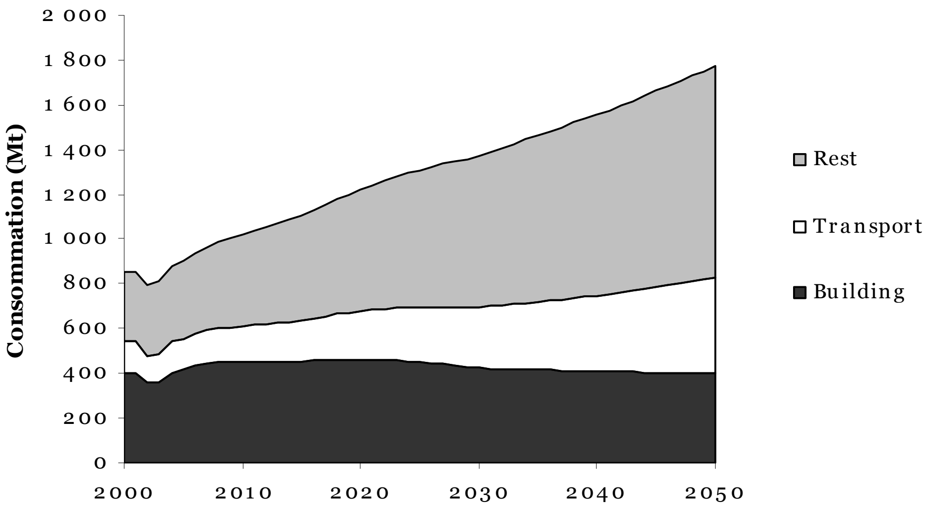

Figure 22: Consumption of steel per sector

Cement use is mainly used for buildings and infrastructures. World population progressive stabilization implies a slowdown of growth after 2020. Aluminium consumption is disaggregated with an additional component relating to the electric infrastructure networks. World consumption enjoys a regular growth over the period with a slight slackening after 2020. The most important increase comes from the transportation sector because of the world automobile stock growth and the increased use of aluminium by this industry. Despite this progression, aluminium consumption remains more than ten times inferior in weight to those of cement or steel.

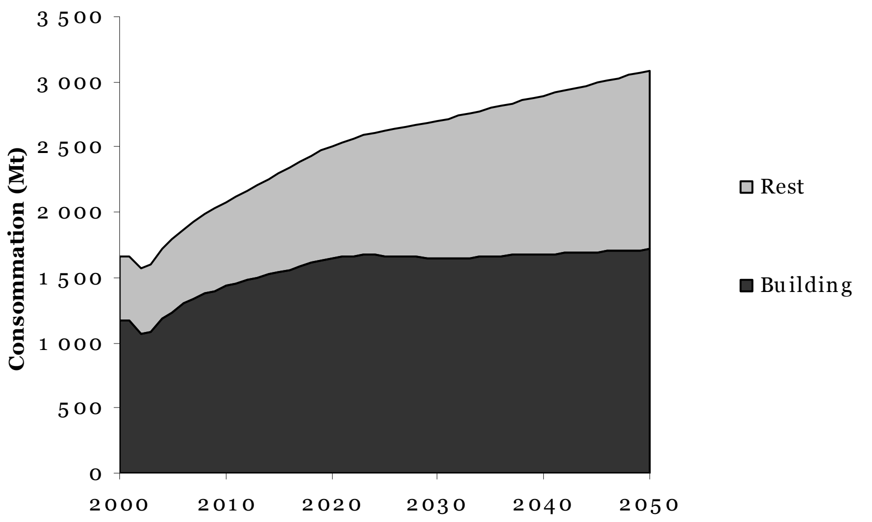

Figure 23: Ciment consumption per sector

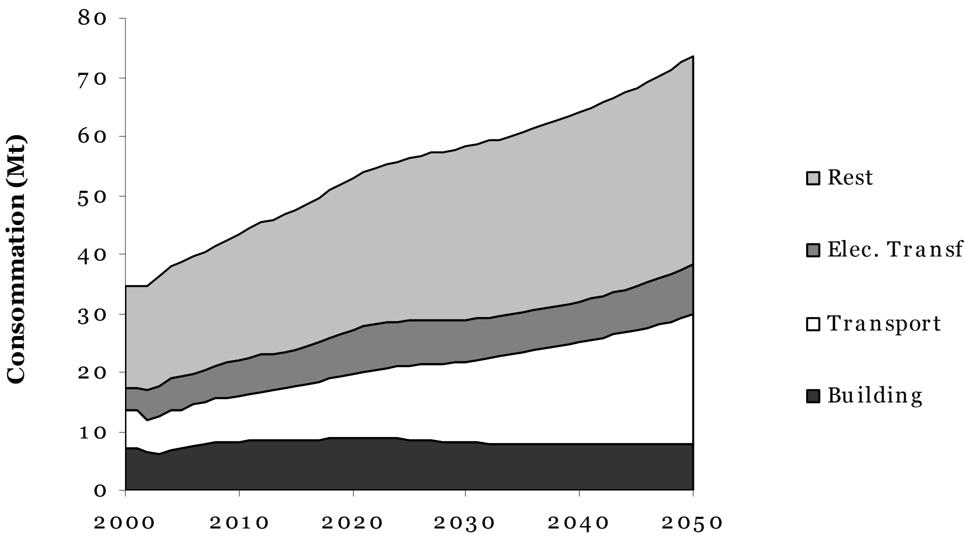

Figure 24: Aluminium consumption per sector

1.5 CO_2 Emissions

In the reference scenario, where there are no strong carbon constraints anywhere, CO_2 emissions rise from 23 $GtCO_2$ today to 54 $GtCO_2$ in 2050. This doubling derives from the increase of the world demand for energy and is a consequence of the rather stable carbon intensity of the world energy mix during this period. The progress of the no-carbon energies, nuclear and renewables are, in fact, compensated by the substitution of oil and gas by coal, the consumption of which considerably increases during the period.

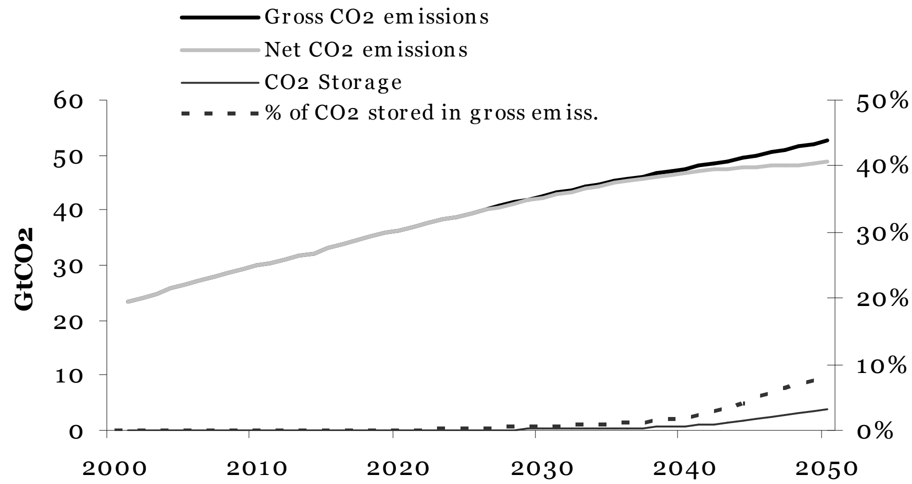

Figure 25: CO_2 Emissions

The relative scarcity of hydrocarbons entails a disruption in the century-old decarbonization trend of the world energy supply. The results of this scenario clearly show the major risk for the climate of a "laissez faire" policy: under these conditions, stabilization profiles after 2050 reach at least 900 ppmv CO_2. According to the IPCC report we should therefore be submitted to a major climate change with average temperature increases over 4°C at the end of the century.

2 Scenario 450 ppmv – F4 mimetic

2.1 Instruments

The 450 ppmv CO_2 concentration stabilization with a reduction factor of 4 (F4) of the emissions in the annex 1 countries (S450-F4) is an answer to the European concern to limit the climate change to an increase in world average temperature that would be less than 2°C over what it was before the industrial age. This requires a strong restriction on emissions, and we hereunder describe its potential impact on the energy system, on the materials production industrial sectors and on the whole economy.

2.1.1 ASSUMPTIONS

Emissions Profile

The 450 ppmv stabilization target requires world emissions be maintained on a very restrictive trail. This translates into ambitious targets concerning emission controls:

- to achieve world emissions inflexion before 2020
- to bring down world emissions in 2050 from two-thirds to three quarters of the 1990 level.

If one adds a burden sharing rule between the different countries which would reflect equity between developed countries and developing and emerging countries by means of convergent long term per capita emission targets, then it becomes necessary to achieve a greater emission reduction in the current industrialized countries.

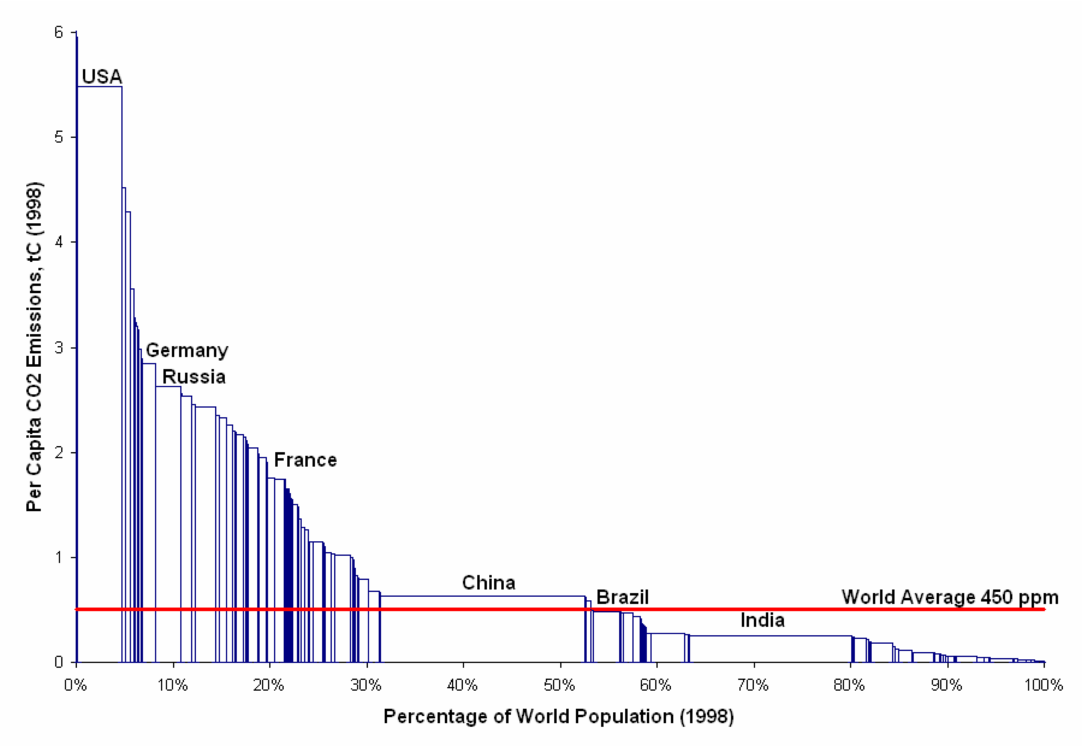

Figure 26: Emissions per habitant and convergence target for a 450 ppm stabilization

The required reduction as compared to the reference scenario is indeed quite large and the bifurcation must be done without delay. This constraint may seem too ambitious, but it is the only kind of path which could provide an answer to the European and French political objectives: a higher emissions profile would unavoidably lead to a higher stabilization profile[7].

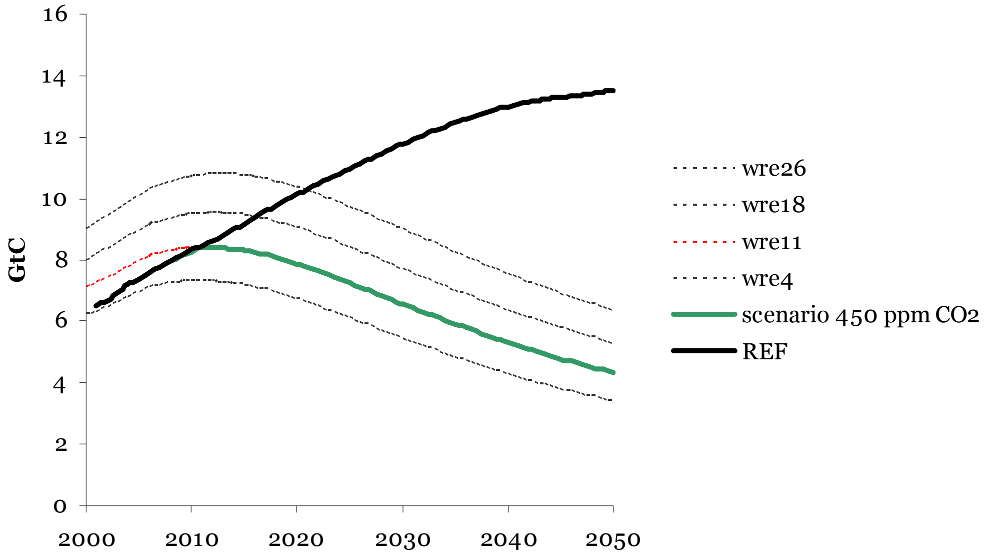

Figure 27: 450 ppm CO_2 stabilization path (green) compared to our reference scenario (black)[8]

Mimetic development styles

To achieve the 450 ppm-F4 scenario, main changes are assumed to take place concerning:

- energy consumption and industrial investment behaviour;
- swift diffusion of very low GHG emitting equipments for buildings, transport and industry;
- development and diffusion of new energy technologies (renewables, third generation nuclear and Carbon Capture and Storage).

However, in this scenario, there are no additional assumptions concerning changes in life-styles, in localization or in urban planning. They will be included later in another scenario.

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[8] In the literature two sets of stabilization paths serve as references : WGI trajectories (IPCC,1994) and WRE scenarios (Wigley, Richels and Edmonds,). The last ones allow for more important emissions in the early decades but a stricter reduction afterwards.

2.1.2 RESULTS

In the POLES-Imaclim modelling system the most convenient way to introduce a carbon constraint is to assume a tax on emissions, which will directly increase the final price of fossil energies. Then this means substitution towards energies without carbon, efficiency improvements, technology changes, polluting activities decreases, etc. Systemic impacts of these changes can then be evaluated by the models, in a limited equilibrium framework (POLES) or a global one (Imaclim-R). Linking an energy model and a macro-economic model makes it possible to evaluate the extent of indirect effects of a very strong carbon constraint on the energy system and the rest of the economy.

Carbon values

In order to obtain the emissions profile that has been described heretofore carbon values are calculated by iteration. In addition these carbon values are differentiated by region to take into account the potential European leadership in emission reduction policies and the adjustment delays of developing countries. In 2050 the carbon value stands between 250 and 350 Euros/tCO_2. This carbon value, which is quite high compared to some more optimistic assessment that can be found in the literature, must be interpreted with caution:

- This value has the meaning of an incentive that must not necessarily be a tax or an allowance price, but it reveals the extent of the implicit constraint that will weigh on the carbon-intensive activities;
- Should this signal be converted into a real tax, this would only translate into a doubling of the gasoline price in Europe in 2050, which seems somewhat in proportion with the four times emission reduction target ;
- finally, this signal does indeed correspond to the marginal signal to be applied to the sectors where reductions are the most difficult to obtain, and not to the average reduction costs.

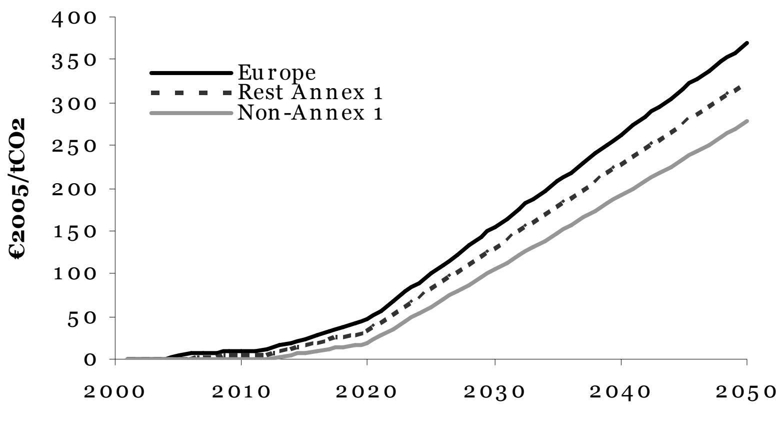

Figure 28: Carbon value – 450 ppm scenario / F4 mimetic

Differences between the three carbon value trajectories should be understood as delays for start up in the Annex 1 countries outside Europe and in the developing countries. These delays are not caught up later at this stage of the study, but this assumption will be changed in later scenarios.

2.2 Energy Development under carbon constraint

Final Energy Demand

Final energy demand is strongly reduced in this scenario. Growing until 2020, the consumption then declines in all activity sectors, so that in 2050 it is only 20 % over the 2000 level and 50 % lower than the reference level. Indeed in this F4 scenario, half of the emission reductions come roughly from energy control.

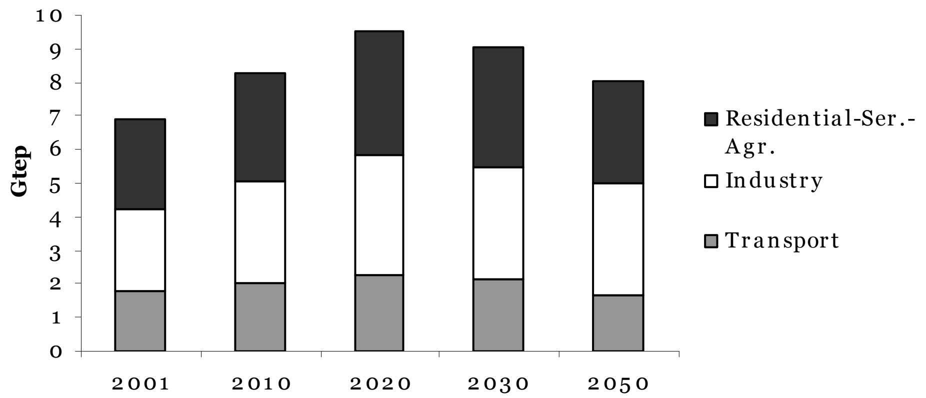

Figure 29: Final energy consumption -World

The change is even more marked in Europe where final consumption levels out from 2010 and declines after 2020 to reach a level that is one third less than the current one.

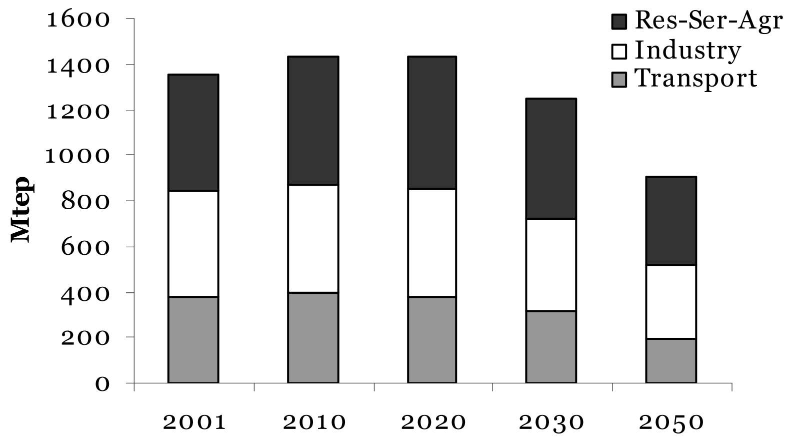

Figure 30: Final energy consumption -Europe

Primary Energy

World primary energy consumption reaches a ceiling at 14 Gtoe in 2020, before declining at13 Gtoe in 2050 – against 24 Gtoe in the reference. The share of non fossil energies - renewable and nuclear - increases significantly to reach 40 % of world energy supply, although in terms of volume these two energy sources are not much above their level in the reference scenario. Here again, the impact of total consumption reduction on the world energy system structure can be clearly identified.

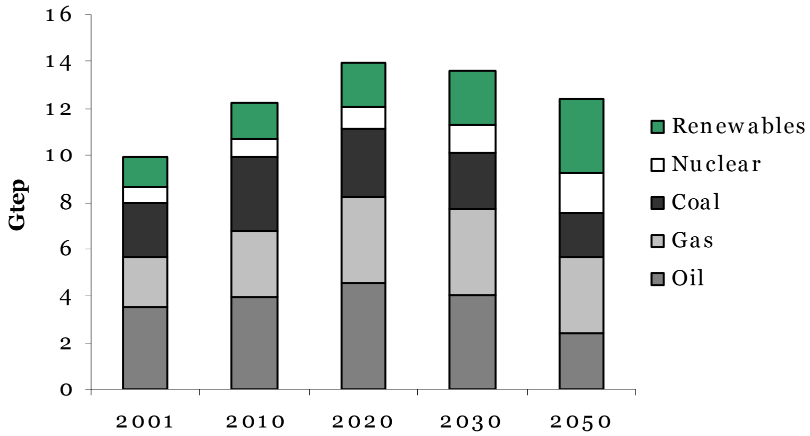

Figure 31: Primary energy production – World

Demand growth is restrained in all the world regions. In northern countries consumption reductions are diverse depending on demand dynamics, price elasticities in the different sectors and carbon value differences. In the emerging and developing regions the primary demand doubles.

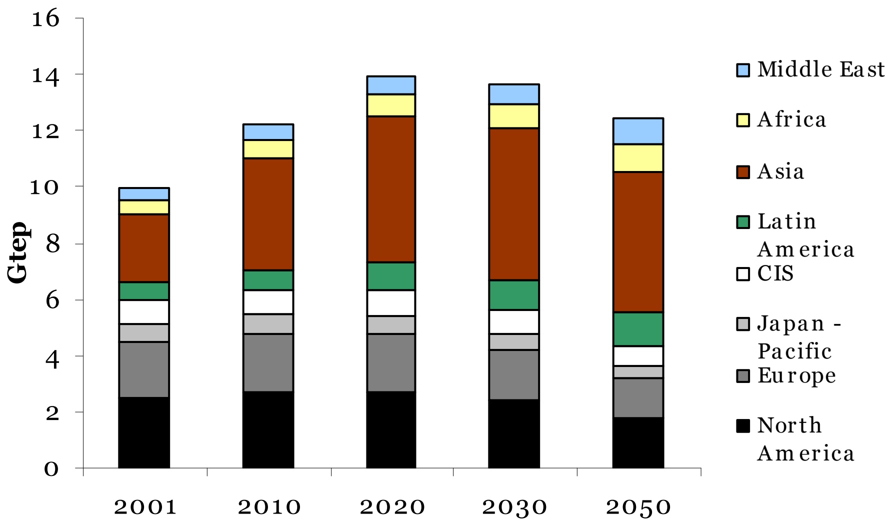

Figure 32: Primary energy demand per region

Technology mix for electricity production

World electricity consumption reaches 40 000 TWh in 2050, (vs. 60 000 in the reference scenario), but it still grows significantly as compared to the initial level. This is because the demand is less sensitive to the introduction of the carbon value, but also because, in many cases, electricity is a useful substitute for decarbonizing the energy system. Indeed in 2050 more than half of the electricity production comes from no-carbon sources, nuclear and renewables, although Carbon Capture and Storage has an important role in the residual fossil thermal electricity production (see below).

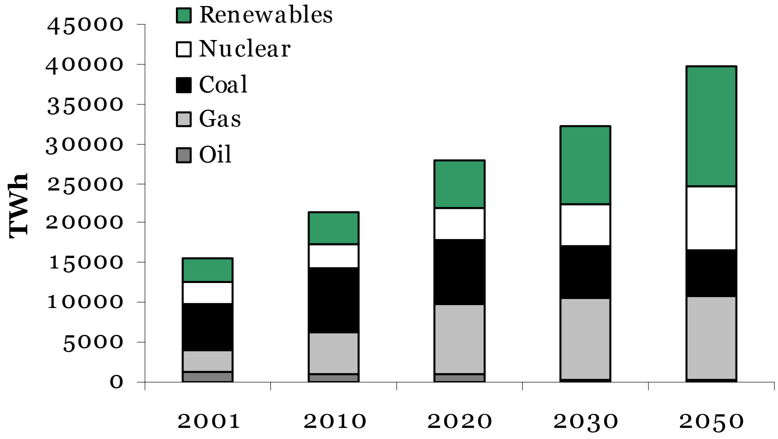

Figure 33: Electricity production mix– World

In Europe the share of non-fossil production plants is even greater and amounts to two thirds in 2050. The European system clearly becomes dominated by renewables and nuclear.

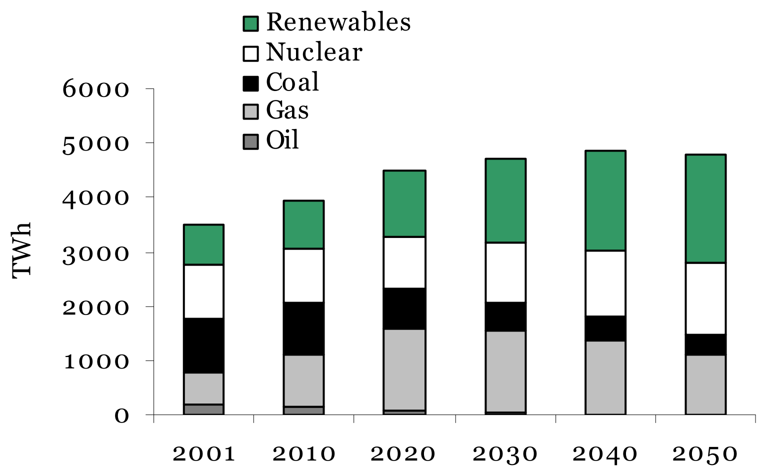

Figure 34: Electricity production mix– Europe

The part for fossil resources

One of the main results of this scenario is that the demand constraint is powerful enough to structurally change the energy market equilibrium. It is especially the case for the oil market with an important restriction of the size of the market which levels out at 100 Mbl/day after 2020. This new equilibrium makes it possible to greatly limit the need to resort to non-conventional oil, which has dramatic environmental impacts, but also to curb the share of the Gulf in the world supply: this share is kept below 50 % during the whole period.

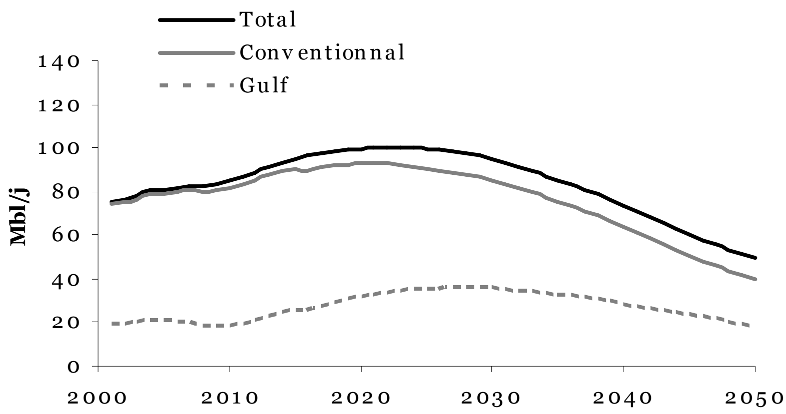

Figure 35: Oil production – scenario 450 / F4

This new dynamics of the world oil market can be observed directly on the oil price. As there is no additional assumption concerning a production cartel in the model, in response to the demand reduction from the consumers, the oil price trajectory is significantly lower. It leads to an oil price levelling out at 40 $/bl until 2050.The high carbon value makes possible a double dividend for the sustainability of the world energy system, through the joint solving of an upstream constraint on oil resources and a downstream constraint on emissions reduction. Other market equilibrium possibilities can be considered, but the basic aspects of the oil issue will inevitably be deeply altered and it will be considerably less acute in the case of a 450 ppmv-F4 scenario.

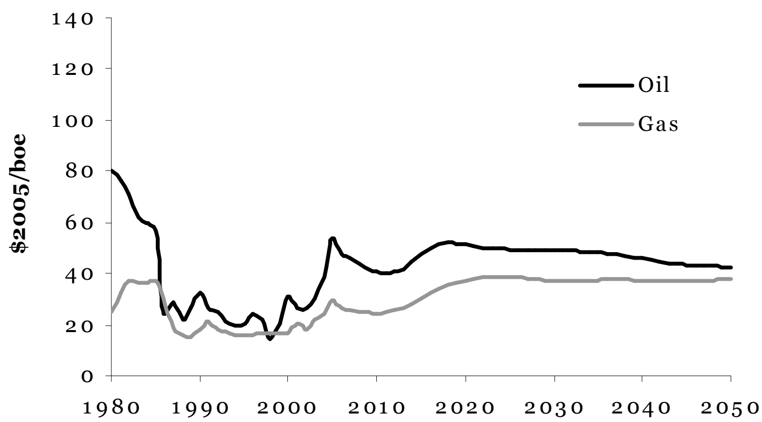

Figure 36: World prices crude oil and natural gas

Carbon Capture and Storage

Capture and storage of CO_2 represents an important part in the scenario as it amounts to 11 $GtCO_2$ worldwide in 2050, and a total cumulative storage of 220 $GtCO_2$ over the entire period. In 2050 it amounts to 40 % of the world gross emissions stored, and corresponds to 40 % of the reductions achieved as compared to the reference.

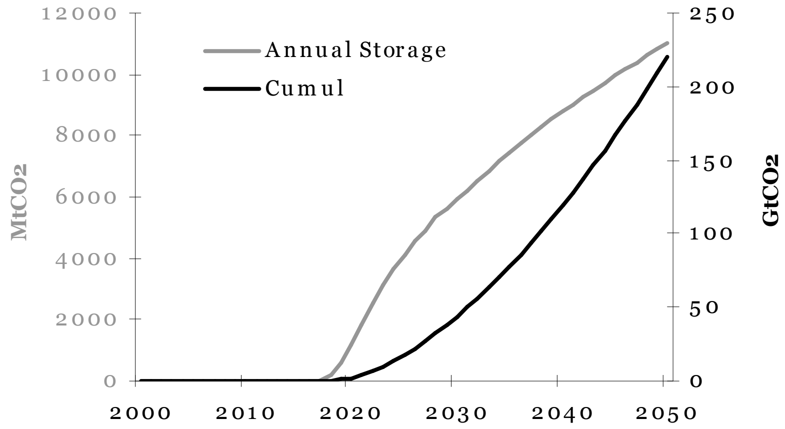

Figure 37: Development of carbon capture and storage

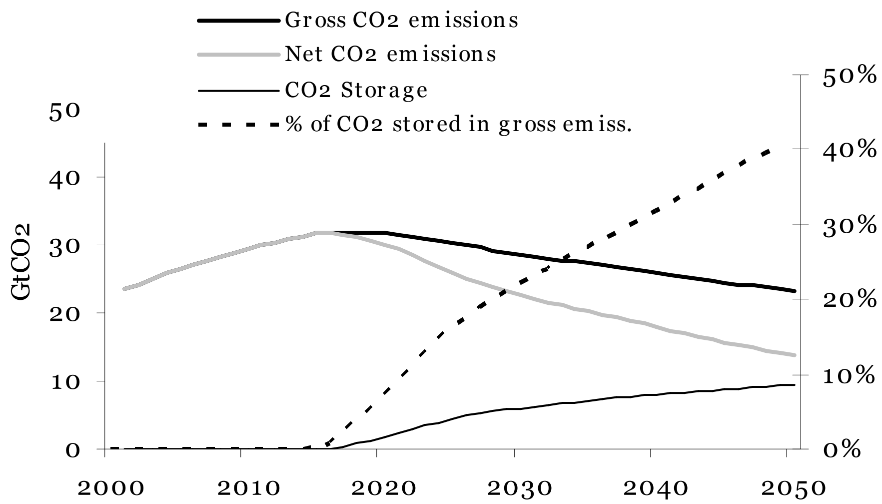

Figure 38: CO_2 emissions and storage level

Energy bill

The impact of the carbon constraint on the energy share in the household budget results on one side from the high value of carbon applied on residual emissions and, on the other side, from saving coming from induced efficiency gains and a decarbonized energy mix. The result is different among regions:

- For North America, South America, Africa and Middle East, the energy burden does not really change, as the increase in the cost of highly taxed residual fossil consumptions compensates the efficiency or decarbonisation gains.
- For the other regions, the bill is not as great as in the reference ; it is particularly true for India, where a significant decarbonization makes it possible to avoid, in the long term, a lock-in in a very expensive carbon-intensive trajectory (notably because of very large imports of highly priced oil), which is the case in the reference scenario.

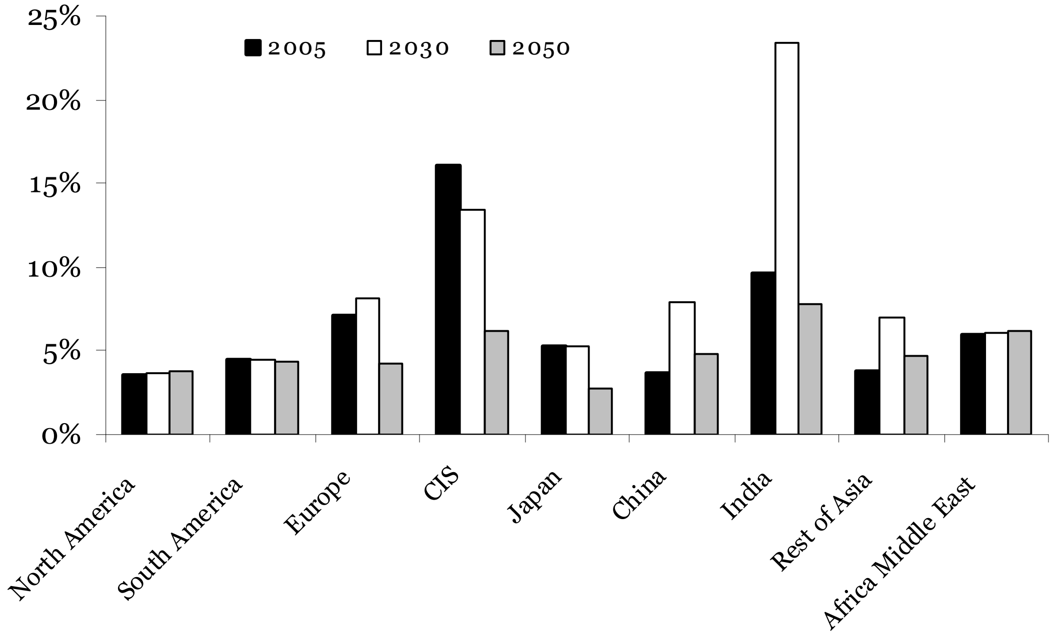

Figure 39: Households' energy bills– scenario 450 / F4

At the macroeconomic level, the transformation of the world energy system which has been described heretofore, and in particular of the oil and gas supply, affects the size of oil and gas imports and exports. The exporting countries receive strongly reduced revenues from their exports. This is a double edged reduction : on one side it is a revenue loss for these regions, but on the other side, and especially in the Middle East, these regions are less subject to very high local prices which critically affect the local demand and the development of non energy sectors : in short, the economic development of these regions is redirected towards non energy sectors, although the net consequence on the growth is highly negative (§2.4).

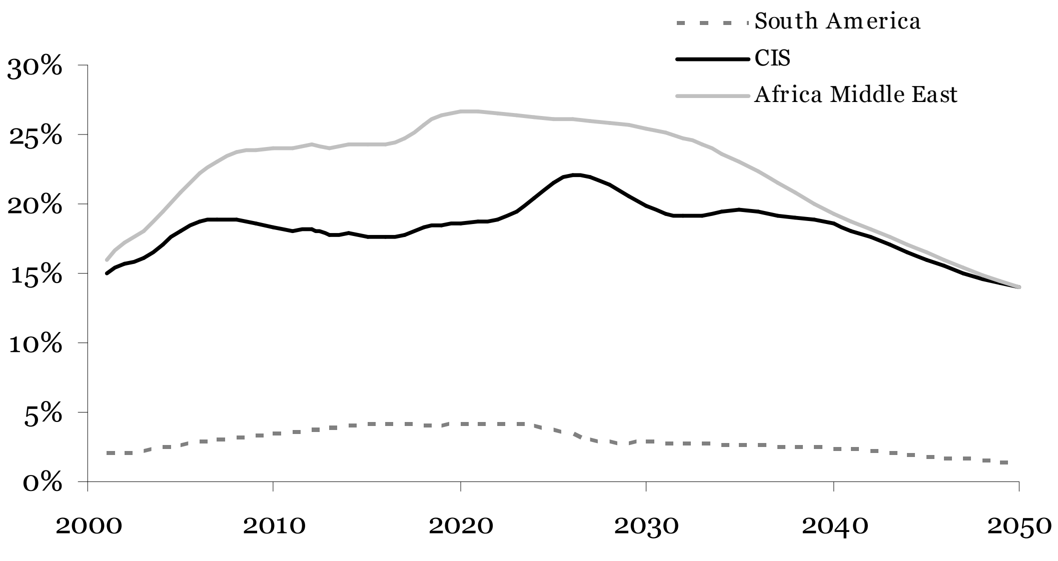

Figure 40: Ratio energy trade balance on GDP– exporting countries

On the contrary, as a consequence of their emission reduction policies, importing countries enjoy a large relief from their energy dependency, with a combination of lower world prices and smaller import volumes.

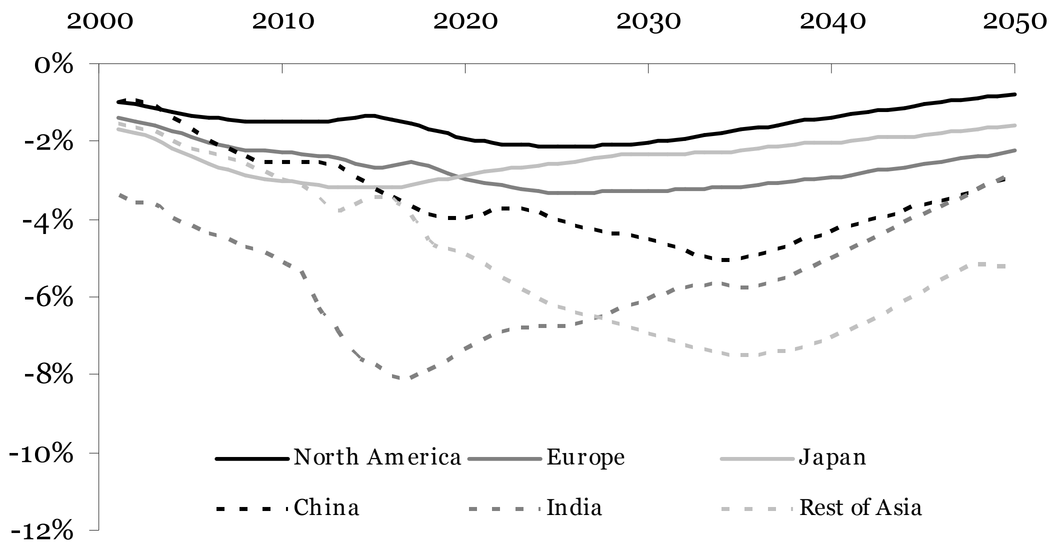

Figure 41: Ratio energy trade balance on GDP– importing countries

2.3 Industrial Sectors

2.3.1 Material Intensity Assumptions

To take into account the specific impact that a F4 emission reduction may have on materials demand, several hypotheses have been taken into consideration. Sectoral issues needed to be answered with experts from industry in order to elaborate these assumptions:

Concerning *buildings,* we needed to establish :

- What are the average materials contents of the different types of buildings (tertiary, private house, condominium building)?
- How much more glass panes for a very low energy housing, both for a private house or a condominium unit?
- What are the conditions (life expectancy, technical feasibility, resistance) that natural materials must satisfy in order to substitute for traditional materials in buildings?

Finally, the carbon constraint effect on buildings has been conveyed at two levels: buildings design and buildings structure.

Building design

A building both picks up solar energy (thermal and luminous) and exchanges heat between the outside climate and the required inside comfort. To design buildings with minimum CO_2 direct or indirect emissions it is necessary to both capture the maximum "useful" solar energy and to minimize the thermal loss. Capturing "useful" solar energy is a particular preoccupation for Northern countries and most often concerns glass panes, and consequently flat glass. Lessening thermal losses is a universal problem, usually dealt with insulating materials, sometimes with well designed air flows, seldom with gross construction materials. The assumptions introduced in the F4 scenario mostly relate to the solar water heater, which can be used anywhere, and to the very low energy housings in the Northern countries, where passive solar contributions represent a major part of the global thermal equilibrium. In our study these amount to:

- A 50 % increase in glass panes in the "cold" regions (Northern America and Europe).
- General use of triple glass windows for very low energy housings.
- General use of solar sanitary water heaters for very low energy housings: 10 m^2/housing in cold regions and 2 m^2/housing in other regions.

Buildings structure

Very low energy new buildings can be built using any kind of materials, but the choice of materials impact the amount of production of clinker, glass, steel, etc, and the associated emissions coming from their production and transformation. The only alternating materials which save CO_2 emissions are the natural ones: wood, raw earth, straw,

In this study, because of the lack of information on technical feasibility, life expectancy and strength of other natural materials (as well as the impact that their use would have on the consumption of the 'traditional' materials), only wood structure has been taken into account. Our F4 scenario assumes a massive spread of wood construction in the building growth which is induced by the carbon constraint (80 % in Africa and in Northern America in 2050, 70 % in Europe, and 32 % in Asia and Latin America). Based on studies of the Consortium for Research on Renewable Industrial Materials (CORRIM)[9], it is estimated that the construction of a wooden structured building would need, per square meter, 12 % less cement and 50 % less steel than the construction of a traditional building.

For *transports* we need to find other accurate data :

- materials content of private cars according to size (2 or 4 people) and to use (urban or regional traffic),
- automobile weight in relation to their type of engine, materials content of collective transportation vehicles.[10]

Vehicles design

Size, weight and power are design features of transportation devices and drive their CO_2 footprint. Size depends on the use, but, also, especially for private cars, on the perception of its utility and its social symbolic value. Weight relates more to security, performance and cost: cars tend to become heavier and planes lighter. Finally power seems to be a complex mix of real performance, use and individual preferences.

If, for private cars, only image and use are taken into account, the "factor 4" trends hare based on an improvement of the adequacy between size, power and weight of the cars on one

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[9] Study available on http://www.corrim.org/reports/

[10] Due to time constraints and to available information from our industrial contacts it was not possible to answer all these questions. At this stage F4 action levers were simplified and assumptions were made. A more thorough examination will be necessary at a later stage.

side, and their major use on the other side : strictly city, versus outskirts and regional, versus long drives.

In this reduction scenario it is assumed that alternative engines are progressively and exclusively used for specific city vehicles (less than 100 km autonomy) and that in the initial multifunction vehicle acquisition by households the share of long drives (over 200 km) progressively decreases while fast rail transport (TGV) develops. However the total number of vehicle-kilometres is not much reduced, except in the developing regions (with more than 5 -10 %) where traffic growth was very important in the reference scenario (Table 12).

	2005	2030	2050
USA	1.00	0.95	0.95
Canada	1.00	0.98	0.98
Broad Europe	1.00	0.97	0.95
Japan	1.00	0.99	0.98
CEI	0.99	0.99	0.96
China	0.99	0.98	0.93
India	0.99	0.84	0.81
Brazil	0.99	0.98	0.98
Midde-East	1.00	0.95	0.85
Africa	1.00	0.96	0.90
Rest of Asia	1.00	0.93	0.85
Rest of Latin America	1.00	0.76	0.70

Table 12: Change in vehicles.kilometre covered (in F4/REF)

Although in the Factor4 "mimetic" scenario, the total vehicle stock slightly decreases, the differentiation of vehicle types allows a fast breakthrough of low emissions cars. Indeed the number of conventional vehicles decreases by 80 % in 2050, while hybrids, electric, and hydrogen cars increase by a factor 2 or more (Table 13).

	2005	2030	2050
Conventional	1.0	0.8	0.2
Gas fuel cell	1.0	1.7	0.4
H2 fuel cell	1.0	2.1	0.7
Hybrid	1.7	3.7	2.5
Electric	1.4	2.6	1.8
H2 Conventionnal	1.0	2.4	1.9

Table 13: Change in engine type of vehicles (in F4/REF)

In this scenario with a carbon constraint it is assumed that the weight of the vehicles is decreasing. This trend applies in different ways according to the type of cars. The data which has been used comes from the assumptions made by the "Programme de Recherche et

D'Innovation dans les Transports Terrestres (PREDIT) for its own studies[11]. On this basis, we have assumed in this study the following weights for private cars:

Vehicle technology	**Weight in 2000 (kg/vehicle)**	**Weight in 2050 (kg/vehicle)**
Conventional	1200	980
Conventional + hydrogen	1300	1070
Electric		680
PAC Gas		720
PAC Hydrogen		720
Hybrids	1300	690

Table 14 : Change of the weight of individual vehicles

This weight decrease impacts essentially steel demand as steel is the main contributor of the car weight. In the follow up of this study it would be interesting to investigate the possible impact of this weight decrease on aluminium demand.

2.3.2 Sustained Material Demand

The Factor 4 effect on the materials industry is significant and both structure and volume of demand are changed. In 2050, steel demand is -8.6 % less in this scenario than in the reference. This decrease is the result of a downward trend related to the decrease of the steel content in cars and in buildings, and an upward trend coming from the assumption of an accelerated reconstruction process and an increase in the turn over of car stocks.

[11] These studies are available on the site: http://www.predit.prd.fr/predit3/homePage.fo

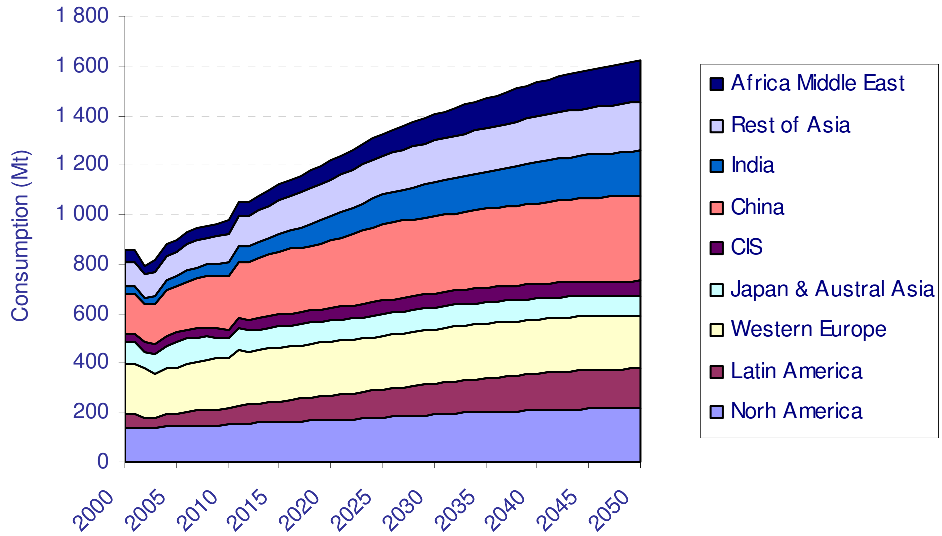

Figure 42: Steel consumption per region

Indeed, comparing with the reference scenario in 2050 the steel consumption in buildings is higher by 22 %, while the consumptions of transportation and of other sectors are lower by, respectively, 32 % and 11 %.

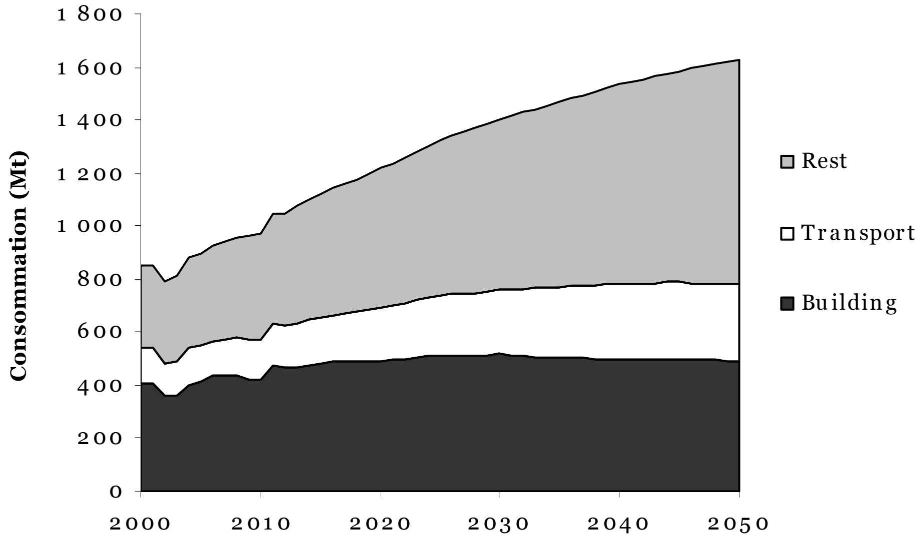

Figure 43: Steel consumption per sector

Cement demand in 2050 is 10 % higher than in the reference scenario because of the assumption of an accelerated reconstruction prevailing over the reduction of cement use per unit.

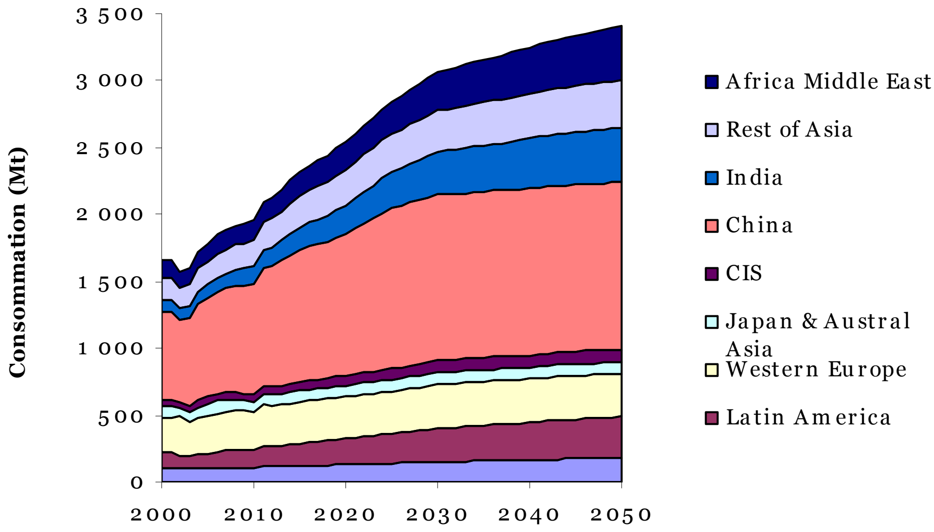

Figure 44: Ciment consumption per region

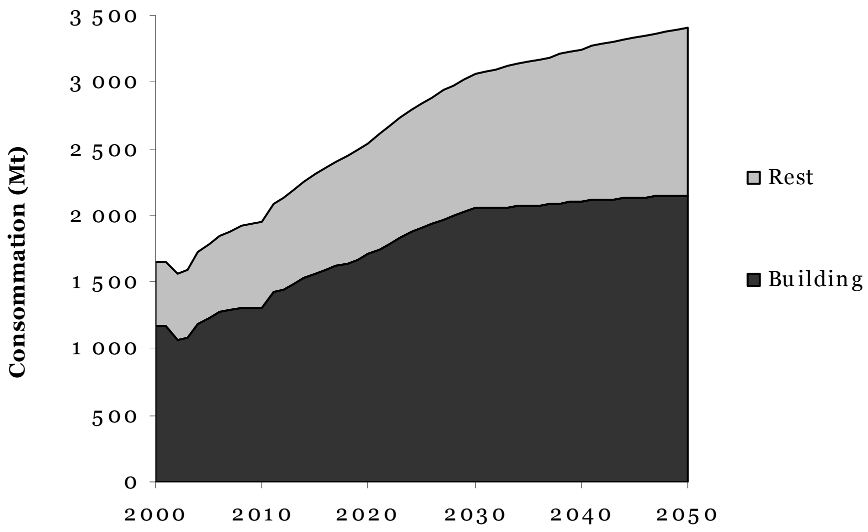

Figure 45: Ciment consumption per sector

Total aluminium demand in 2050 is slightly less (-7 %) in the F4 scenario than in the reference. It is higher by 29 % in buildings, while there is a 50 % reduction in the electric network investments and a small reduction in transportation and in the other sectors (3 % and 5 % respectively).

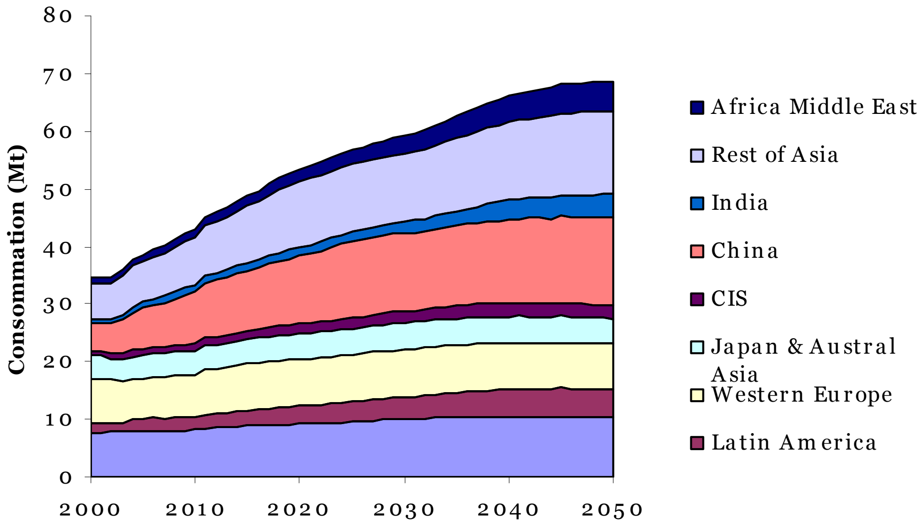

Figure 46: Aluminium consumption per region

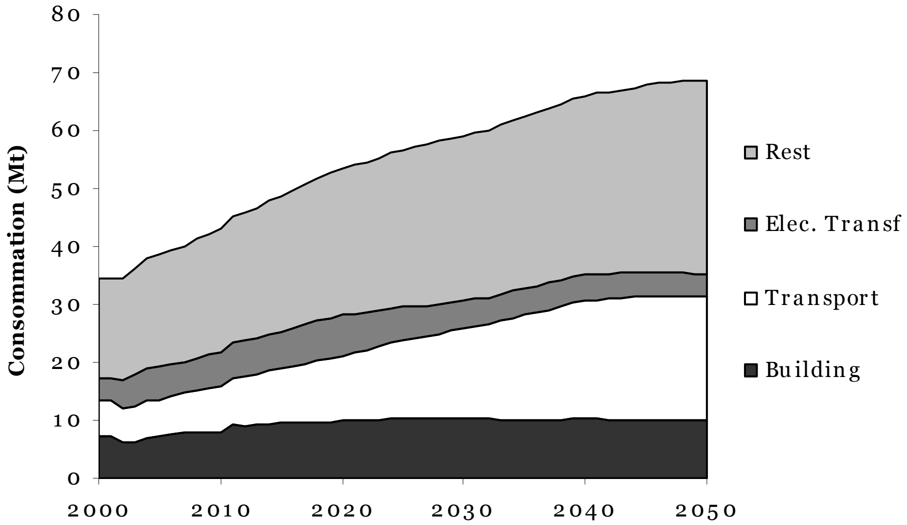

Figure 47: Aluminium consumption per sector

Glass panes demand in 2050 is higher by 63 % in the F4 scenario than in the reference, in relation with the assumption of a massive development of double pane windows, solar water heaters and the increase in unit consumption of glass. This demand comes mostly from buildings (double consumption than in reference). Transportation demand is not modified and the consumption of other sectors is lower by 16 % in this scenario.

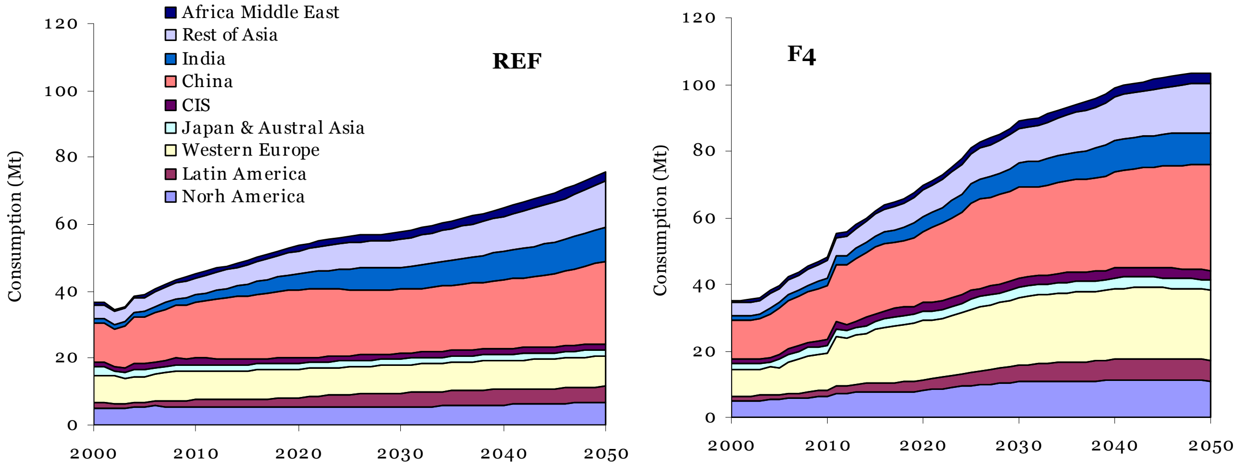

Figure 48: Flat glass consumption per region

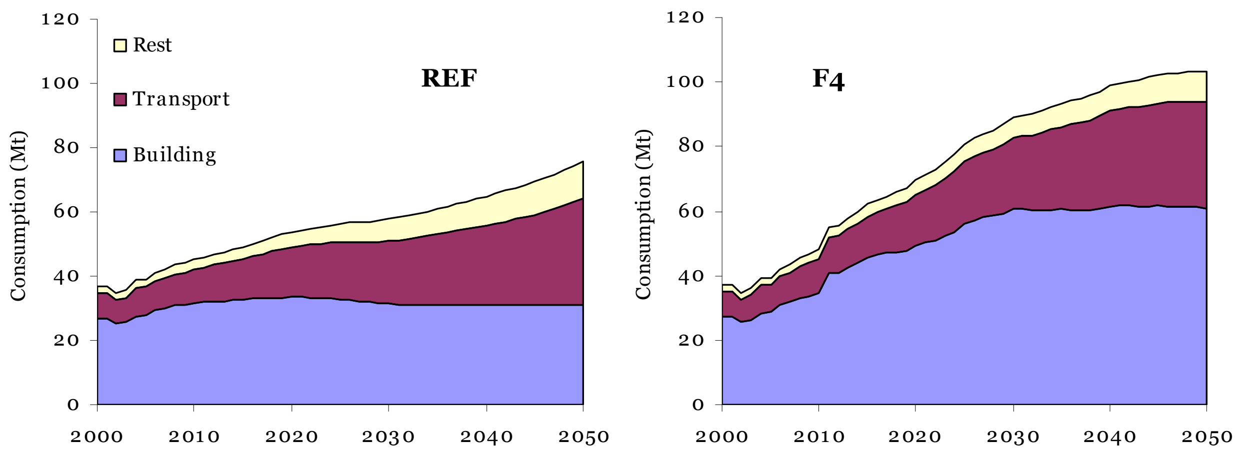

Figure 49: Fat glass demand per sector

2.4 Economic Assessment

As mentioned in the introduction, any comparison of two paths of aggregated GDP over the large regions and related to two scenarios which are strongly divergent both in the energy system and in terms of structural change must be interpreted cautiously. However this comparison has some advantages: on one side it may reveal some significant economic facts, and on the other side because such comparisons may be used as arguments for the pros and cons of climate policies.

The figure below shows the losses and the gains of the real GDP between the reduction scenario and the reference scenario. This figure needs several comments:

- For all regions of the world the carbon constraint entails an economic cost during several decades, but for most regions less than 5 %.

- Fossil resources exporting countries undergo a drastic decrease of their external revenue, which explains a continuous revenue loss for these countries (CIS and OPEC) which can reach 20 % in 2050.
- The few percents delay in the economic growth induced by the carbon constraint is caught up, and even reversed, at the end of the period because of the induced reduction of the energy bill and of the greater independence of the economies from the fossil fuels. These become scarce and their cost increases much more in the reference scenario.

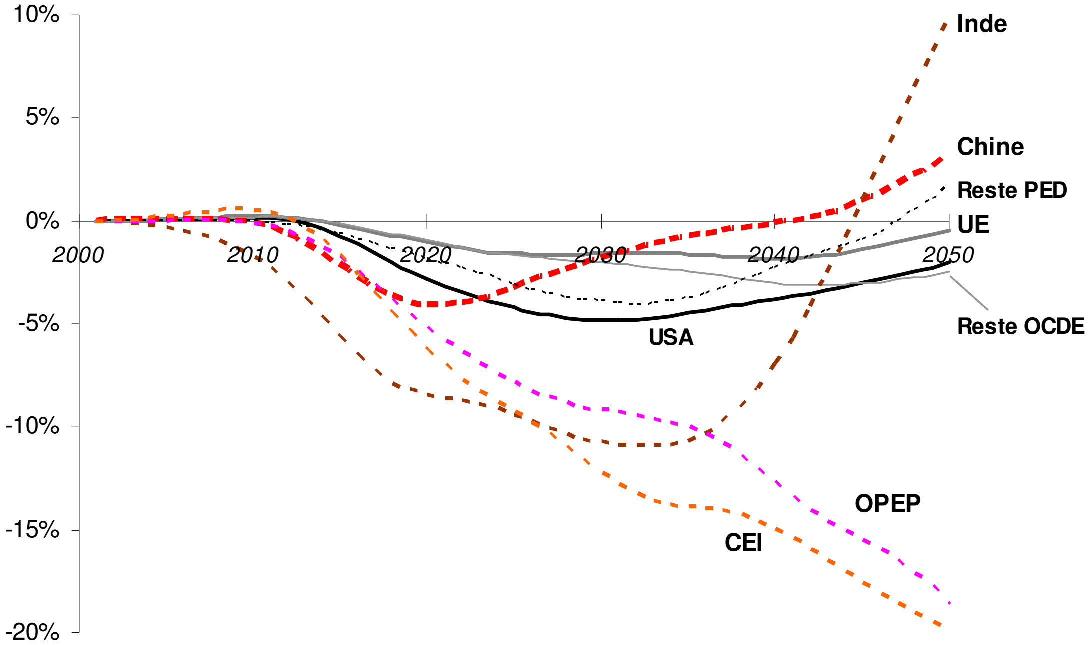

Figure 50: Variations of GDP PPA between scenarios REF and 450 ppm / F4

The figure shows that the carbon constraint is above all a transition problem rather than a long term one, *except for the oil and gas main exporters (CIS and OPEP).*

Because a coarse carbon constraint based on a single price signal, with a linear growth and without any compensations for the most vulnerable regions in the short term has been set in our scenario, it means that a more subtle implementation of this carbon constraint would make it possible to significantly reduce the slow down during the transition phase necessary for the decarbonization. This will be studied in the next reduction scenarios which will use different instruments.

3 Intermediate Conclusions: acquired knowledge and future work

The work accomplished in 2006 has led to the development of two harmonized scenarios, a necessary reference scenario and a first emission reduction scenario with a F4-450 ppm target. This was achieved through an important modelling effort, with harmonization of the two models involved. This first 450 ppmv-F4 provides some preliminary insights:

1. Considering the technological and macroeconomic conditions of this scenario, the 450 ppmv concentration stabilization target is achievable through emissions reductions induced by a high price signal in 2050: between 250 and 350 € per ton of C02.
2. The macroeconomic balance of this constraint *in 2050* appears comforting, especially because efficiency gains and decarbonisation of the economy make it possible to avoid the strong future dependency on oil and gas, which will become rare and very expansive. On the other hand large fossil fuels exporters suffer very significant revenue losses and, consequently, GDP losses.
3. Transition costs can be high in some countries, especially when the fast growing carbon price puts an additional burden on the energy bill while the decarbonization process has just begun (in India for instance).
4. These transition costs can be alleviated by a better-timed price signal profile, by launching earlier a clear and credible price signal, which will enable economic agents to anticipate better the future constraint, or by setting well targeted compensation measures.
5. On the opposite side, the macroeconomic balance may be burdened by various barriers or delays which are not or insufficiently represented in our present scenarios: delays in the spreading of technological innovations, perverse effects on the revenue distribution and growth "jamming", wrong incentives and institutional failures.
6. This 450 ppmv-F4 scenario assumes sustained technical progresses, in all directions, without any acceptability problem: CO_2 capture and storage reaches 40 % of emissions in 2050 (9.4 Gt CO_2); simultaneous penetration of all innovative technologies (hybrids 38 %, electric 24 %, hydrogen 18 %) make for a diversified automobile stock and nothing stands against a large development of nuclear and renewable energies (respectively 14 % and 25 % of primary energy in 2050).
7. Materials demand is sustained by new and faster renovation of buildings and infrastructures. There is a great uncertainty concerning the materials demand for sectors outside the transportation and the building sectors. This demand will be confronted to the substitution potentials of other materials and of the materials price increase induced by the carbon constraint.
8. The technical evolution towards the decarbonizing path of the industrial sectors studied here will need a strong development of materials recycling. This does not only rely upon industrial strategies but also implies to set up a global system for collecting and improving.

In 2007 our work will be to proceed with the development of 450 ppmv-F4 scenarios along two axes and to analyse the evolution of the materials industrial sectors inside these two scenarios :

First we plan to build up and analyze an alternative scenario with different future development styles and assuming different land and urban development trends as well as housing and mobility needs.

Secondly, we shall try to study a more clever "policy mix" than the present one which relies on a single price signal; by tailoring the instruments (timing and level) for each sector and trying to evaluate the cost of Policies and Measures and how they relate to the carbon value.

Finally, a scenario where the international climate coordination is postponed will be tested, with delayed action in the developing and emerging countries.

4 Addendum: some minor revisions of the reference scenario and the Stabilisation Scenario with « mimetic » development

Thanks to frequent meetings of the steering committee, the scenarios have been reviewed extensively by industrial experts. All commentaries and criticisms have been treated and incorporated in one global revision of the two scenarios. In the meantime, the coupling method applied to POLES and IMACLIM had also been improved, which led to scenarios with a stronger internal consistency.

4.1 Reference Scenario

In terms of final output, the reference scenario appeared not significantly changed during the revision process. The main corrections aimed at (i) trimming of functions linking the equipment level of households in private cars and their dwelling surface with the per capita revenue expressed in purchasing power parity, (ii) strengthening the coupling between POLES and IMACLIM on the material components of the GDP which led to some modification of the structural change in the POLES simulations. These modifications led to an increase of the primary energy produced in the world in 2050 (24 Gtoe in the scenario presented before and 28 Gtoe in the revised scenario). This upward correction is mostly the result of the trimming of the household equipment function: the first results appeared indeed quite pessimistic concerning the economic catch up in emerging countries. The primary energy mix is not really modified: fossil energies make up three quarters of the supply, the remaining is equally divided between nuclear and renewables.

4.2 Stabilization scenario under mimetic development styles

Because of the changes made in the reference scenario, the results of the stabilization scenario have also been improved. The world primary energy production reaches 15 Gtoe while it was limited at 12 Gtoe in the first scenario. This primary energy increase is supplied by fossil energies – their emissions are captured by an increase in CCS – and by a more important nuclear development. The results concerning industrial sectors and the macroeconomic cost of stabilization have not been significantly modified, except for the fossil resources exporting countries (OPEP and CIS) where the revenue losses are increased because of larger fossil resources consumption in the reference scenario.

Second Part:

A Stabilization scenario under “non-mimetic” development styles

Two sensitivity tests about the potential delay of action in developing countries and carbon capture and sequestration availability

5 'Non–mimetic' scenario

This scenario, based on a different development style, was produced after a methodological and political diagnosis built on the mimetic scenario. Following this diagnosis, a 'non-mimetic' scenario was elaborated in three stages: (i) a different storyline underlying the modified assumptions was drawn up, (ii) these changes were quantified into new assumptions for running the models, and (iii) the POLES / IMACLIM-R modelling platform was used to analyze the consequences of this new set of assumptions in a consistent long run scenario.

5.1 Rationale for a « non mimetic » scenario

5.1.1 The questionable plausibility of the mimetic scenario

The 'mimetic' F4 scenario was achieved by imposing a growing carbon value in the whole world economy in order to induce technical change towards technologies that would be less energy intensive and/or low carbon emitters. Some of the basic assumptions made in the reference scenario were not modified in the first stabilization scenario, as the development toward a world-wide economy, a progressive economic catch up by developing countries, the evolution of households' equipment and preferences (based on past trends) and the choices for urban planning and infrastructures. This very common method gave rise to two comments.

First, it does mean that some really critical economic driving forces are not sensitive to a growing carbon value. For example the carbon value has no significant effect on how development styles (preferences, spatial organization, etc.) converge or not. Surely, this is not a pure fiction as a very robust catch up movement exists in the economy:

- *A technological convergence*: any significant change of technological path would require some main technological innovations, and the 'least effort' trajectory remains a catch-up of the *current* technologies in all countries. As a consequence, a globalized economy brings some uniformity in the available technological level in all regions.
- *A catch up in life-styles:* in all countries people yearn for the same urban services: mobility, space, energy, information, spare time activities, etc. The desire for private car ownership and spacious dwellings are particularly strong as average income increases.
- *Public policies* are not willing to change people's priorities or long term sustainable land management because of short term political mandates, other urgent matters, lack of popular appeal of these policies.

Secondly, the high carbon value reached in the first scenario may be hardly bearable. Even before that level is reached, the carbon value will be subject to political and economic lobbies' contention which cannot be modelled. This scenario requires very fast and efficient spread of the low carbon technologies. It also questions the likelihood of all these technologies being available for a factor 4 cut of emissions in Annex 1 countries and a factor 2 in the world. Significant transition costs entailed by such a scenario also questions its coherence. In fact, personal choices will likely be progressively modified by the technological revolution derived from such an increasing carbon value. Moreover, policy makers will implement additional policies and measures in order to find a less costly reduction strategy. In addition, other factors could convince countries to implement policies and measures that will change the organization pattern and life-styles: a quick deterioration in the quality of life and in the economic efficiency of urban regions, a difficult world energy context, the increase in climate damages in a few decades.

As a consequence, the production of this new scenario, called 'non-mimetic', is based on two concerns: on one hand, considering a different evolution of life-styles and how this evolution contributes to the reduction of emissions, on the other hand, correcting some of the non plausible evolutions in the previous scenario. As a consequence, some differences between the two reduction scenarios will be related to changes in the development styles, and others will be corrections of non plausible results.

5.1.2 MITIGATION STRATEGIES AND LIFE STYLE EVOLUTION

There is a striking paradox in most of the reports dedicated to climate policies. On one side, the discursive analysis of the ways to reduce emissions mentions a large set of tools, policies and measures, which largely goes beyond the sole classic instruments: taxes, allowances, norms. The Executive Summary of the last IPCC report points out:

> « A wide variety of national policies and instruments are available to governments to create the incentives for mitigation action. Their applicability depends on national circumstances and an understanding of their interactions, but experience from implementation in various countries and sectors shows there are advantages and disadvantages for any given instrument. […] Policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG products, technologies and processes. Such policies could include economic instruments, government funding and regulation » (SPM, Working Group III, p. 22)

On the other side, the way in which models represent climate policies is amazingly poor, as it usually only relies on a uniform carbon value, generally a tax or a tradable allowances system. This carbon value can be considered as an indicator of the constraint put on emissions through a whole set of diversified policies and measures, but this simplification progressively introduces a bias in the analysis of climate policies: one usually concludes that a uniform carbon price applied in the world economy will entail the stabilization of GHG concentration, cost a few percents of the GDP in 2050 and that what is at stakes is purely a matter of technology. The modelling architecture which has been used has made it possible to show precisely what are the consequences of that view in the "mimetic" scenario. In the POLES / IMACLIM modelling platform, the factors responsible for the emissions are explicitly represented: amount of private cars, dwelling surface and per capita equipments are a function of revenue per capita; infrastructure decisions rest upon progressive needs of the economy. Most other models resort to production or utility functions with substitution factors, which underestimate the strength of these dynamisms even with a high carbon tax. Because of our representation choices, we have clearly shown that a world climate policy which does not modify these upstream factors of emissions might entail high costs, or miss the target if the technologies are not available in time. In other words, an increasing carbon price in the world economy might run against the large issue of development choices.

These new assumptions have also corrected some less plausible evolutions, but, more significantly, they precise our choice to explore a scenario with climate policies relying partly upon a change in development, land and urban planning, and energy system structure choices.

These additional levers are key factors for industrialized countries and crucial for emerging and developing countries. One must first looks for levers that will put any ambitious climate policy back in the mainstream of a sustainable economic development by, for instance, promoting the efficient use of rare natural resources and by restricting local pollutions. Secondly, it is critical to avoid the *lock* in very carbon and energy intensive trajectories that would derive from almost irreversible spatial planning and infrastructure choices. Referring to the usual diagnosis that a growing carbon price policy based will not be costly, one would miss these two targets, and would run the risk of a high transition cost and of the inefficacy of the carbon price signal on land and urban planning, activities localization and infrastructure choices. Even worse, not taking into account other decision levers than the single carbon price may lead to economic absurdity, when the infrastructures development is totally disconnected from the constraint (via taxes or emissions trading) on emissions :

> « In Britain, early 2007 found the Environment Secretary announcing his enthusiasm for personal carbon allowances (…) this policy debate is being conducted alongside other governmental priorities that have a quite different focus. The government is raising the marginal costs of train travel, making plans to expand airports, widen motorways, build roads, and build large numbers of new houses in food-plains. » (G. Prins et S. Rayner, 2007, pp. 5-6)

5.2 Storyline of the non mimetic scenario

The assumptions of the first reduction scenario were modified in three areas: dwelling space, mobility of persons and goods, industrial production organization. The main idea is to assume a change of paradigm in the energy system, from the stock-energies (fossil) paradigm – abundant and used inside a very concentrated organization with a centralized production – to a flux-energies (mainly renewable) paradigm – with a much more decentralized organization and a widely distributed production mode.

5.2.1 DAILY LIVING SPACE

Concerning the daily living space, we may look at two opposite paths:

- **A scattered type of dwelling with autonomous energy**: requiring a maximum of solar panels in order to fulfil both stationary needs inside the buildings (electricity and heat) and mobility needs outside (recharge for electric or hybrid cars), together with an increase scattering of buildings and an increase in mobility needs.
- **A concentrated type of dwelling with an optimized and concentrated energy system:** achieving a more dense urban space would make it possible to reduce the mobility needs and the concentration of energy production to fulfil the stationary demand, while making use of more concentrated but globally limited energy resources like biomass, waste, deep geothermal or off-shore wind.

Each option can suit to local or national context, so that to define the new assumptions, we need first to look at the regional contexts.

In industrialized countries where the urbanization level is already very high and the demographic projections are low, the trends will be severely constrained by the current organization of the urban space. In the scattered urban space, such as North American cities or the outskirts of European cities, the most logical evolution would be the development of solar and wind energies and their use on-site to fulfill the stationary and mobility needs. In the highly concentrated urban sites, a concentrated energy production system would remain the dominant one, but using locally renewable energies such as biomass, wastes, wind farms.

In developing countries, where co-exist side-by-side some of the largest urban concentrations in the world and a significant rural population, the space organization could be largely reorganized under the double pressure of a large population growth and of the economic development. We shall separate the cases of existing megalopolis, new future cities and the rest of the territory.

Industrialized countries, dispersed housing areas

The structural evolution of dwellings should follow two trends:

- For new construction and renewal of private houses a progressive generalizing of "positive energy" houses with the combination of a climate adapted architecture, solar thermal collectors for hot water and photovoltaic solar cells, which will have the appropriate size to fulfil the internal electricity needs (except heating) of the house and the daily mobility needs of rechargeable hybrid cars.
- For habitat renovation, improvement in thermal isolation and equipment with thermal solar collectors and photovoltaic cells designed such as to fulfil the internal electricity needs (except heating) of the dwelling as well as the daily mobility needs of rechargeable hybrid cars.

In these dispersed living areas, daily mobility would be provided by two additional means:

- private rechargeable hybrid cars, with the maximum possible use of batteries within the limitations of battery improvements on one side and of the solar electricity surplus on the other side.
- mass transportation with privileged tracks and with a network of parkings, the size of the mesh being chosen in relation with the electric private cars autonomy and the distances to work and shopping.

Industrial countries, densely populated areas

Two trends should influence the condominium stock in the dense areas:

- the progressive thermal renovation will decrease heating and cooling needs in the dwellings
- the spread of heat networks will fulfil heating and hot water requirements with such concentrated renewable energies as biomass, wastes and geothermal and/or with cogeneration.

In these densely populated areas, the current use of private cars will be gradually discarded and replaced by a combination of soft modes, mass transportation and common use cars (taxis, short term rental, etc.). Respective shares of these modes will depend on the size of the city. This would mean a strong decrease in private car ownership for people living inside these areas.

Developing countries, new cities

For these new cities the basic rule could be strict energy autonomy based on renewable energies, as well for the inside needs of the residential and tertiary buildings as for the mobility required inside the city limits. Depending on the population densities and the climate this basic rule would have differentiated applications in terms of building types, building density, energy network, transportation network and modes, and in the level of private vehicles.

Developing countries, mega polis

In outlying areas of these mega olis, where small and low quality private dwellings predominate, a massive renovation could be contemplated. The building and energy equipment standards could be either those of industrialized countries with dispersed dwellings (positive energy buildings) if the demography is suitable, or, on the contrary, those of new dense cities.

In the inner zones, usually quite dense, where large buildings prevail, the only main action should be the thermal retrofitting, generally based on reducing cooling requirements.

The current private cars development would be highly discouraged in these mega cities, then it would progressively be banned from the city centres, and be replaced by a multimodal system with a combination of soft modes, mass transportation, and common use vehicles (taxis, short rentals, etc…), each part of the city deciding its own sharing of these different modes. As a consequence, there would be a strong reduction in the private car ownership as compared to the industrial countries current level, with similar revenue levels.

Developing countries, other areas

In other areas, the most significant factor will be the strong spread of the small and middle sized cities resulting from the migration of the still numerous rural populations and from the attempts at fighting against the exodus toward the mega polis, which will be themselves already close to asphyxia.

If there is enough sunshine and a lot of available space, construction could follow the same path as in the dispersed areas of industrialized countries. At least if weather conditions are similar, with solar panel surfaces adapted to the conditions prevailing in these countries.

In other areas it would be rational to resort to a dense construction system with high thermal performance (mostly on cooling) and to chose the site in relation with the mass transportation network.

In all cases, urban planning will be carried out in order to maximize the attractiveness of mass transportation and to limit the requirements for a private car, which, in any way, would be autonomous from an electricity supply (that is rechargeable hybrid with solar panels).

5.2.2 PEOPLE AND GOODS MOBILITY

Up to now, in industrial countries, people and goods mobility has developed with the following characteristics:

- The time assigned by people for their mobility has been stable, around an average of one hour per day per person. The increase in the average travelling speed has made it possible to increase the individual mobility in terms of kilometres per year.
- The increase in the average travelling speed *for persons* has a relatively stable elasticity relation with GDP which is similar in all countries: it is currently possible to link the

average speed spreads (and consequently the km/year/person as the time budget for mobility remains stable) to the GDP/capita with this same elasticity.

- The increase in the average travelling speed *for goods* is related to the GDP with the value per ton of transported goods increasing faster than the cost of speed. This has led to a continuous increase in the transportation distance for goods.

The increase in the average travelling speed for persons and for goods was mainly accelerated by substituting slow modes (draught horses, rivers and canals, later train) by more rapid modes (trains, trucks and planes). The development of mobility is economically rational because the increase of the transportation cost coming with the increase in speed has always remained less significant than the increase in the value of time (based, for instance, on the cost of the working time) and also in the per ton value of goods.

The "mimetic" scenario was based on the extension of these trends in developed countries and their adaptation to developing countries. On the contrary, the "non mimetic" scenario assumes a reversal of these trends in developed countries and a different path for developing countries. This assumes policies against the drift in speed increase coming from the per capita revenue increase and the per ton value increase of transported goods. While restricting speed, it is important to avoid any drop of the global utility of mobility or of the efficient operation of production facilities, as well as the potential lengthening of the time-budget for transportation. At last, together with the speed restriction, there are two possible technology paths: either a breakthrough toward alternate engines, like hybrids or full-electric, or internal combustion engines with green fuels or hydrogen produced with non fossil electricity.

The "non mimetic" scenario relies on three linked outlooks:

- link the development of the household car equipment with, on one side, the evolution of the living areas and on the other side the potential motorisation choices, taking into account the speed and the time-budget constraints;
- combine the use of road vehicles with a limited autonomy (resulting from the renunciation to energy dense fuels), with a change of behaviour concerning long distance travels which would not increase air traffic;
- exchange speed against proximity, for leisure times as well as for the organization of the moving of goods, so as to favour slower modes and/or with less autonomy.

In industrial countries, the reversal of these trends could be induced on one side by an increase in the cost of transportation as the speed increases, faster than the time value and the per ton value of goods, and on the other side by breaking up transportation time-budgets and/or distance usefulness.

In developing countries mass transportation systems (like High Speed trains) could offer faster travelling speed than the road vehicles for long distance trips and also for daily short distance moves because of restrictions set on the use of the infrastructures by cars.

People mobility in the industrialised countries

Although most households will still be equipped with private cars, the constraints on their use will tarnish their role as a status symbol and as the sign of freedom of mobility. The household equipment will de deeply modified, with (i) a decrease of cars multi ownership for two- persons- or- plus households in all urban areas with a good mass transportation network, (ii) a decrease of one car ownership in all dense urban zones, (iii) the emergence of cars for a single use which could be privately, collectively or publicly owned.

In order to minimize the time spent for the journeys, increased better interconnected other modes of transportation will progressively fulfil the mobility needs and will also be interconnected with the road network. These interconnections will take place at three levels:

- inside the urban area (hub, park and ride) for daily moves
- between the urban area and the inter-urban areas
- in the inter-urban areas with multi-modal platforms (road/railway/air)

In urban areas, cars will offer mobility required as soon as the distance to the public transportation access exceeds the reasonable distances for the soft mobility modes. The design of the public transportation networks will be dependent on the autonomy of the solar electric engine vehicles, more and more rechargeable hybrids. Car use for long distance journeys will decrease as infrastructures for high speed trains get developed. Cars will keep the leading part for short distance journeys outside the urban area, but the reduced level of cars ownership and the increased density and interconnection of the alternate modes will make these more attractive.

On the whole, this "non mimetic" scenario would mean less cars, with less kilometres per year because the average speed has been reduced (main consequence of the changes in the use of infrastructures and of traffic restrictions in the urban areas) and with a larger share of these kilometres made with electricity. The decrease in people's travel by cars would be compensated in three ways: new location for socio-economic activities and for living areas so as to reduce raw mobility needs (km/capita/yr) through a growing use of soft modes and an increased use of public transports.

The decrease in the mobility requirements will come from constraints set on time spent in transports. In an urban area, already largely organized and developed, bringing closer people and activities will limit the increase in the daily time spent in transports while the average travelling speed decreases. Thus restrictions on car uses and less cars owners will enforce a general slowing down of movements inside urban areas.

Resorting to soft modes is a direct and unavoidable consequence of the reduced car equipment and of the increased use of public transportation. The increase in the traffic of public transport will include (i) movements inside the city, particularly compulsory ones (home-work, home-school), (ii) private and professional long distance travels, (iii) short and middle distance travels between cities.

Electricity becomes the main energy for public transports: already the case for railways, then with hybrids for urban and local road transport. This electricity is mainly produced with renewable energies: wind, solar, biomass depending on the area. Only middle and long distance public road transports would maintain internal combustion engines, with second generation bio fuels progressively becoming the energy supply.

People mobility in developing countries

Households'car equipment keeps increasing but in a socio-economic context quite different comparing to industrialized countries fifty years ago when the use of car spred out. It would guarantee freedom of movement but not a high speed anymore, and become very expansive. Three consequences follow:

- in the urban areas households' car equipment gets saturated at a much lower level than in industrialized countries;
- in urban areas a mighty development of common place car services;
- low multi-equipment in households of two or more people.

The unavoidable increase in mobility needs will be preferentially satisfied by other modes than cars. These modes will be designed from the start as being interconnected so as to make it practically possible to live without a car:

- interconnection inside the urban area for daily mobility
- interconnection between the urban area and the outside
- interconnection in the areas between cities

Urban planning is thus designed so as to limit as much as possible the need for a car and to restrict its use to the solar electricity powered car autonomy, which will have become rechargeable hybrids.

Land transport infrastructures first starts with high speed trains so as to avoid the use of cars for long distance journeys.

Cars remain the choice for short and middle distance travels outside of the urban area, but the low level of car equipment in dense urban zones gets alternate modes more attractive.

On the whole, this "non mimetic" scenario leads to a much reduced car stock compared to the "mimetic" scenario one and with fewer kilometres driven because of a lower average speed (major impact of infrastructure choices, of structural changes in the use of cars and of traffic restrictions in urban areas) and more of these kilometres relying on electricity.

The relative decrease in car traffic (as compared to the "mimetic" scenario) derives from three changes : a new space sharing of the urban area for people and their socio-economic activities which reduces the daily mobility requirements (km/capita/yr), an increase in soft modes and public transport use.

Mobility needs are reduced because the urban area is built and organized so as to minimize the distances between people and their daily activities, and not in order to increase the speed of travelling.

The increased use of soft modes is a direct and unavoidable consequence of a smaller car equipment and of the increased use of public transports.

The increased use of public transports coming from a more coherent infrastructure development is related to:

- on one side the journeys within the city, first the compulsory ones (home-work, home-school), eventually the secondary ones (shopping, social relations);
- on the other side all the private and professional long distance travels
- partly, the short and middle distance journeys from city to city.

Electricity becomes the main energy for rail and road (through hybrids) public transports. It is mostly produced with renewable energies (wind, solar and biomass according to the areas).

Only middle and long distance public road transports would maintain internal combustion engines, with second generation bio fuels progressively becoming the energy supply

Goods mobility

Road transport remains a main way for goods transportation. But it does not contribute anymore to the increase in speed of the goods flow and to the merchandizing area increase. High speed goods transportation infrastructures for long distances (over 500 km) are developed and well connected with the traditional road network. This will lead to:

- a move of part of the existing road traffic toward these infrastructures
- the setting up of production and logistic facilities on this high speed network.

In the industrialized countries, as the expressway networks are already set up and the localization of production and logistic capacities rather stable, only the first trend will be really significant.

In the developing countries where the main transport infrastructures have yet to be built, the second trend should be more significant.

Besides, the increase in the cost of speed being faster than the increase in the average value of the transported ton of product, it should logically induce some reorganization of the localization of the production chains: moving the production of high value products closer to the consumers areas, lengthening the transport distances for primary and secondary materials with a low value per ton and where travelling time has no significant economic impact.

These different movements entail:

- a decrease (as compared to the mimetic scenario) in the tons-kilometres share carried by traditional road transport, and concentration on short and middle distance travels which are suitable for hybrid engines.
- an increase in the share of slow modes (river and canal, sea, traditional railway)
- a significant share for high speed land rail transportation for goods.

5.2.3 INDUSTRIAL PRODUCTION

Over the long term, the value of goods per ton has increased faster than the cost of transport. Firms sought for cost reductions by increasing the concentration of these productions, thus leading to a growth in transportation distances and speeds. More recently the growth in transports was sustained by the “just in time” concept and the real time arbitration of available production capacities.

The “non mimetic” scenario assumes a de-concentrated and de-centralized paradigm, with two main ideas, here applied to the cement and steel sectors:

- offset cost benefit of large production centres by savings on the energy cost induced by resorting to local available energies (for instance, wind for electro-metallurgy or cement);
- offset cost benefit of large production centres by savings on transport with the decrease of distance travelled by high value products, even if it means increasing the distance travelled by lower value materials (inside Europe the global distance by one ton of large secondary materials at different levels of the production cycle remains relatively the same nowadays).

Steel

Today two main technologies are currently used: the primary conversion in blast oxygen furnaces of iron ore into cast iron, then into steel, and the electric arc furnace for scrap iron recycling.

The quest for scaling up savings first led to bigger and bigger iron ore conversion facilities. Scrap iron smelting was later developed in order to fulfil recycling needs and to supply the deficiency of primary conversion facilities (market size too small, investment barriers, etc…). When both technologies are present, they compete for the use of scrap iron, which also improves the blast furnace yield.

In the “non mimetic” scenario, moving the production of highly technological (and as such high value) steel products closer to the consumer areas is assumed to lead to the multiplication of small special steel production facilities, as the savings achieved on energy and transport costs counterbalance the lack of savings which came from the concentration of production. Regarding current technologies available, these facilities would make use of the electric arc furnace, but new primary conversion technologies, such as the direct reduction process-H2 based, for which scale-up savings would be much less important than for blast furnaces, could appear.

Cement

Cement is produced by mixing clinker and add on, their proportions vary according to the country and the quality required. Today clinker production is mostly done with the so-called “dry” process in facilities with capacities in the 0.5 to 2 Mt/yr range. The scaling up savings have systematically led until today toward increasing the size of the capacities.

In the “non mimetic” scenario this trend is reversed by counterbalancing the scaling up savings by two impulses: energy from renewables and from available local wastes is getting increasingly cheaper than fossil fuels and electricity from the network; there is a strong increase in the cost of road transport.

5.3 Quantification of the narrative assumptions

In order to translate these assumptions into new parameters for the model, we first had to identify the supporting variables inside the modelling platform, particularly in the POLES model, as it was in charge of the detailed picture of the technological evolutions. Table 15 shows the set of variables for which ENERDATA has quantified their evolution. This quantification was done not in absolute terms but as a deviation from the mimetic scenario results. It represents the “normative” vision of the narrative projections which have been explained above.

Dwellings	Surface per person Installed photovoltaic power Share of very low energy buildings in the stock
People mobility	Household equipment Passenger-kilometres by plane Passenger-kilometres by rail Passenger-kilometres by road common transportation Passenger-kilometres by private car
Goods mobility	Tons- kilometres by road Tons kilometres by rail

Materials demand	Cement content of buildings Steel content of buildings Steel content of cars Steel content in transport infrastructures Cement content of transport infrastructures

Table 15 : Supporting variables for non mimetic variations

Then, to represent the different possible paths as defined above, regions were classified, taking into account the climate of each area – temperature, sunshine, wind – as well as biomass availability and whether there was any sea front. Considering these features, different types of areas and of urban planning (3 for industrialised countries, 4 for developing countries) were defined and assigned to the different regions in POLES. Compounding assumptions for each urban planning scheme made it then possible to work out average dwelling space per capita and also the energy parameters.

5.4 Policies and Measures

5.4.1 POLICIES AND MEASURES

The changes in the non mimetic scenario story above cannot be deemed as spontaneous evolutions of the economic system induced by an increasing carbon value. Indeed, some of them could happen, especially in developing countries, outside the framework of GHG emission reduction targets. But most of these changes will only fully occur as the consequence of well designed policies and measures, implemented early enough to achieve a significant change before 2050. Among the policies and measures, some can be pointed out:

- **A change in the technology trend** through an ambitious research program, innovation incentives, and incentives to disseminate these innovations in the economic system. Our scenario assumes that such policies are in place for the photovoltaic, new car engines and also to facilitate the necessary reorganization of the industrial logistics.
- **A framework for a new organization of the electric network** in order to induce the development of a decentralized network in dispersed housing areas and to maximize the use of renewable sources in densely populated areas. This may need deep institutional changes in the electricity sector, or significant modifications of price signals sent to the electricity producers in free markets.
- **A constraint set on the transportation infrastructures,** including some constraints or some important changes in road infrastructures, so as to decrease the average speed and induce modal transfers. It will be coupled with a massive development of common transport infrastructures both in dense and dispersed living areas, as well as between cities.
- **A vigorous planning for the development and the renewal of cities,** such as to promote retrofitting existing buildings and the dissemination of positive energy buildings in the dispersed housing areas within a few decades. It will also aim at applying a sustainable development policy to the rapidly growing cities in the developing and emerging countries.

These policies are underlying our non mimetic quantitative forecasts, but taking into account their costs remains a problem. The learning process for these new technologies is not well known, the cost of a significant scheme of residential renovation is unknown and the infrastructure costs are only succinctly taken into account in the IMACLIM model.

5.4.2 CARBON VALUE TRAJECTORY

Because of the changes made in the non mimetic scenario compared to the previous stabilization scenario, it was necessary to compute again the carbon value trajectory in order to achieve the same emissions between 2010 and 2050. By trial and error we found that the necessary carbon value could be 12 % lower all over the period than in the mimetic scenario and would reach 320 € /tCO_2 in 2050 instead of 370 €/t$C0_2$.

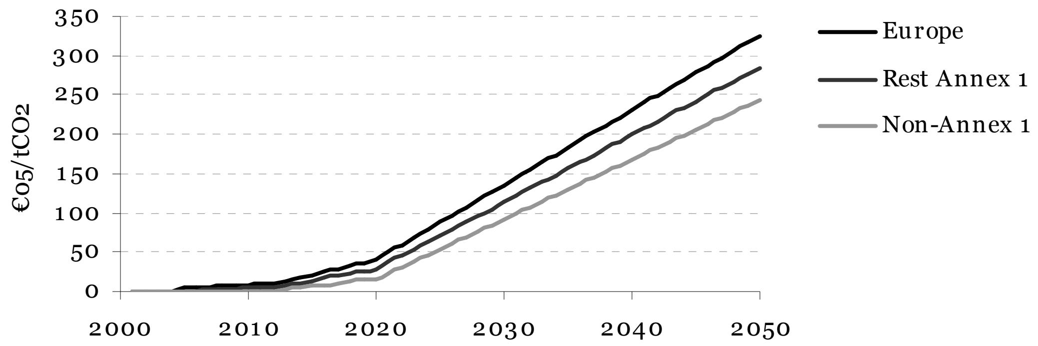

Figure 51: Carbon value path per group of regions

5.5 Energy system evolution

5.5.1 ENERGY FINAL DEMAND

The assumptions of the "non mimetic" scenario lead to a stabilized final energy demand between 2030 and 2050 around 9700 Mtoe :

Contrary to most of the published scenarios, the share of transports in the total demand decreases throughout the whole period, from 25 % in 2010 to 15 % in 2050, decreasing from 2030 in absolute terms of -1.5 % per year. This decrease comes not only from a transfer towards common transports in many countries, but also from a decreasing people's general mobility, as it has been assumed concerning land and urban planning. In China, for instance, the growth in mobility per inhabitant is 4 % per year between 2020 and 2030, then 3 % until 2040, and 1 % until 2050 when it reaches 6800 km per year. It remains quite lower than the average 10600 km per year being currently travelled by a European citizen.

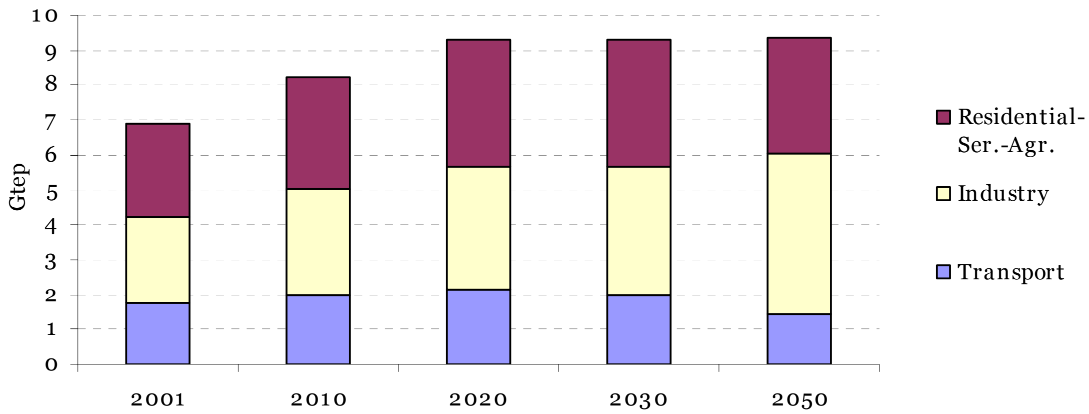

Figure 52: Energy final demand per sector

The industrial energy demand grows steadily by 1 % throughout the whole period and finally reaches close to 50 % of the total demand. The remaining part, that is residential, services and agriculture, slightly decreases from 2020 onward from 39.2 % to 35.8 %. The decrease of the demand amounts to 275 Mtoe between 2020 and 2050.

At the regional level, these trends follow local economic dynamics. For industrialized countries, the decrease in the transport demand starts in 2010 by -1.5 % per year, then accelerates after 2030 to an average of -2.5 % per year. In emerging economies, mobility first increases vigorously as the final energy demand for transports until 2030 because of the economic catch up, before levelling up and then slowly decreasing at the end of the period.

It is the same overall trend for the energy demand from services, agriculture and residential. The strong growth of emerging and developing countries gives large access to modern residential energy services and to a significant increase in services. The energy demand from this sector does not decrease throughout this period, it only slows down around 2050. On the contrary, in industrialized countries, the final demand decreases as soon as 2010 because efficiency gains are larger than the weak growth in final services needs.

Sharing out final energy demand by energy vector shows a large electrification of final uses: the share of electricity grows from 15 % in 2001 to 35 % in 2050. Simultaneously coal slightly decreases from 11 % to 8 %, refined oil from 42 % to 27 % and gas remains stable around 15 %, the rest comes from biomass and wastes (from 14 to 12 %), heat from cogeneration (3 to 2 %) and a small penetration of hydrogen (2 % at the end of the period).

5.5.2 PRIMARY ENERGY

The supply of this final energy requires a vigorous growth of primary energy production in the world from 10130 Mtoe in 2010 to 14140 in 2030, then much more slowly to 15440 Mtoe in 2050. The global yield of the world energy (ratio of final energy over primary energy) slowly degrades from 0.70 to 0.65, because of both the electrification of the energy system and the increasing use of the carbon capture and storage after 2030.

The share of fossil energies in the total primary energy production decreases from 81 % in 2010 to 61 % in 2050. Shares of coal and oil are decreasing, although the display of carbon capture and storage keeps the coal share at 18 % (about 2600 Mtoe) after 2030. Oil world production first increases until 2020 reaching 4370 Mtoe (about 90 Mbl/day), then steadfastly decreases to a level of 20 % , less than the 2000 level. World gas production strongly increases until 2030, from 2100 Mtoe to 3800 Mtoe in 2030, then remains stable through the next two decades. This two-steps dynamism comes first from a move toward gas for electricity production, then from a progressive use of carbon capture and storage for gas power plants (8.4 % would be fitted in 2050).

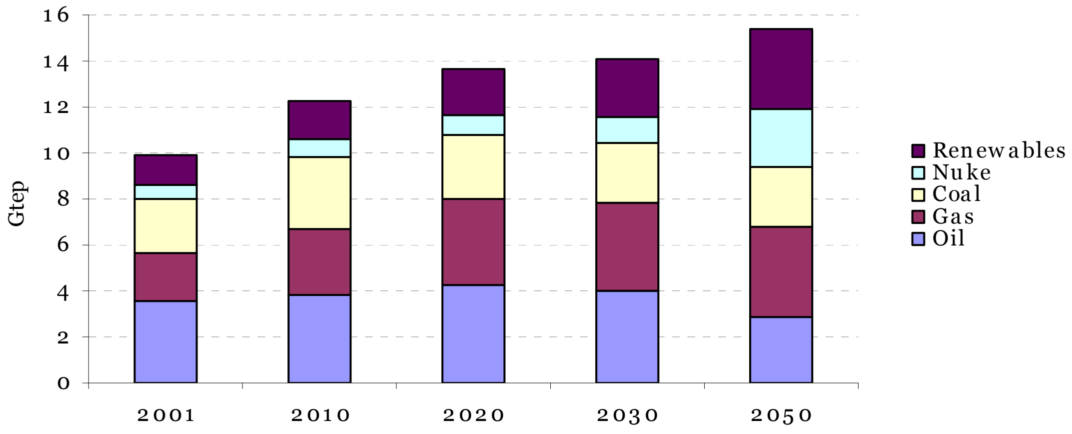

Figure 53: Primary energy consumption (World, non mimetic scenario)

The figure above clearly shows the decline of fossil energies within the world primary energy mix from 2020. To supply the final energy demand nuclear and renewable energies must grow very strongly. In 2050 nuclear supplies 16 % of the world primary energy (2550 Mtoe) about four times the current level. This growth, which takes place mostly after 2030, requires to set up each year between 2030 and 2050 an additional 56 GW, not taking into account the replacement of power plants at the end of their lives.

The vigorous development of renewable energies is also required, so as to supply nearly 3000 Mtoe of primary energy in 2050 (1000 in 2000). Solar and wind energies are strongly developed in order to produce 160 Mtoe in 2020, then 860 Mtoe in 2050, while biomass and wastes energies double between 2000 and 2050 in order to reach 2120 Mtoe at the end of the period.

5.5.3 ELECTRICITY PRODUCTION

Because of the growing supply by electricity of the final energy services, the world electricity production enjoys a very dynamic growth: it is multiplied by 3.2 as it climbs from 15460 TWh (1330 Mtoe) to 51340 TWh (4415 Mtoe). This growth is partly based on gas, which increases from 2933 TWh (252 Mtoe) to 11830 TWh (1017 Mtoe) with a share in the total production increasing from 19 % to 23 %. In 2050 all gas fired power plants are of the combined cycle type (85 %) or operated in the cogeneration mode (15 %). Oil fired power plants have practically disappeared after 2030. Coal share decreases but remains significant with 16 % of the total production in 2050 (38 % at the start of the period). After 2030, there are only supercritical production units with the carbon capture and storage add-on which will be in place in 10 % of the production units in 2050.

The remaining of the production relies on nuclear and renewables. 70 % of new nuclear power plants being built between 2030 and 2050 will be located in Asia (+270 GW in China, +160 GW in India, + 340 GW in the rest of Asia) and 12 % in Europe (+135 GW).

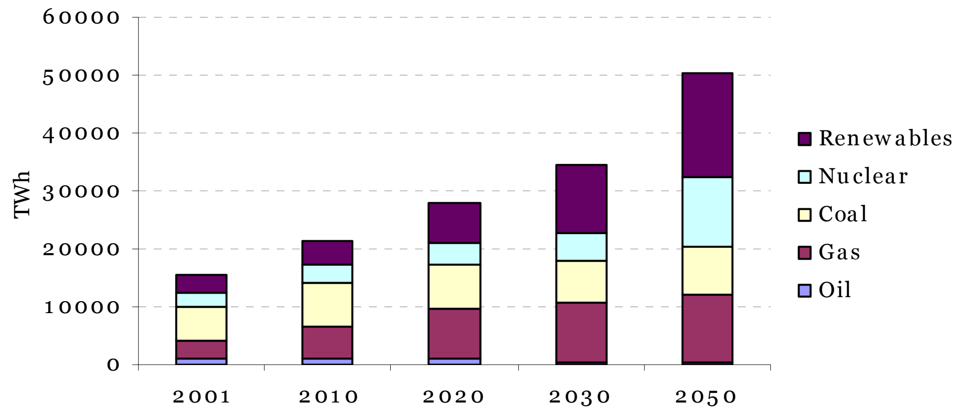

Figure 54: Electricity world production per energy source

Through the development of all renewable energy resources, these account for a growing share of the production. Hydroelectricity capacity is multiplied by 2 between 2000 and 2050 with 740 GW added: 295 GW in China, 117 GW in India and 90 GW In Brazil.[12] In 2050, hydroelectricity accounts for 12 % of the production. Wind energy increase is really spectacular, moving from 24 GW in 2001 to 2522 GW in 2050,[13] with an evenly distributed development all over the world. In 2050 it accounts for 19 % of world capacities, and 10 % of the production, nearly as much as hydroelectricity. Solar energy development is as vigorous, growing from 1 GW in 2001 to 1585 GW in 2050, that is 12 % of the whole installed capacity in 2050. However, the production of all this solar invested capacity is only 2290 TWh (197 Mtoe), that is 4 % of the total production. Biomass supplies 5 % of the total production in 2050, with also a very dynamic increase in capacities, from 26 GW in 2001 to 447 GW in 2050.

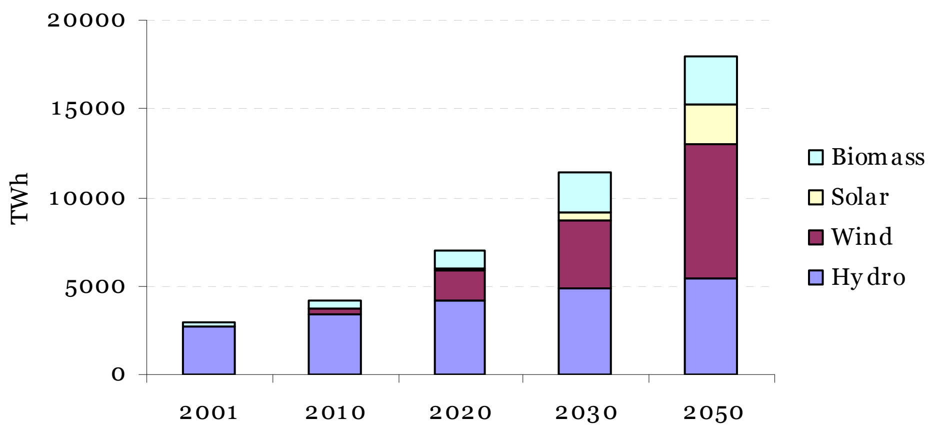

Figure 55: World Electricity production from renewables

[12] For comparison stake, the Three Gorges Dam on the Yangtze river in China is built to produce 18.2 GW
[13] In 2007 the world installed capacity has reached 94 GW (source: GWEC)

5.5.4 IMPACT ON FOSSIL FUEL MARKET

Decarbonising the energy system entails a ceiling of oil production around 2020, then a slow decrease (1.3 % per year) so that, in 2040 the world production is lower than in 2000 (75 Mbl/day).

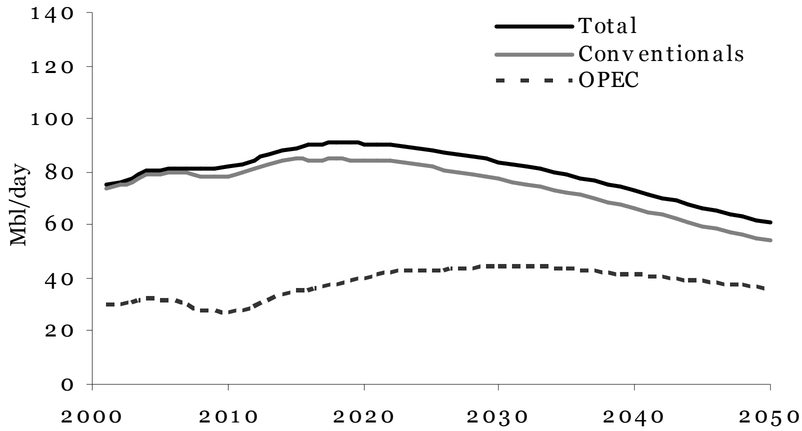

Figure 56: World oil production

Together with this decrease of the world production, OPEP's market share increases from 40 % to 60 %. This increase in the market power is linked with an oil price levelling at 50 dollars per barrel. Regarding this price the production cost discrepancy of the OPEP reserves is a significant drawback for its competitors. There is no incentive to set more costly resources in production, particularly the non conventional resources which remain quite small in 2050 (10 Millions of barrels per day coming from Canada and Venezuela).

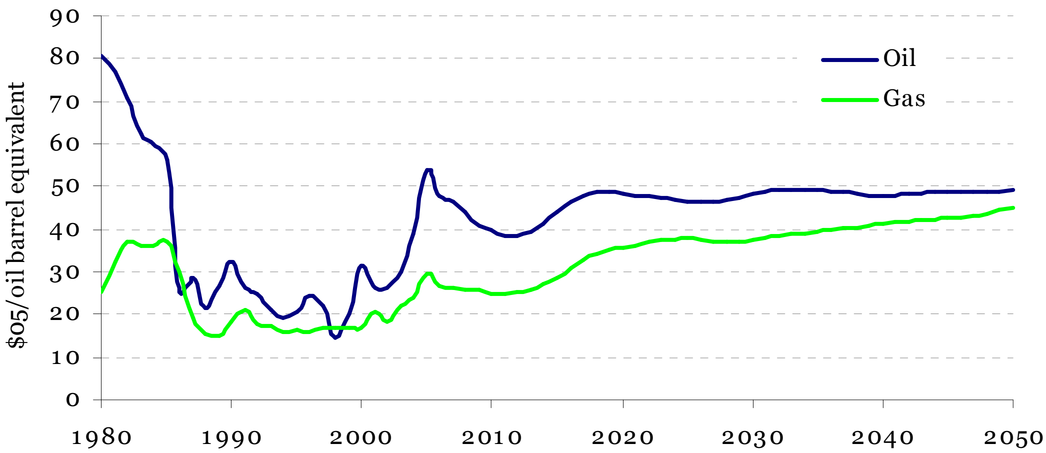

Figure 57: World prices of crude oil and natural gas

The gas price comes progressively closer to the oil price, when using a common energy unit of measure, because of the rise in the world demand for gas.

5.5.5 CARBON CAPTURE AND STORAGE

The carbon capture and storage devices start spreading in 2020, they are put in 9 % of coal power plants and in 4 % of gas power plants, reaching a total of 233GW (3.5 % of the capacity of all electricity power plants). This CCS spread makes it possible for coal and gas to remain suitable investment opportunities in the production mix. As a consequence, in 2050 there are still 15 % of coal power plants and 20 % of gas power plants in the world. 70 % of the coal power plants and 43 % of the gas fired plants have a CCS unit. Although incomplete, this spread of CCS gives the possibility to capture 20 $GtCO_2$ in 2050 that is 80 % of gross emissions of the electricity sector[14] and almost 40 % of total emissions.

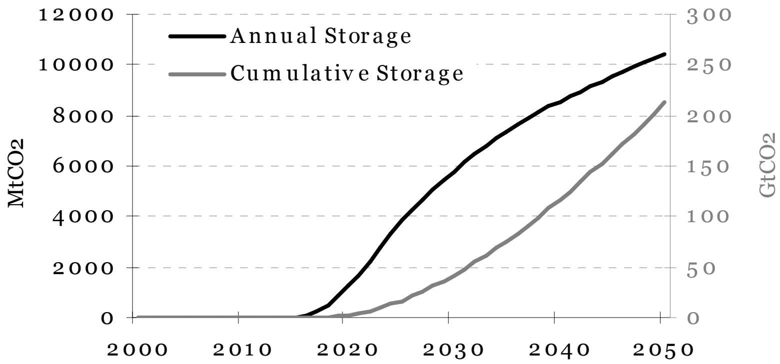

Figure 58: Carbon storage evolution

5.6 Industrial sectors development

5.6.1 STEEL

Steel demand grows steadfastly at a rate of 1.8 % per year within 2050. This grows is mostly significant in Asia: China accounts for 30 % of the supplementary demand, India for 24 % and the rest of Asia 15 %. In 2050 North America, Europe, Japan and Oceania only account for 29 % of the demand versus 54 % in 2001. Transport infrastructure represents the most dynamic demand with an average growth of the demand of 2.2 % per year, while the demand for the building sector grows at an average rate of 1.2 % per year.

The steel sector undertakes a continuous technological change in order to divide by three the specific CO_2 emissions per ton of steel produced, reaching 600 kg of CO_2 per ton of steel in 2050. Steel production by electric arc furnace is assumed to account for 50 % of production versus 37 % in 2001. The new processes (smelting reduction and direct reduction) are being developed and account for one third of the production in 2050. World CO_2 emissions from this sector in 2050 are back at their 2000 level of 1.3 $GtCO_2$.

[14]Thermal power plants without CCS are in a very bad position in the « merit order » and, consequently less put in operation than the ones with CCS.

5.6.2 ALUMINIUM PRODUCTION

World demand for aluminium is rapidly increasing with an average rate of 2.3 % per year, here again largely sustained by Asia needs which account for 62 % of the increase in the demand between 2010 and 2050. Demand growth inside OECD remains strong with an average rate of 1.4 % per year.

On the supply side, there is no significant breakthrough in the mix of currently available technologies which keep their shares of the world production. The only significant change is the progress in recycling, which accounts for 40 % of the total output, against 26 % in 2001. The direct carbon intensity of the production remains the same at 160 kilograms of CO_2 per ton of Aluminium.

5.6.3 CEMENT PRODUCTION

World cement demand grows with an average rate of 2.5 %/yr. For infrastructures the demand grows at a faster rate (3.3 %/yr) than the demand for buildings (2 %/yr). Between 2010 and 2050 the demand growth comes from Asia for 73 % (China 43 %; India 20 %). In 2050 68 % of the production is located in Asia, versus 50 % in 2010. Europe only represents 5 % of the production in 2050, against 15 % in 2001. This change is similar to what we pointed out in the reference scenario. It is better explained by the demand locating than of the climate policy.

On the offer side, carbon intensity of the cement sector decreases by 15 % between 2010 and 2050, wet and semi-wet processes disappearing progressively while pre-heaters (80%) and pre-burners (63 %) are spreading.

5.6.4 FLOAT GLASS PRODUCTION

World demand for glass panes grows at an average rate of 2.1 %/yr between 2020 and 2050. The building sector needs 40 % more glass than in the reference scenario because of the significant development of decentralized photovoltaic equipment in this scenario.

5.7 CO_2 Emissions

In this scenario the emission path is defined so as to achieve the stabilization of CO_2 at 450 ppm in 2100. Carbon capture and storage for thermal coal and gas power plants allows for 60 % more CO_2 gross emissions (10 $GtCO_2$) than the maximum authorized by the emission path (18 $GtCO_2$).

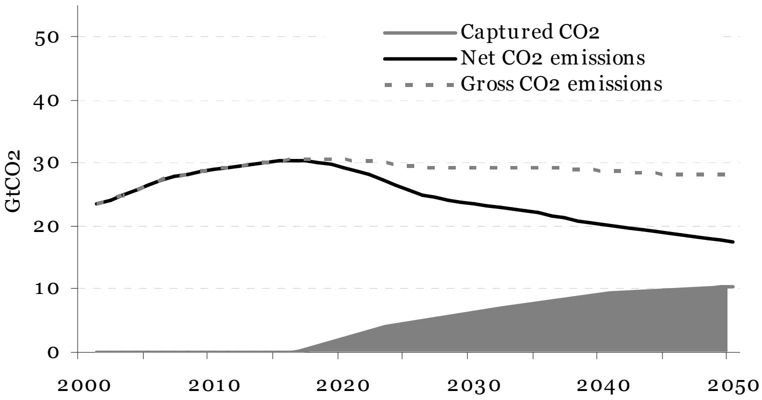

Figure 59: World CO2 emissions – Non mimetic scenario

In 2050 the electricity production accounts for 46 % of gross emissions, but for only 14 % of net emissions thanks to carbon capture and storage. Transports emit only 2.3 $GtCO_2$ versus 5.3 GtCO2 in 2001. Industrial emissions only grow by 10 % between 2001 and 2050.

The regional sharing out of emissions shows the significant reduction of the industrialized countries (CIS included) as soon as 2010, from 15 $GtCO_2$ in 2001 to 5.5 $GtCO_2$ in 2050. Emissions from emerging and developing countries grow until 2020 (16 $GtCO_2$) before declining by 20 % in 30 years in spite of a vigorous economic development.

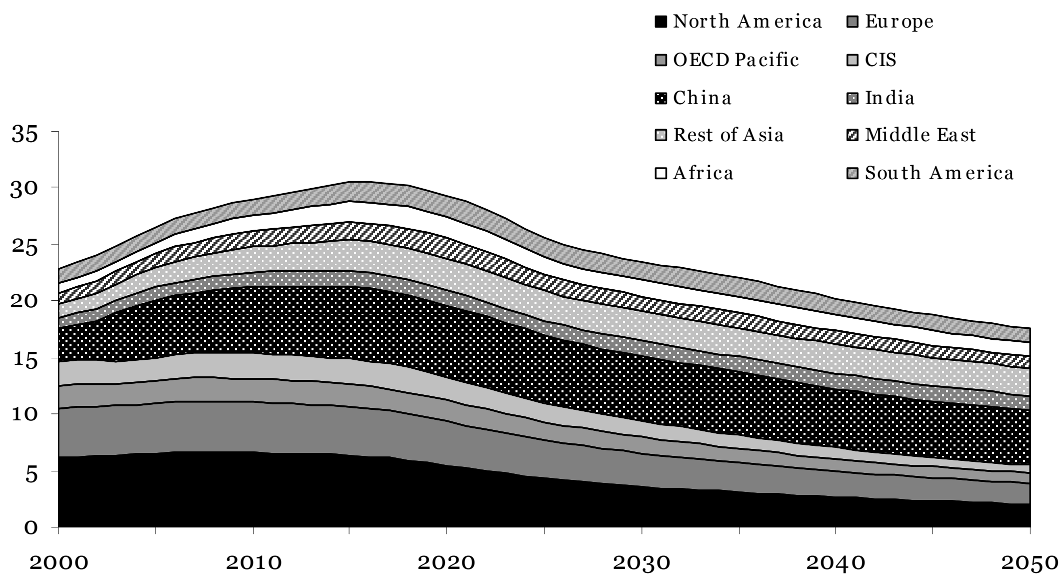

Figure 60: CO_2 emissions by region (GtCO2)

Concerning per capita emissions in the developing countries, they also reach a maximum as soon as 2020 although they are still at a very low level compared to the current levels in OECD. Per capita emissions of American people are divided by 4, of European people by 2.4, of Russian people by 2.5. Should the future international coordination system be based on a "reduction and convergence" allowance scheme, then the difference between real emissions and allowances would lead to very large capital transfers. Using a first order computation, not taking into account the macroeconomic effects of these transfers, they would be equivalent to an inflow of capital representing 17 % of GDP in India and 19 % of GDP in Africa. China would buy allowances for an amount equal to 9 % of its nominal GDP.[15] OECD countries should spend 1 % or 2 % of their GDP in order to acquire allowances.

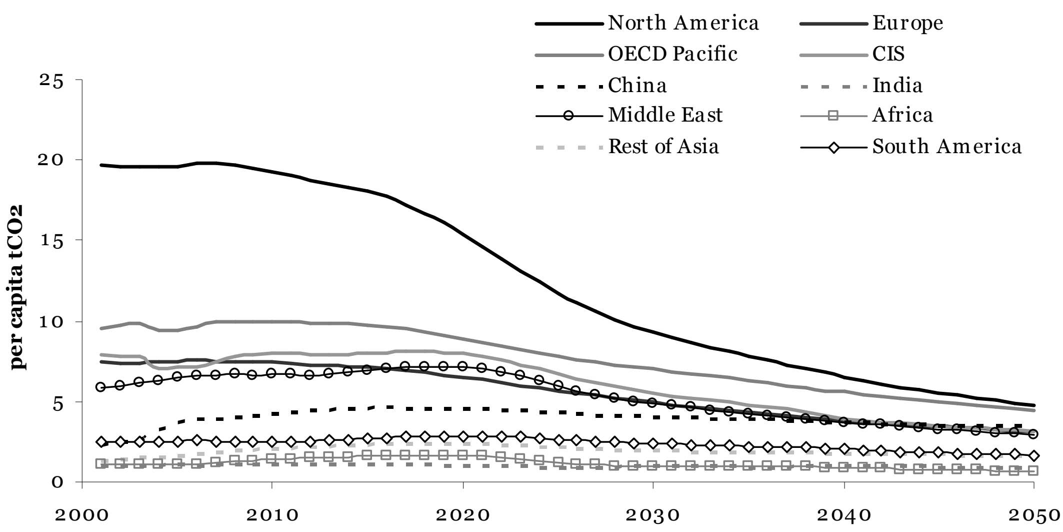

Figure 61: Per capita emissions

5.8 Macroeconomic assessment

5.8.1 HOUSEHOLD ENERGY BILL

In all regions household budgets are submitted to (i) the growing tax on CO_2 emissions, (ii) equipment dynamism and increasing energy needs caused by the economic development, (iii) progressive decarbonisation of the energy system, (iv) additional efficiency improvements induced by the carbon tax. In most regions, the net result of these simultaneous mechanisms on household's energy burden will entail a "hump" profile : in the first period the effect of the tax is predominant, reinforced by the swift growth of personal energy needs in emerging countries, and this induces an eviction effect on the rest of the household budget. This impact can be quite significant, such as in India, where the energy burden explodes and reaches 25 % of the household budget after 2030. Indeed this is only possible if energy needs have priority over other consumers' goods and services[16]. In the industrialized countries this transition burden seems much more bearable because (i) average income is much higher; (ii) taxes on energy are already in place.

The transition period covers two or three decades before the decarbonisation of the system overtakes the effect of the rising cost of carbon. This is indeed a fundamental feature of the

[15] 1.4 billion people each emitting 1.5 ton of CO_2 too much, with a world price of CO_2 at 320 $/t$CO_2$

[16] In our models, we assume this to be the case, by linking the energy services demand to the acquired equipments and to the per capita income, whatever be the cost of energy.

impact of our simulation of the climate policy: it is not in the long term, when the carbon value will be very high, that the economy will suffer under an excessive burden, but during the transition period when the carbon price stands between 50 and 150 $/tCO_2$.

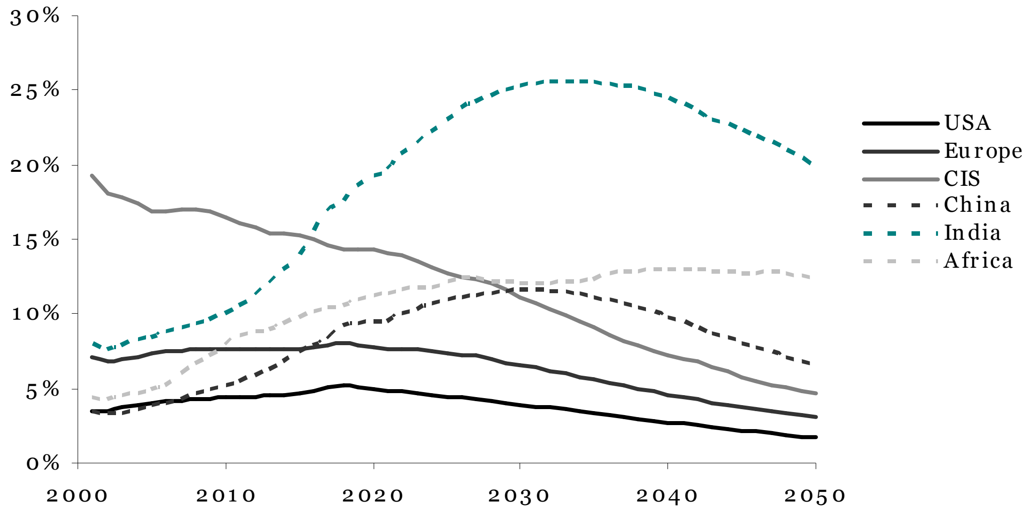

Figure 62: Energy share in household budgets

CIS has currently a particularly high household energy burden. Regarding the very large potential efficiency improvements and a less vigorous equipment dynamic than in the emerging countries, the net effect comes out as a progressive decrease of the energy burden, until it reaches the developed countries level at the end of the period.

5.8.1 Transition macroeconomic costs

GDP evolutions as compared to the reference scenario lead us to four conclusions:

- fossil resources exporting countries suffer regular losses which slacken their growth throughout the whole period ; it is especially the case for the Middle East and for CIS confronting a cumulative slow down reaching 20 % of the reference GDP in 2050 ; it is also the case for Canada, Africa and the rest of Latin America[17].
- Industrialized countries (except Canada) undergo a weak slow down, less than 3 % of the reference GDP between 2010 and 2030, while at the end of the period their GDP is higher by a few per cent than in the reference scenario GDP (up to 3.5 % for the USA, which is penalized by its low efficiency as compared to other OECD countries in the reference scenario).
- Emerging countries like China and India experience a strong slow down between 2015 and 2030, before catching up, then largely overshooting the reference scenario, as soon as 2024 in China and 2032 in India. Brazil and the rest of Asia face the same trend.

[17] In Africa the decrease of the world consumption of gas and coal can entail a revenue loss of 8 % of the reference GDP in 2050 ; For the Rest of Latin America this revenue loss reaches 3.5 % of the reference GDP in 2050.

- Some of the developing countries like Africa and Latin America except Brazil suffer more by the climate policy and do not enjoy any catch up phase after 2020.

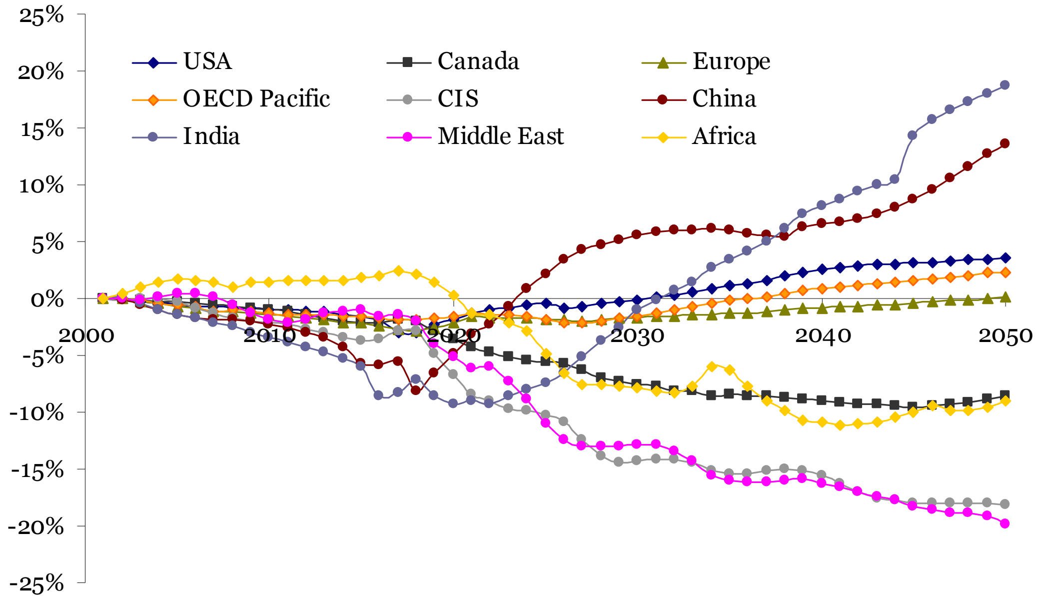

Figure 63: Real GDP changes from the reference scenario

Other modelling experiments have showed that the significance of transition costs largely depends on the methods used for implementing internal policies and measures for each country and each region, for instance concerning the different possibilities for the recycling of the revenues coming from the carbon tax. Besides, in the present state of knowledge and regarding the available models, quantifying the cost of the policies that will be necessary to enable the change toward non mimetic development styles and organisation schemes is really limited, especially concerning the costs of buildings renovation and of infrastructures.

Taking these two remarks into account, the results presented above must be interpreted with caution. Some main features are robust to the simulation variations and can be retained:

- transition costs could be high if climate policies do not include necessary compensation measures for the most sensitive sectors or household types ;
- as a consequence of the significant decoupling between economic growth and fossil resources, a significant potential profit can be obtained after a few decades for all the countries dependant on fossil energies ;
- all fossil resources exporting countries suffer a permanent revenue loss.

Finally, comparing with the intermediary mimetic scenario shows that a correctly anticipated change towards more sustainable development styles could reduce transition costs, bringing forward the period when climate policies induce an improvement as compared to the reference scenario, and increase this improvement for the next decades.

6 Two critical sensitivity tests

We made a technological variation scenario without CCS but with the same hypotheses as described above and with the same carbon tax. The only difference lies in the assumption concerning the availability of the carbon capture and storage system. Hereunder we assume that the cost for the use of this technology remains prohibitive and that no power plant (except pilot plant) is equipped before 2050.

6.1 Technological variation without CCS

6.1.1 CO_2 EMISSIONS

Because of the lack of CCS, electricity producers try to avoid as much as possible using fossil fuels power plants. Considering these conditions and in order to keep CO_2 at the same level as before, it would be necessary to increase the level of taxation, so as to mobilize new reduction potentials, not yet used because of their higher cost. As we kept the tax path as it was in the previous scenario, these potential reductions cannot be mobilized and, consequently, the level of emissions is higher than in the previous scenario.

Over the whole period, emerging and developing countries emit 10 additional Gt of CO_2 and the OECD countries 13 Gt. However after 2040 the emission path gets back to the non mimetic scenario one. This emission surplus is toned down by additional investments in nuclear energy.

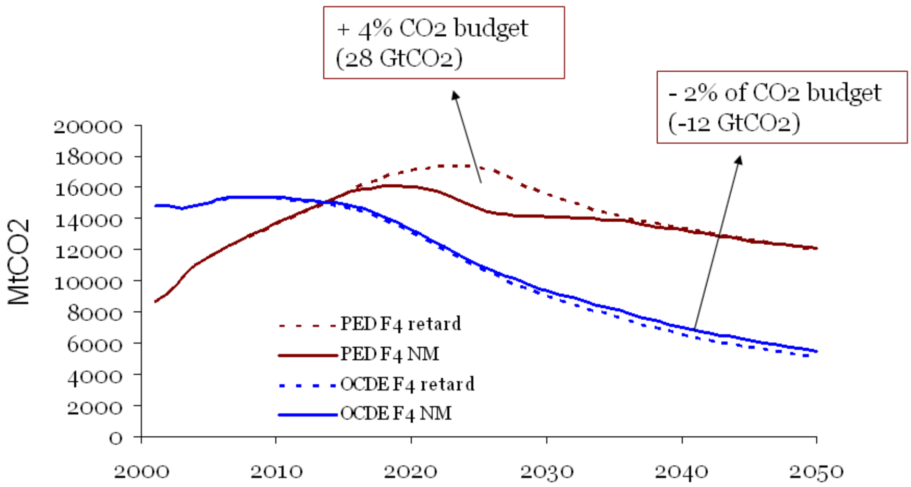

Figure 64: CO_2 emission surplus because of lack of CCS

6.1.2 ENERGY SYSTEM DEVELOPMENT

The energy system development path is only modified after 2040, because CCS systems came into use after that date. From 2020 to 2050 the world final energy demand is slightly changed: the demand is 3 % less in 2030 than in the non mimetic scenario and 2 % less in 2050. This difference is precisely similar to the economic slow down, entailed by the necessary over-investment in non fossil energies that cannot be equipped with CCS (see macroeconomic assessment below). The primary energy demand shows a similar decrease, but its content is quite changed. Instead of remaining an important electricity production supplier, coal decreases significantly: the world energy mix in 2050 includes 1150 less Mtoe of coal (- 45 %) than in the non mimetic scenario (2610 Mtoe). In the same way gas, although in great use, is also restrained because of the lack of CCS : There is a 550 Mtoe decrease in gas production with 3350 Mtoe in 2050 instead of 3900 Mtoe in the non mimetic scenario. The missing primary energy is provided by nuclear for 78 %, biomass and wastes combustion for 19 %, and solar for 3 %, which, indeed, needs 20 % (320 GW) more installed solar capacity. The world nuclear capacity reaches 2530 GW in 2050, which is 54 % more than in the non mimetic scenario. This means a very ambitious construction development between 2020 and 2050 with an average construction of 65 GW /year of new nuclear power plants.

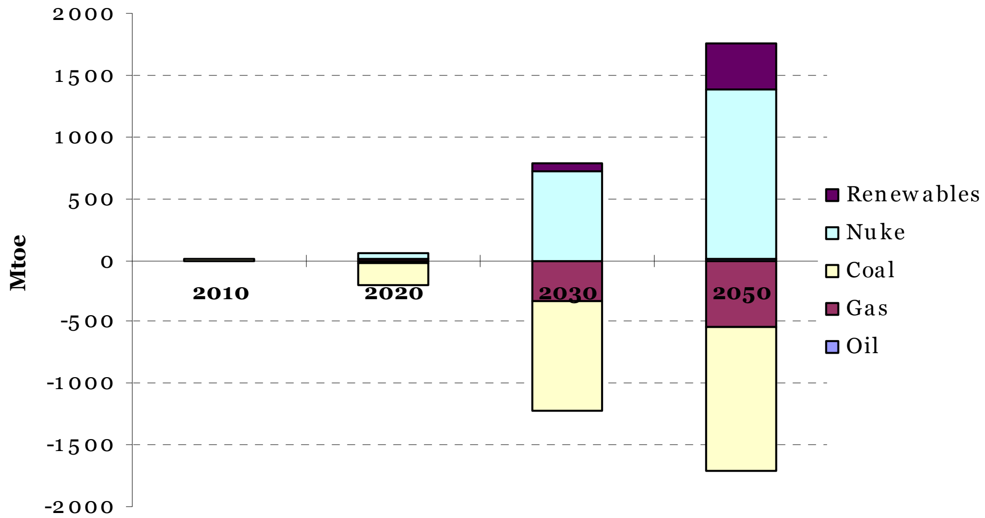

Figure 65: World primary energy mix;
Variation without CCS compared with the non mimetic scenario.

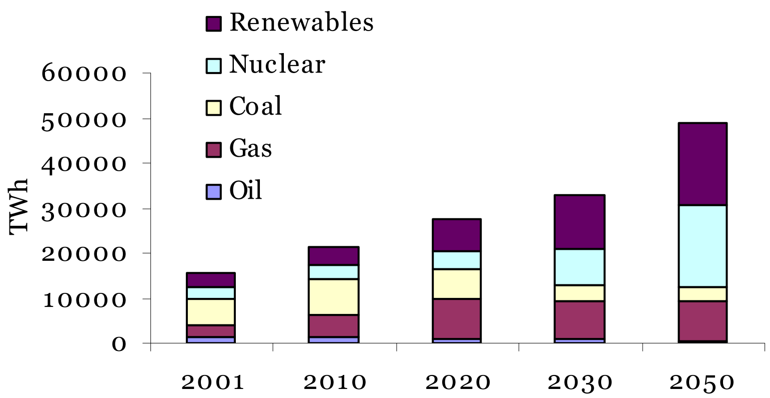

Figure 66: World electricity production, energy sources

Regarding the production of electricity, nuclear becomes the first source of energy with 18200 TWh in the world (35 % of the production), the rest of thermal power plants coming second with 15025 TWh (30 % of production).

Such a development of civilian nuclear energy raises the questions of proliferation and of security, which already appeared in the previous scenarios as this development takes place in all the world regions. For the economy, there is some change in the investment volumes coming from this power plant spreading out. Between 2020 and 2035 the investment volume is lower, because, during the transition period, the electricity demand is lower (-5 % in 2030), and also, because the CCS technology is more expansive as there has not been any learning process in the previous decade which could have brought the cost down. Later on, the investment required for the additional nuclear power plants is higher than for thermal power plants with a CCS equipment. Between 2020 and 2050 cumulative investment in the world electricity sector in the scenario without CCS is 30 % higher than in the non mimetic scenario.

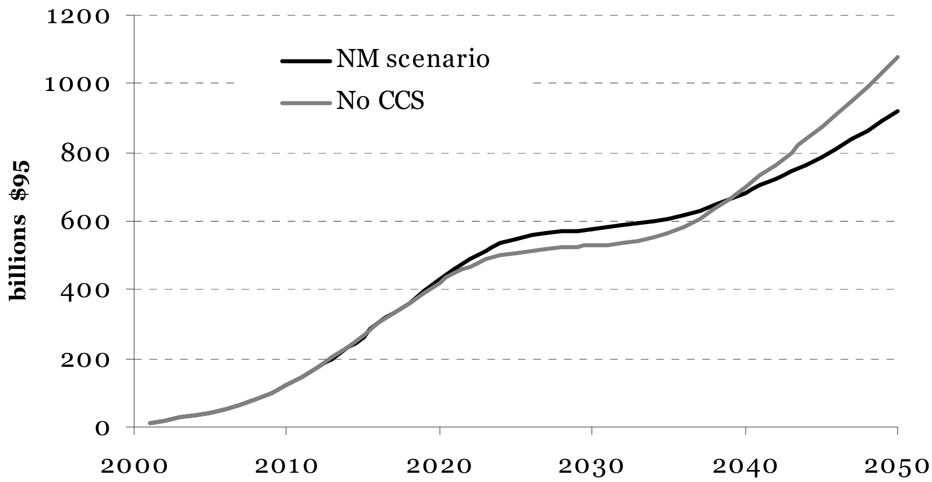

Figure 67: Cumulative world investment in the electricity sector

6.1.3 MACROECONOMIC ASSESSMENT

Without CCS, the carbon increasing value entails an additional slowing down of the growth as it becomes more difficult to decarbonise the system. In China and India, where coal is the primary energy source for electricity production, this additional cost reaches respectively 6 % and 9 % of the GDP. This additional burden is linked with the increase of the electricity cost, and increases the energy cost for households and industries between 2020 and 2030 (see figure 64). For the fossil resources exporting countries, there benefit from additional oil and gas exports as these are more interesting fuels than the coal without CCS. Thus they gain between 1 % and 3 % of GDP, while other industrialised countries slow down by 1 % to 3 %.

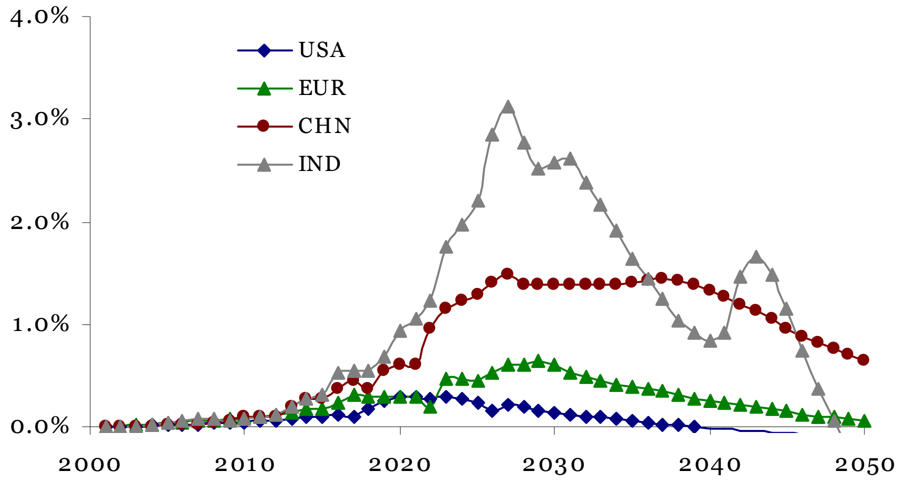

Figure 68: Rise in the energy burden as compared with the non mimetic scenario

6.2 Variation with delaying the implementation of a carbon constraint in developing countries by 5 years.

This scenario was elaborated with the same assumptions as in the non mimetic scenario, but with delaying by 5 years the carbon value trajectory for the emerging and developing countries. For these regions the carbon value reaches 222 €/tCO2 in 2050 instead of 264 €/tCO2.

6.2.1 Macroeconomic assessment: the world slows down

A delay in applying the reduction policies in the emerging and developing countries is not beneficial for growth. These five years delay is, in fact, the period for a large development in the equipments and in the construction of buildings and infrastructures. Without climate policies, this growth will rely on the large use of fossil resources, thus increasing the energy dependency of developing countries and making their economies more sensitive to the carbon price, when it is finally enforced five years later. For instance, Figure 65 shows that the burden of the oil trade balance for China is worsened by the delay in the climate policy: in 2020 it goes over 9 %, instead of 7 %, an additional burden which will remain at least until 2050.

The negative impact entailed by the delay in reduction policies in the developing and emerging countries is of the same order of magnitude as the gain we have seen in the non mimetic scenario over the reference scenario. In 2050 the GDP of China and India remains lower than in the reference scenario. This means that there is a particular «window of opportunity» in the developing countries, before settling in a system mainly based on fossil resources needed by these countries for the large infrastructures build up, for the buildings and for the catch up in the equipment level.

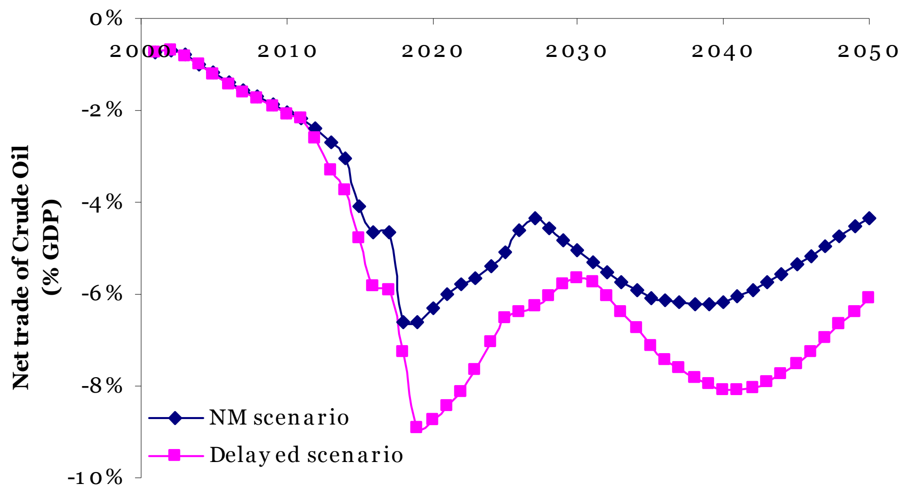

Figure 69: Weight of the external debt for oil – China

Through the rebound effect, the delay of climate policies in the developing countries affects the growth of all the countries in the word. The US and Europe undergo a cumulative slow down of, respectively, 10 % and 6 % in 2050. This comes both from the loss of drive from the developing world, and from the greater spread in the carbon values. It is only the Middle East which profits from the delay in climate policy, but its economic growth remains much lower than in the reference scenario.

6.2.2 WORLD EMISSIONS

The energy demand from developing countries is changed by two factors: the economic slow down which reduces the final demand, and the 5 years delay on the path for the carbon value. Figure 66 illustrates clearly the case for China:

- In 2020 the delay for the carbon constraint induces an energy mix richer in coal, with less renewable, gas and nuclear energies.
- From 2030 on, the economic slow down, coming from the increasing value of carbon, induces a clear decrease of the final demand, and, consequently of the primary energy production. This decrease mainly concerns the nuclear (56 % of the decrease), but also coal (30 % of the decrease), gas and renewables. This effect keeps growing until 2050, where Chinese primary energy production is 13 % less than in the non mimetic scenario;

In India, almost all of the decrease in final energy demand, coming from the economic slow down, affects the nuclear development.

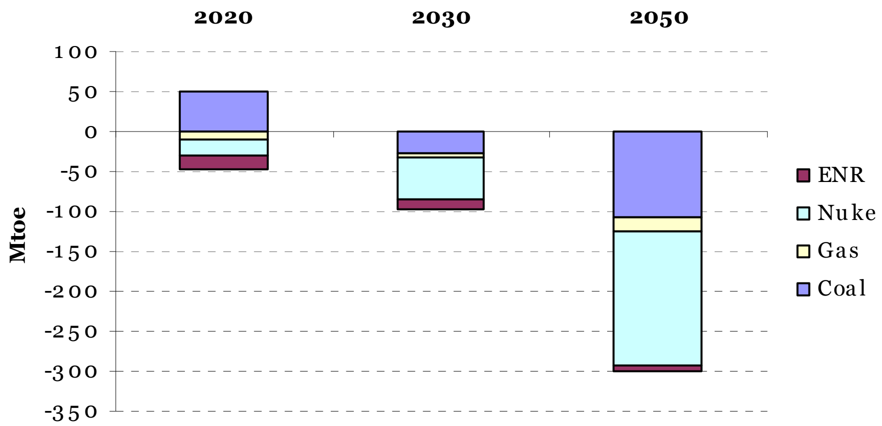

Figure 70: Volume change in the primary energy production : China Scenario with delay as compared to the non mimetic scenario

Globally the primary energy production is 1200 Mtoe (8 %) less in 2050 , which means a saving of 540 Mtoe of nuclear energy, of 240 Mtoe of gas, of 190 Mtoe of coal, of 80 Mtoe of renewable energy. As a consequence, world emissions in 2050 are 3 % less than in the non mimetic scenario.

However, during the transition period, world emissions have a higher growth because of the delay of climate policies in the developing countries. As illustrated in Figure 67, the emissions coming from these developing countries keep growing until 2025, before coming down, thus emitting globally 20 Gt more of CO_2 between 2020 and 2035. Further on, the economy growth decrease brings down the overall emission surplus of developing countries to 10 $GtCO_2$.

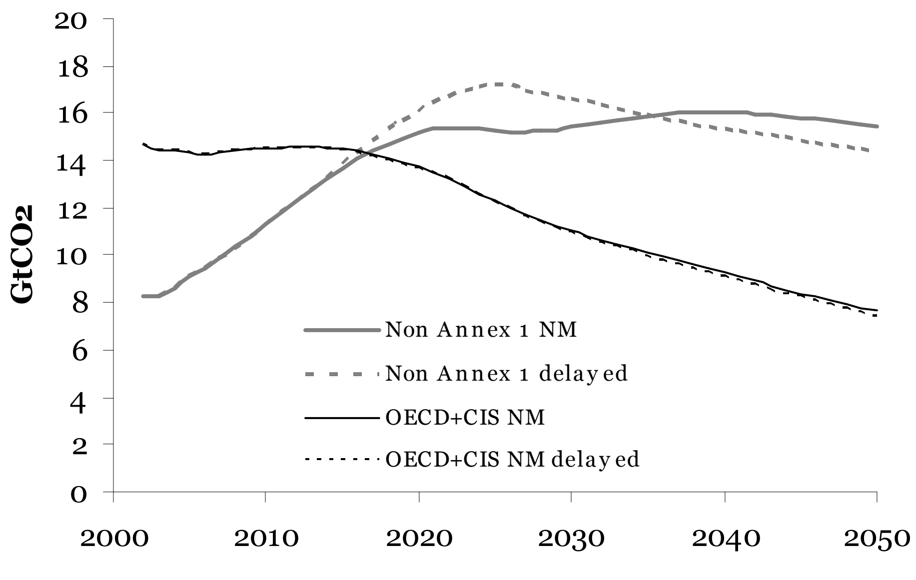

Figure 71: CO_2 Emissions, impact of the delay for climate policies in developing countries

7 Conclusion

The non mimetic scenario, which has been described above, features a new approach for modelling and evaluating climate policies, including potential changes in development styles and land planning. Usually modelling is limited to the setting of a growing carbon value and to the investigation of the technological changes induced by this carbon value, without studying how infrastructures, life styles or variations in land planning contribute to the development of greenhouse gases emissions. The establishment of this non mimetic scenario is founded on the acknowledgment of this hiatus and offers a first attempt to cope with it, through the inclusion in the workings of the POLES and IMACLIM-R models of fundamental changes for infrastructures, buildings, and life styles, which are specific to regional conditions.

In comparison with the previous scenario, the results obtained in this non mimetic scenario clearly show that integrated climate policies, including not only an increasing carbon price, but also coherent measures concerning buildings, the electricity production system and transport infrastructures, would make GHG emission reductions feasible, so as to achieve a 450 ppm CO_2 stabilisation, while at the same time making room for a supplementary growth as soon as 2020, through the induced anticipated decoupling from fossil resources.

The two variations shown in the second part of this report aim to clear up two special items, which characterise the climate policies examined in the previous scenarios :

- The variation without carbon capture and storage clearly shows that this technology, nuclear and renewable energies are all three fundamentally essential for any 450 ppm stabilisation scenario. Without CCS, and in order to achieve the emission reductions, an additional investment in nuclear power plants and renewable energies becomes necessary, and this is supplementary to the non mimetic scenario, which already contains very ambitious targets for these technologies. In countries where the energy system remains for a long time based on coal, additional cost, derived from the lack of CCS, are higher.

- The variation with the 5 year delay for the starting of climate policies in developing and emerging countries shows that there is a significant “window of opportunity” through which climate policies can also induce an economic growth opportunity, as long as the developing and emerging economies are not locked in carbon intensive organisation and infrastructure systems. This economic window of opportunity is in step with a limited opportunity window for the climate as the decrease of world emissions before 2030 is required in order to achieve a 450 ppm CO_2 stabilisation.