Transformation Patterns of the Worldwide Energy System – Scenarios for the Century with the POLES Model

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This paper presents a long-term assessment of the worldwide energy system in scenarios ranging from a baseline to a very low greenhouse gas stabilization, using the energy model POLES. Despite improved energy efficiency, the baseline scenario would lead to a doubling in energy consumption by 2050 increasing further thereafter. CO_2 emissions would continue rising, driven by the coal consumed in the power production which roughly follows the GDP growth; the scarcity of oil resources would trigger the development of alternative vehicles. Conversely, a 400 ppm CO_2 eq stabilization case would lead to drastic changes in supply (renewables - biomass), transformation (carbon capture and storage) and demand (low energy technologies). It transpires that the contribution to the reduction effort of low stabilization compared to a baseline scenario would be similar for final consumption (36% efficiency and 10% fuel mix) and for the power sector (25% renewables, 25% CCS, 4% nuclear). In addition this low emission scenario would alleviate the tensions on fossil energy markets.

1. INTRODUCTION

1.1 How Would the Continuation Of Current Energy Development Trends Affect the World?

The combination of the growth in world population up to the middle of this century and in Gross World Product before and beyond this horizon, will, in the absence of dedicated policies, lead to a steady growth in energy consumption. Even though energy use becomes increasingly efficient (approximately twofold by 2050), the primary energy consumption doubles by 2050, compared to 2000 levels, and keeps increasing (albeit at a slower pace) until the end of the century.

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Simultaneously, the World energy system will be increasingly electrified, as electricity consumption broadly follows the growth in Gross Domestic Product (GDP).

Carbon dioxide ($CO_{2)}$ emissions from the energy system double by 2050 and then continue to increase more moderately, with the power sector becoming the main emitting sector. In this type of scenario, the projected CO_2 emissions and concentration reach levels far above the recommendations of the Intergovernmental Panel on Climate Change (IPCC).

In terms of resources, oil and gas are depleted progressively, leading to strong tensions on international markets. In the second half of the century, the energy system is primarily based on coal, nuclear and renewable energies, while the intensified use of biomass for energy purposes raises issues of competition in land use.

1.2 What Should Be Done in the Energy System to Keep the Earth's Temperature Increase Below 2°C?

In order to minimize major uncertainties and discontinuities when addressing the climate change issue, a very low stabilization scenario (400 parts per million CO_2 equivalent concentration by 2100, referred to as "400ppm") will need to be adopted. This necessitates engaging in comprehensive and ambitious policies, encompassing radical technological innovations, and making changes to organizations and behaviors, on both the demand and supply sides.

The institutional and policy framework should thus be designed in order to spur such innovations as positive energy buildings, very low emission cars or new industrial processes and products. The scenario would lead to a significant release of the pressure on fossil resources over the long term, and most notably on the oil market. It would require massive parallel developments of radically new technologies, such as carbon capture and storage (CCS), and increase the recourse to alternative fuels such as energy biomass. This may however trigger a new variety of energy-related tensions or even conflicts, particularly in land use.

1.3 Use of the POLES Model

This study has been performed using the POLES World energy model, a recursive simulation model of the World energy system that includes full equilibrium of the energy markets. Integrating a very detailed regional, sectoral and technological specification, the POLES model allows detailed assessments of greenhouse gas (GHG) mitigation policies (see short descriptions in Appendix 1 and Appendix 2).

This model facilitates a simultaneous assessment of energy demand and supply options under various constraint conditions, most especially resource availability and GHG emission objectives. Explicit technological description is used for secondary fuels production (power and hydrogen), but also on the demand side for buildings and vehicles. In addition, econometric functions allow evolving consumption patterns, not connected to any particular technological option, to be taken into account. These functions include both behavioral changes (short term price effect) and investment decisions (long term price effect).

As a consequence, the POLES model reacts to any type of constraint not only in the way energy needs are satisfied, but also through changes in the energy needs themselves. Most especially, low energy technologies tend to penetrate the energy system when emission constraints increase. The combined changes triggered by emission constraints in energy demand and in the fuel-mix are examined in detail throughout this paper.

1.4 Limits and Uncertainties

Given the extremely strong emission constraint and the time horizon that are considered, the quantitative results for the long-term should be used with caution. This is because the model cannot capture all the uncertainties that the future holds on many aspects of societies and technologies.

Firstly, the levels of resources used and potentially serious climate change may lead to increasing societal and environmental tensions, inducing some unexpected feedbacks. As an example the level of biomass use in the energy system is subject to concerns regarding the competition with other land uses. Secondly, the identification of technologies in the model is limited to what is currently known, both already implemented or at a well documented stage, while it should be kept in mind that unanticipated scientific developments may lead to dramatic changes in the next century. Finally, structural changes in society and development patterns could take place while, in parallel, individual behaviors partly modelled on historical trends will also be affected by the new global environment within which human societies will evolve.

2. ENERGY NEEDS IN THE 21ST CENTURY AND THE CLIMATE CHANGE CHALLENGE: CONTRASTED IMAGES OF THE FUTURE

In this first section we present the projected World energy needs for the XXI^st^ century and its link with the climate change challenge. Two very contrasting scenarios are analyzed: a “baseline” case, in which climate change is not considered a serious issue, and a “very low stabilization” scenario that leads to extremely low levels of GHG concentrations (400 ppm CO_2eq, with all GHGs considered[1]). These scenarios have been developed within the ADAM project and with the World energy model POLES. The baseline has been produced jointly with the IMAGE-TIMER model (“harmonized POLES-TIMER baseline”, see van Vuuren et al., 2009). It leads to a concentration (for energy CO_2 only) of 500

1 “All GHGs” refers here to the basket of gases of the Annex A of the Kyoto Protocol: CO_2, CH4, N2O, SF6, HFCs, PFCs. NF3 or other substances are not included.

ppm in 2050 and 700 ppm in 2100[2], with a continuing increase thereafter. The emission profile required to meet the very low concentration stabilization has been produced by the IMAGE model and is referred to as "400ppm" (concentration in CO_2eq). POLES has then produced its own long term energy picture.

Future energy needs will depend on two main socio-economic drivers: the development of world populations and the development of their material wealth, which drives the use of physical resources for key societal functions like shelter or mobility. The evolution of consumption patterns, which heavily depend on the way societies value environmental issues, will be a major driver in the dynamics of energy needs.

In this paper we focus on the climate change issue, considered as a global and "multi-dimensional" concern. Other specific environmental problems, such as access to water, biodiversity management or land erosion may also play a role in future economic development patterns. They are however, not considered in this modeling exercise and are just briefly mentioned as potential limitations to the proposed analysis.

2.1 Key Socio-economic Drivers of Energy Demand

The two main exogenous drivers of energy demand in POLES are the population and per capita GDP increase. Figure 1 and Table 1 present the assumptions considered in this study.

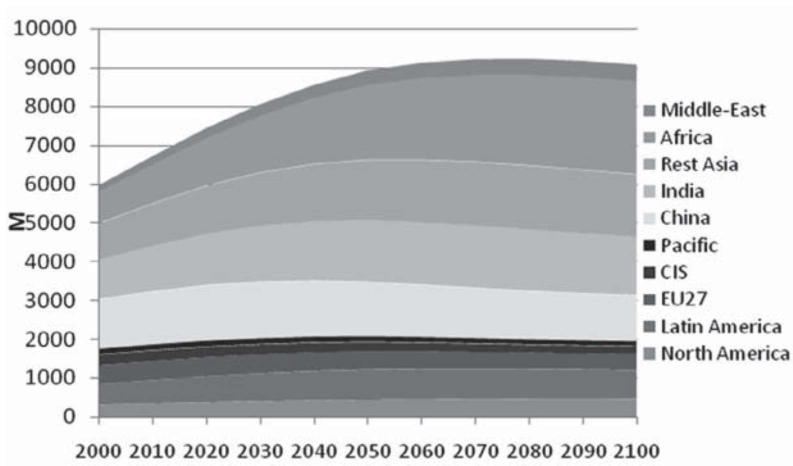
World population is predicted to increase up to 2050, beyond which it would roughly stabilize. After 2030 many regions see their population decrease: Europe, the Community of Independent States (CIS), China, and the Pacific, joined by Latin America and India after 2050. The fastest growing populations are in the Middle-East and Africa, with the latter reaching two billion inhabitants in 2050 continuing to increase thereafter.

Per capita GDP increases worldwide over the entire period, with the poorest regions growing more rapidly than the richest leading to a general convergence across world regions. Differences in material wealth thus tend to diminish in relative terms, although they may still become larger in absolute terms. Africa remains by far the poorest region at the end of the century. Some regions, like China or the Middle-East, catch up with current industrialized countries and end up with similar per capita incomes.

In both emission scenarios, identical assumptions on future GDP growth are applied. This raises possible consistency issues due to the multiplicity and complexity of the economic feed-backs. These include changes in the macro-economic dynamics, economic opportunities created by innovations in technology and organization, geopolitical impacts of resource scarcity and consequences of environmental diseases. However, taking the same assumption in both scenarios facilitates focusing strictly on the evolution of the energy sector, while quantitatively assessing alternative futures in terms of energy requirements

2. Estimation with the MAGIC model

Figure 1. World Population Assumption



bn	2000	2020	2050	2100	2000-2020	2020-2050	2050-2100
World	6.08	7.57	9.07	9.20	1.1%	0.6%	0.0%
North America	0.31	0.37	0.44	0.46	0.9%	0.5%	0.1%
Latin America	0.52	0.67	0.78	0.75	1.2%	0.5%	-0.1%
EU27	0.48	0.49	0.47	0.41	0.1%	-0.2%	-0.3%
CIS	0.28	0.27	0.24	0.20	-0.2%	-0.4%	-0.4%
Pacific	0.16	0.17	0.16	0.14	0.2%	-0.1%	-0.3%
China	1.27	1.42	1.39	1.18	0.6%	-0.1%	-0.3%
India	1.02	1.33	1.59	1.52	1.3%	0.6%	-0.1%
Rest Asia	0.93	1.23	1.55	1.60	1.4%	0.8%	0.1%
Africa	0.81	1.23	1.94	2.41	2.1%	1.5%	0.4%
Middle-East	0.17	0.26	0.37	0.42	2.0%	1.2%	0.3%

Source : UN median scenario, 2004 estimates

Table 1. GDP Per Capita Growth ($2000, Market Exchange Rates)

	2000-2030	2030-2050	2050-2100
World	2.2%	2.0%	1.7%
North America	1.6%	1.1%	1.1%
Latin America	1.9%	2.3%	2.2%
EU27	2.3%	1.8%	1.1%
CIS	6.0%	3.2%	1.5%
Pacific	2.0%	1.8%	0.9%
China	8.6%	4.6%	1.8%
India	6.1%	4.2%	3.0%
Rest Asia	3.9%	3.0%	2.7%
Africa	1.7%	1.8%	3.3%
Middle-East	1.8%	2.1%	3.5%

Source : ADAM Project, see van Vuuren (2009) and fuel-mix of a given growth trajectory. This trajectory indeed lies in the range of the GDP projections proposed by the other models in the ADAM "Low Stabilization Scenario" exercise (Edenhofer et al., 2010).

In any case, for the very long term, one has to remain very careful while considering GDP growth; how much corresponds to actual increases in the quantity of goods and services produced and consumed, and how much corresponds to the increased value perceived by the consumers due to qualitative changes in the nature of these goods and services? From an energy demand viewpoint, increase in quantities is by far the main driver, whilst changes in values have a rather limited impact.

In this exercise, the key societal needs – the demand for shelter and for mobility – are similar in both scenarios even though the policy framework of the two scenarios and the technologies and equipment used to meet the needs are very different.

2.2 Energy Demand

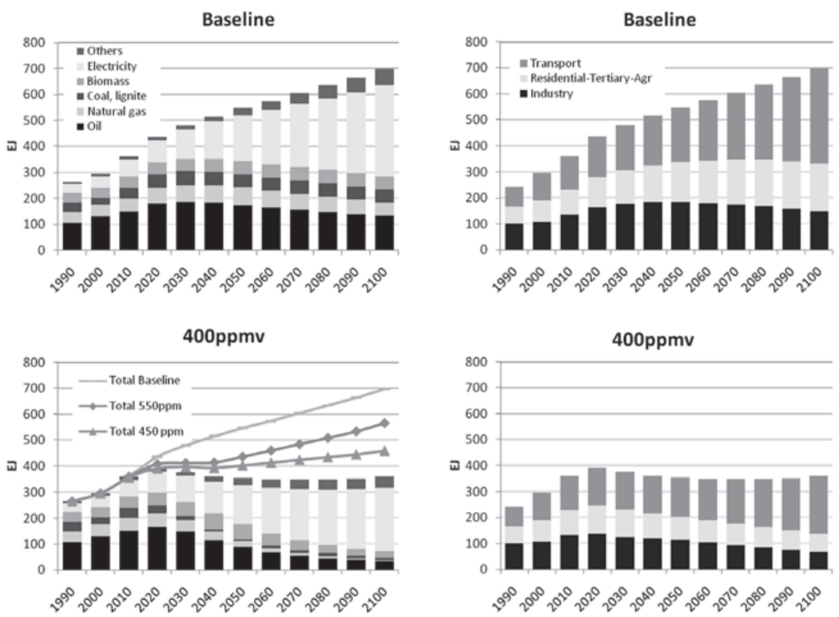
The dynamics in energy demand depend on various key parameters: activity, resource scarcity and CO_2 abatement policies (the latter two factors acting on energy prices and technology competition processes). In this study, upstream activity indicators (GDP, population) and resource availability are identical in both scenarios; therefore the differentiating drivers lie in the policy response to climate change and, as an indirect impact, on its consequences on resource use and scarcity.

2.2.1 Final Energy Demand

The World final demand projected by POLES in the baseline scenario more than doubles over the XXIst century, from 300 EJ p.a. in 2000 to 700 EJ p.a. in 2100, with an average per capita demand of 1.8 GJ in 2100 versus 1.16 GJ in 2000. The future final energy mix is increasingly electrified, with electricity representing 17% of the total in 2007, 32% in 2050 and up to 50% by the end of the century. The corresponding growth rate of the electricity demand is +3.2% for 2000-2020, +2.4% for 2020-2050 and +1.4% after 2050, against +3.3% for 1980-2007. This growth roughly follows GDP growth over the entire period. In addition, the demand for hydrogen also becomes significant in the second half of the century, resulting primarily from its development as a transportation fuel.

This trend of increasing demand for secondary energy carriers can be explained by a growing scarcity of "easy to use fuels" (transportable and storable), like oil and gas, and by the growing importance of coal, which is more conveniently used in large conversion facilities than used directly in dispersed locations such as buildings. The rise of electricity and hydrogen is also a result of the large development of renewables.

Figure 2. World Final Energy Demand by Fuel (left) and Sector (right) in the Two Scenarios



The" 550ppm" and the "450ppm" scenarios have also been developed within the ADAM project (see Edenhofer et al. (2010) and van Vuuren et al. (2009)).

In the 400ppm scenario, the total final energy demand is significantly lower than in the baseline case, and remains below 400 EJ p.a. in 2100, i.e. at its 2020 level. Although electricity consumption is slightly lower than in the baseline, its market share is much greater, reaching 43% in 2050 (150 EJ p.a.) and almost two thirds of the total by the end of the century. In that scenario indeed, distributed emissions at the consumer level (from vehicles or buildings) disappear because of emission abatement policies. They are "transferred" to large emitting sources, like power or hydrogen production plants, where options like Carbon Capture and Storage are more easily implemented.

In both scenarios, it transpires that fossil fuels are handled increasingly at the level of the transformation sector, and less at the final consumer level as was historically the case. This is for two different reasons: firstly the increasing scarcity of easy-to-store fossil fuels in the baseline (see second section below on supplying the needs), and secondly the constraint on GHG emissions in the 400ppm scenario.

2.2.2 Key Demand Technologies Penetration

Figure 3 and Table 2 show the technological and sectoral mix of future energy demand. In both scenarios, cars based on alternative technologies (mostly pluggable hybrids and pure electric cars) start penetrating the road vehicles market after 2015 and progressively replace the conventional oil-based internal combustion engines (ICE). In both cases this is mainly due to the growing competitiveness and technology improvement of alternative vehicles, but the increase in automotive fuel prices also plays a role. In the baseline it is connected to high oil prices resulting from the depletion of oil resource and in the 400ppm scenario it is due to the high carbon value.

This substitution however is quicker in the 400ppm scenario, with new technologies accounting for 70% of the total vehicles stock in 2050 compared to 55% in the baseline case. By the turn of the century, in both scenarios, the majority of cars will be plugged to the electricity network. Complex dynamics in learning processes and relative evolutions of fuel prices and carbon value lead to differentiated distributions of electricity and hydrogen-powered vehicles in the scenarios.

Table 2. Distribution of Vehicle-km (Light Vehicles) Among Competing Technologies

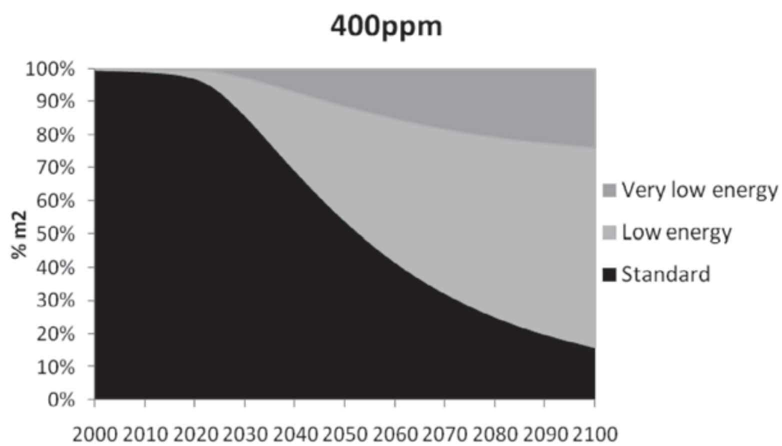
	2000		2050		2100	
	Baseline	400ppm	Baseline	400ppm	Baseline	400ppm
Light vehicles shares						
Conventional	100%	100%	44%	29%	10%	4%
Hybrid Plug-in	0%	0%	28%	33%	34%	30%
Elec	0%	0%	18%	26%	26%	29%
H2 ICE	0%	0%	11%	12%	17%	27%
H2 FC	0%	0%	0%	0%	9%	8%
Gas FC	0%	0%	0%	0%	4%	1%
Energy consumption (EJ)	906	906	1650	928	1698	718

Of course, this picture displays a World in which no specific technology “takes it all” and where there is a co-existence of various types of cars, which does not fit with observed past development of vehicle fleets, where strong lock-out effects took place. This reflects some current features of the POLES model, which, in contrast to a pure optimization model, tends to develop a diversified and resilient system, where several technological options remain available (Criqui and Mima 2008a, Criqui et al. 2009). Sensitivity analyses on the introduction of “network effects”, with accelerated deployment of technologies due to mimetic behavior and club effects show that the early lock-in of electrical vehicles is more likely than of hydrogen-power vehicles (Criqui and Mima 2008b). These results are also consistent with the findings of previous studies, like the WETO-H2 project (see Lapillonne et al., 2007).

The main difference over the long term between the two scenarios, though, appears to be the evolution of specific fuel consumption. In the baseline consumption in 2100 is a third of that in 2000 – partly due to the increasing share of electric vehicles.In the 400ppm scenario it is reduced to a sixth. The 400ppm scenario requires a "downsizing" of cars to models much smaller and lighter to those of today, and requiring less energy consumption.

In the POLES model, three categories of building technologies are considered, which can be differentiated according to their energy performance : (1) "standard" buildings, for which the thermal performance evolves through long term price-elasticities and historical trends (energy consumption decreases by an average -0.4% p.a. per m^2 for the entire stock); (2) "low energy" buildings for which the thermal performance is twice that of the standard buildings technology; and (3) "very low energy" buildings for which the thermal performance is four times that of "standard" buildings technology (i.e. energy consumption per square meter is divided by four).

Figure 3. Penetration of Low and Very Low Energy Buildings in the 400ppm Scenario



Alternative technologies involve extra investment costs that are hardly cost-effective through the century in the baseline scenario, despite the growing scarcity of oil and gas. This situation changes drastically in the 400ppm scenario, where the introduction of the carbon value brings the energy prices to a sufficiently high level. "Low energy" and "very low energy" buildings penetrate progressively into the building stock through new construction and the retrofitting of existing buildings. In the 400ppm scenario these new building technologies account for almost 50% of the building stock in 2050 and for most of the stock and all new buildings by the end of the century.

2.2.3 Primary Energy Demand

Primary energy demand[3] results both from the amount of final energy needed and from the structure of the energy system designed to meet this final demand. In the baseline scenario, easily tradable and storable energy resources are relatively widely available and used, as is coal over the century or even gas and oil during its first half. As good transportation routes already exist, this scenario represents a “globally linked” world, increasingly interconnected for its energy supply.

Conversely, there is a great pressure in the 400ppm scenario to limit the consumption of fossil fuels when carbon is not captured and stored. This scenario gives priority to decarbonised energy sources, which are often more difficult to handle than fossil fuels, encountering storage and transportation problems. This is the case for solar and wind energies, and even nuclear energy, which can only produce electricity and heat. In addition, renewable energy sources are diffuse and their availability is limited by physical constraints and social acceptability. Consequently, the energy system evolves under a new set of constraints, incorporating energy conservation, with consequences on urban planning and mobility. Such a constrained world for CO_2 emissions can be considered as a rather “localized” world, as far as the energy pattern is concerned, compared with the “globally linked” world of the baseline or of some other ADAM models used in the mitigation assessment (see Edenhofer et al., 2010). In POLES, energy efficiency and low energy end-use technologies constitute first-rank options to cope with severe climate constraints. Only strong hypotheses on the massive implementation of large scale networks of transport and storage for renewable energy sources (most especially solar from desert areas to consuming regions) may change this picture.

While the average energy consumption per capita keeps increasing in the baseline, doubling to 3.5 GJ p.a. by the end of the century, energy intensity improves over time, and is almost divided by four. In the 400ppm scenario, primary energy per capita is roughly stabilized around 1.5 GJ p.a., while energy intensity is divided by eight.

As shown in Figure 4, the annual evolution of energy intensity in the baseline is -1.2% for primary and -1.4% for final energy and in the 400ppm scenario, -1.9% for primary and -2.1% for final energy. The increase in primary energy consumption per capita follows a similar pattern to that of final energy demand in both scenarios, although at a slightly higher pace because of the growing role of secondary fuels and the attached transformation efficiency factor. In the baseline, it more than doubles between 2000 and 2050 (880 EJ p.a. in 2050 vs. 400 EJ p.a. in 2000) and still increases by 50% up to the turn of the century, while it stabilizes around 600 EJ p.a. from 2030 in the 400ppm scenario.

3. Primary energy demand by fuel is calculated using the IEA convention.

Figure 4. Energy Per Capita and Energy Intensity in the Two Scenarios

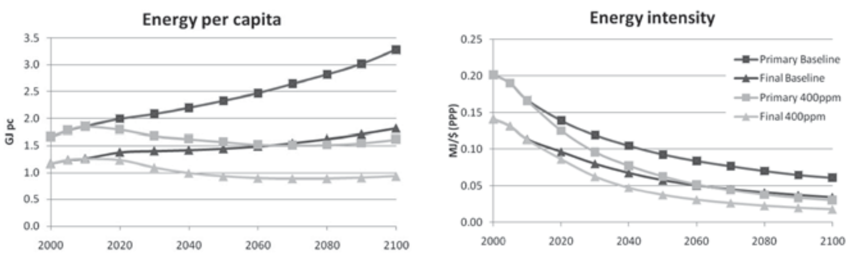
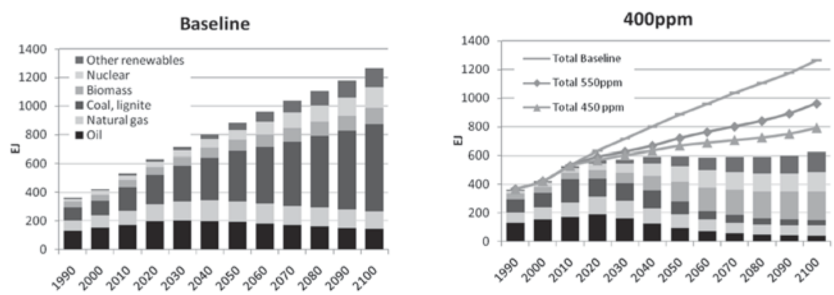


Figure 5. Primary Energy Consumption in the Two Scenarios



In the baseline scenario, coal becomes the dominant primary source of energy, while oil slowly declines after 2030 and non-fossil energies get an increasing role. In the 400ppm scenario, fossil fuels are reduced to a 50% share of total primary energy consumption by 2050, and are marginalized by the end of the century. They are partly substituted by biomass and their development is also significantly limited by energy efficiency due to the diffusion of more efficient demand-side equipment. The level of the demand for other renewables and nuclear energy is only slightly higher in the 400ppm than in the baseline scenario, but the share of these sources in total primary demand is much higher, due to the much lower level of the total demand.

2.3 Resulting CO_2 Emissions

Energy CO_2 emissions in the 400ppm scenario are produced by POLES within the "all GHGs"[4] profile (energy and industry) provided by the IMAGE model (see Van Vuuren et al., 2009). In Figure 6 the large increase in emissions in the baseline (from 24 $GtCO_2$ in 2000 to 50 $GtCO_2$ in 2050, and nearly 70 $GtCO_2$ at the end of the century) is mostly driven by the power sector, which uses an increasing amount of coal, as the cheapest option in the absence of any

4. According the Kyoto Protocol Annex A gases definition.

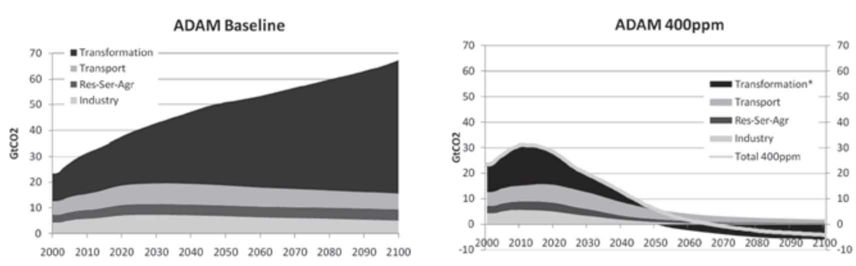
environmentally driven policy. The emissions from electricity only represent, by the end of the century, twice the current total emissions.

In contrast, the 400ppm case displays a very striking profile, with future "negative" CO_2 emissions (and a fully decarbonised power generation system by 2050). This profile is generated by the objective of remaining below a GHG concentration level in the atmosphere low enough to ensure a high probability of remaining permanently below +2° temperature increase (IPCC 2007). In this scenario, almost all "direct" emissions disappear (very marginal emissions in air and road transport), while the transformation system (power and hydrogen) displays globally "negative" emissions. These negative emissions actually result from the fact that CO_2 emissions from biomass plants (considered as "neutral") are captured and stored underground, the whole process acting as a "carbon pump" from the atmosphere (see van Vuuren et al., 2007).

Various technological options are required to reach the very low emission profile of 400ppm and contribute to these emission reductions (see Figure 7). Almost 50% of the differential cumulative reductions are achieved directly in the final sectors : 36% from efficiency and 10% from a shift towards low carbon fuels on the demand side.

On the supply side, sequestration is a key factor generating 25% of the differential cumulative emission reductions, while renewables achieve 25% (the impact of biomass with CCS is accounted for in both options) and nuclear 4% (assessed through the share of nuclear per kWh produced – it must be noted that there is already a substantial amount of nuclear power in the Baseline – see part 3.2 below). Fossil fuel switch from coal to gas occurs only at the beginning of the period and represents virtually 0% of the cumulative reductions by 2100. The cumulative difference in CO_2 emission reductions[5] between the two scenarios reach 3900 $GtCO_2$ by the end of the century.

Figure 6. Energy CO_2 Emissions by Sector in the Two Scenarios



* emissions in Transformation become negative after 2050, total emissions become negative from 2065.

5. The cumulative reduction is the integral of the annual emission differences between the two scenarios throughout the period.

Figure 7. Contribution of Options to Emission Reductions Between the Baseline and 400ppm Scenarios[6]

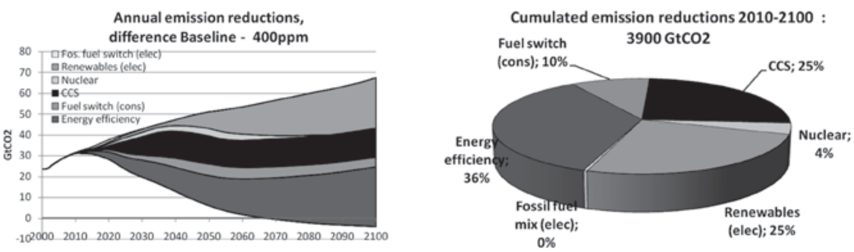


Figure 8 shows the evolution of annual and cumulative volume of CO_2 emissions captured in power plants and industrial facilities and then stored. After a sharp increase by 2050, the annual amount of emissions captured stabilizes at around 14 $GtCO_2$. It must be noted that the model accounts for losses at the capture level, which are then impacted by the carbon values applied[7]. This aspect significantly affects the development of coal plants associated with CCS in large countries using large amounts of coal, such as China or the USA, at around 2050 when the carbon value is relatively high (see Figure 9), leading to the slight decline observed. The underlying assumptions on long-term storage technologies and the long-term reliability of such storage are very speculative.

The carbon value that is necessary to keep the emissions down throughout the period appears to be very important (500 $/$tCO_2$ in 2050 and 2000 $/$tCO_2$ in 2100 – see Figure 9), but it should be noted that it applies to a very small quantity of emissions.[8]

Such high values can represent an almost complete ban of CO_2 emissions in the modeling system. The post-2050 result should also be used carefully, given the very large uncertainties and the difficulty in satisfactorily describing

6. The contribution of each option is calculated as follows: (1) the reductions due to energy efficiency are first calculated through the comparison of the carbon content of final energy demand and electricity production in both scenarios; the remaining reductions are thus due to fuel and technology switch: (2) the contribution of CCS is directly identified. In the power sector each option (after removal of CCS) contributes to the remaining reductions depending on its additional production compared to the baseline; (3) finally fuel switch in the demand side is deduced to match total reductions on the demand side.

7. The minimum losses have been set at 5% for power generation and 25% for industrial activities when the carbon value reaches 200 $/$tCO_2$ (against 13% and 30% respectively at 0$/tCO2).

8 The carbon value regularly increases over time: this is actually a standard POLES result when associated with gradually increasing emission constraints (here, the emission profile provided by IMAGE) in a continuing economic growth. This is due to different factors : (1) the absence of back-stop technologies in POLES that would generate large amount of reductions at a capped cost; (2) the fact that all technologies are associated with technical or physical potentials that restrict their development and lead to increasing costs, and (3) the necessity to avoid rebound effects on final demand through an increasing price signal.

Figure 8. CO_2 Emissions Captured and Stored (Annual and Cumulative)

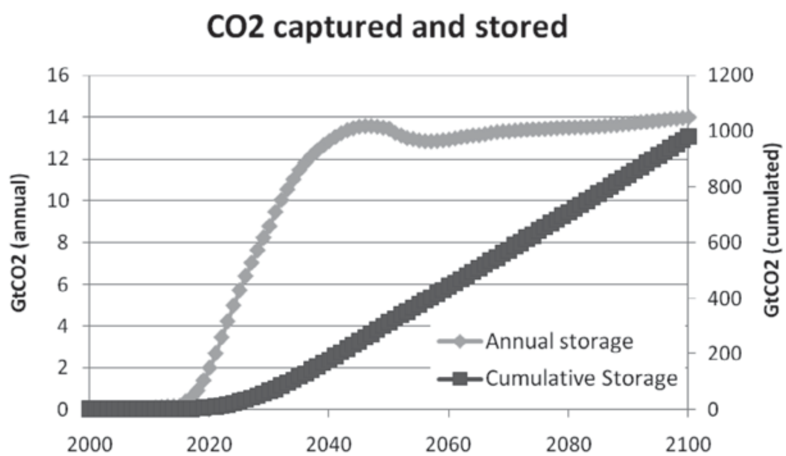
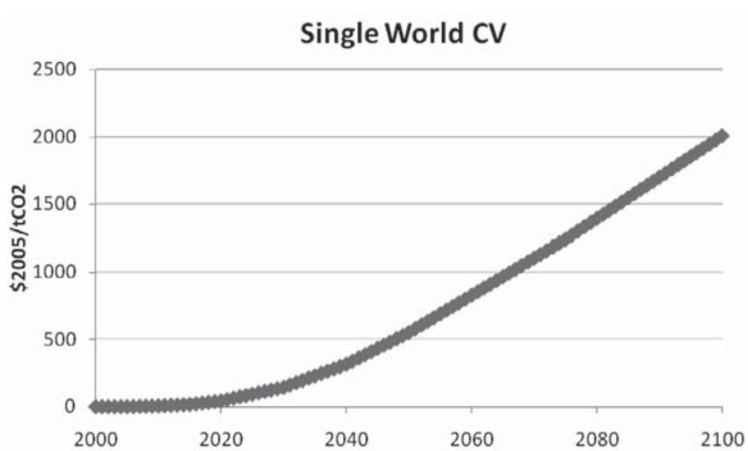


Figure 9. World Carbon Value (400ppm Scenario)



technico-economic systems in long-term projections. In a sense, the level of the carbon price reflects this uncertainty.

The associated sectoral abatement cost at World level to reach the 400ppm scenario increases regularly up to 2.5% of total GDP in 2050 before stabilizing, and even slightly decreasing at the end of the period (see Figure 17 in the 4th part of the article). Indeed, although the marginal cost of emission reductions keeps increasing (the carbon value displayed in Figure 9), the decreasing amount of required reductions limits the total abatement cost (Figure 7 shows that the pace of reductions decreases after 2050).

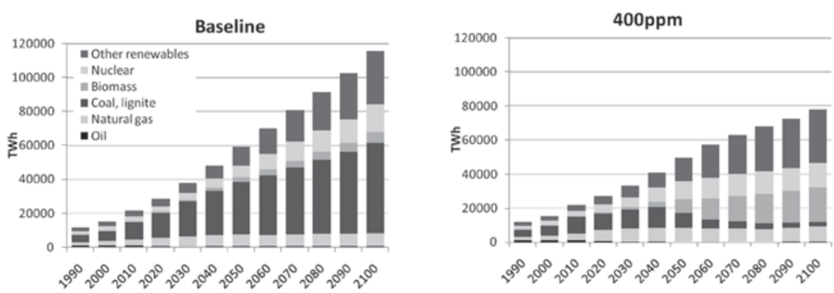
3. ENERGY SUPPLY: SATISFYING THE NEEDS IN CONTRASTED FUTURES

The above scenarios represent very contrasting futures in terms of energy needs. They imply different patterns for the organization of the connection between supply and demand areas, as well as different levels of stress on resources, be it minerals resources or land. This section describes part of these characteristics: for fossil fuels consumptions and for land areas that are dedicated to energy purposes.

3.1 Transformation Sector: Power and H2 Production

The evolution of power production in the two scenarios is given in Figure 10 below. The relatively fast growth of electricity demand in the baseline scenario (+2.1% p.a.) implies a significant development of coal demand (electricity from coal grows at +2.2% p.a.) and of non-hydro renewables. Nuclear energy also develops substantially (+1.9% p.a.). In the 400ppm scenario, power demand increases more slowly, but by a factor of four over the century (+1.7% p.a.). In this scenario, the production of electricity from nuclear and non-biomass renewables is at the same level as in the baseline case. Biomass use is substantially increased and represents 25% of the total. This result stems directly from the emission profile which drives biomass to be used primarily in the transformation sectors, for electricity or hydrogen production, where its emissions can be easily captured and then stored in order to get the necessary negative emissions.

Figure 10. World Electricity Production in the Two Scenarios

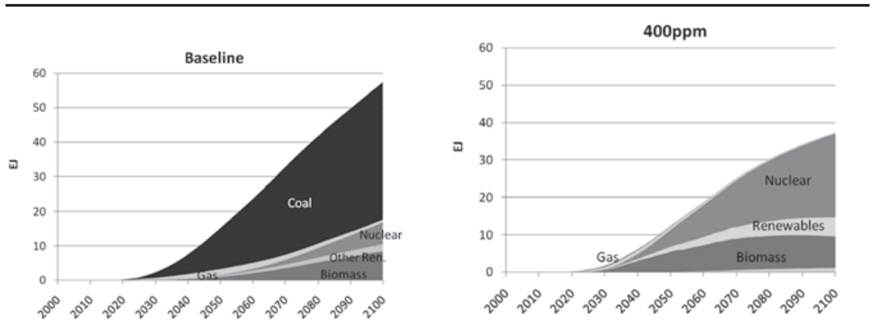


The 400ppm scenario shows an increasing share of intermittent sources of electricity in the mix, especially compared to potential back-up capacities: for instance wind capacity represents 30% of total thermal capacity in 2050 (12% of the electricity production) and almost 70% in 2100 (26% of the production). The underlying assumption is that future grid management will be much helped by Information and Communication Technologies (ICTs) development and storage technologies (which role is not modelled explicitly here), allowing for larger contribution of intermittent energy sources. It must be noted that power generation becomes decarbonised as early as 2050 : remaining fossil fuel use is associated with CCS, and "negative" emissions from biomass in electricity offset the emissions losses at the capture level.

Hydrogen production remains fairly limited in the energy picture, compared to electricity. In 2050 it accounts for respectively 5% and 7% of the final consumption in the baseline and 400ppm scenarios (around 15 EJ p.a. in both scenarios). It keeps increasing afterwards with a market share that reaches 10% at the end of the century. Hydrogen indeed appears to have limited interest for stationary uses, mostly because of the penetration of low energy buildings, but also due to the fact that hydrogen can only be mixed to a certain level with natural gas for direct heating in POLES model, and is constrained in the 400ppm scenario by the carbon content of natural gas. However, hydrogen does penetrate substantially in transport, although being less attractive than electricity over the whole projection period (see Table 2 above in part 2.2). Indeed there are five times more power-connected vehicles by 2050, and almost twice more at the end of the century.

In the baseline, most of the hydrogen production is based on coal (almost 75% at World level), while in the 400ppm case, nuclear (60%) and biomass (25%) are the largest primary fuels used (see Figure 11).

Figure 11. World Hydrogen Production in the Two Scenarios

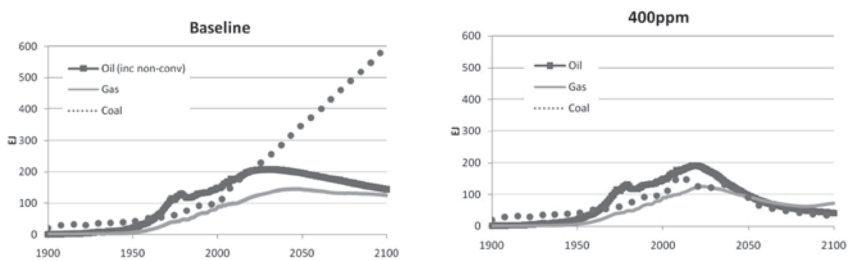


3.2 Fossil Fuel and Uranium Resources

3.2.1 Fossil Fuels

In the baseline the future productions of the different fossil fuels display very divergent profiles (see Figure 12); oil production declines from 2030 and gas production from 2040, while coal production keeps increasing over the entire period.

Figure 12. Past and Future Production of Fossil Fuels, 1900-2100



Oil and gas production are strongly impacted by the depletion of resources[9], even though the system anticipates a plateau around 2030, rather than a sharp peak due to new discoveries, technological progress in recovery rates and development of non-conventional oils (similar findings as Aguilera et al., 2009). In the long term, though, the system adapts through substantially higher international prices, which trigger substitution processes, either to other fuels or to other technologies (for instance the penetration of electrical cars, see in previous section). It must be noted that the baseline scenario assumes no oligopolistic behavior by producing countries and, consequently, that production capacities are built to supply the needs: there are no political restrictions on upstream investments.

Coal development in the baseline raises questions on the possibility of supplying huge quantities of coal over such a long period without any feedback effects on the availability of resources, prices and finally, on demand. Indeed, between 2000 and 2100, around 850 Gt of coal are consumed in this scenario, roughly the current estimates of total current reserves (WEC, 2007a), while the consumption level at the end of the century keeps increasing. These dynamics of coal consumption are consistent with significantly broader coal resources, and, as a consequence, the baseline results must be considered with caution on this issue. One has to keep in mind the fact that the model for now does not describe the full detail of the impact of lowering coal resources on coal markets as it does for oil and gas (for which lowering resources lead to higher prices, and therefore lower fuel consumption).

With the severe carbon constraint in the 400ppm scenario, fossil fuel consumption is strongly affected, and most notably the demand for coal declines over the entire period after an early shock between 2010 and 2030. The observed peaks for oil and gas production (2020-2025) are in this case mainly demand-driven, and not linked to the availability of resources as in the baseline. In addition it must be noted that production processes that emit substantial amounts of CO_2 (e.g. tar sands, Coal-to-Liquids (CTL)) are also very impacted by the carbon constraint. Finally, as a reaction to lower demand and to consequently

9. Resources data come from BGR (2006) and USGS (2000)

lower international prices, oil and gas discoveries and ultimately recoverable resources (URRs) are less important (see Table 3). In that case, large hydrocarbon resources remain available for long-term demand.

Table 3. Evolution of Cumulative Production vs. Resources[10]

Oil (conventional) *(Gbl)*	2000	2050 Baseline	2050 400ppm	2100 Baseline	2100 400ppm
Cumulative Production	880	2400	2140	3450	2500
Cumulative Discoveries*	1920	3280	3000	3800	3100
URR**	2660	4050	3570	4750	3550

Gas *(Tm3)*	2000	2050 Baseline	2050 400ppm	2100 Baseline	2100 400ppm
Cumulative Production	63	250	230	450	350
Cumulative Discoveries*	220	430	400	550	400
URR**	440	520	490	550	500

** : Discoveries evolve with drilling effort, that depends on oil price and a decreasing return function*
*** : Ultimately Recoverable Resources, is a function of the recovery rate (which depends on oil price)*

As shown in Table 4, the regional concentration of conventional oil production and reserves increase over time in both scenarios[11]. Interestingly, the concentration happens to be greater in the 400ppm than in the baseline case: indeed, in a context of lower stress on resources and need for exploration effort, the remaining production in the former scenario concentrates in low cost areas only because of the associated lower international prices (due to seriously restrained demand) that do not incentivize investment in exploration and production in costly areas.

Table 4. Regional Concentration of Conventional Oil Production and Reserves (% of the World Total)

		2000	2050 Baseline	2050 400ppm	2100 Baseline	2100 400ppm
Production	3 largest countries	31%	42%	43%	32%	43%
	5 largest countries	41%	54%	56%	50%	61%
	10 largest countries	61%	77%	76%	80%	87%
Reserves	3 largest countries	39%	45%	46%	41%	56%
	5 largest countries	59%	64%	67%	60%	77%
	10 largest countries	82%	92%	94%	90%	97%

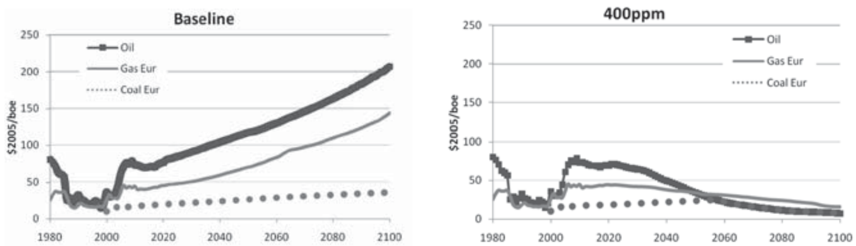
Of course, the increased regional concentration of production and reserves in the 400ppm scenario does compare with a decreased energy security in the baseline as, at the same time, total oil quantity required is much lower

10. 2000-2005 data for all producing countries come from : BGR (2006) and USGS (2000) for URRs and recovery rates; Oil & Gas Journal for reserves; 2050-2100 figures are results from the POLES model.

11 See Appendix 2 for a description of the 71 countries identified in the oil & gas module of the POLES model.

(see Figure 5). Figure 13 shows the impact of extreme mitigation policies on the evolution of international markets (given the amount of oil resources detailed above). Such climate policies have a strong timing impact on international prices through a constantly diminishing demand of fossil fuels.

Figure 13. Fossil Fuel Prices



The reaction of producers to keep international prices high through production limitation and very high access costs to the resources, cannot be excluded, at least in the short and medium term. However, over the long term, the capability of exporting countries to exert market power is questionable in a context of climate change policies that tend to foster carbon-neutral fuels to the detriment of fossil fuels.

Table 5 shows the impact of changing consumption, production patterns and prices on the revenues of exporters and compares them with the revenues from carbon taxation for governments. Revenues from fuel exports keep increasing over time in the baseline scenario, due to both higher international prices and a greater regional concentration of production inducing more international trade. On the other hand, these revenues peak between 2025 and 2050 in the 400ppm scenario before decreasing sharply later on.

Table 5. Revenues for Energy Exporters vs. Government Revenues from Carbon Tax (G$05)

G$05	2000	2025		2050		2100	
	Baseline	Baseline	400ppm	Baseline	400ppm	Baseline	400ppm
External revenues of fossil fuel exporters*, of which	**550**	**2130**	**1610**	**3150**	**700**	**5950**	**200**
Gas[1]	80	350	360	650	250	2100	140
Oil	450	1670	1200	2250	400	3150	40
Government revenues from carbon value ("tax"), of which	-	-	**1970**	-	**2970**	-	**0**
energy importing countries**	-	-	54%	-	64%	-	-

** : calculated as the sum of net exports of gas + oil + coal for the POLES 47 key countries / regions (see Appendix 2)*

*** : defined as countries that have total net positive fossil fuel import (in $) in the Baseline scenario*

[1] : the sharp increase after 2050 in the Baseline is linked to the increasing number of importing countries zones because of lower resources, leading to increased international trade, even though total consumed gas quantities stabilize

The revenues for government from carbon emissions taxation in the 400ppm scenario first increase dramatically by 2025 and 2050, before disappearing over the long-term because of the drastic reduction in emissions. It is noticeable that these government revenues also exist for fossil fuel exporting countries, which are usually large emitters themselves.

3.2.2 Uranium

In POLES, nuclear production is split into current types of reactors and the so-called "4th Generation" reactors, described through a generic technology which does not penetrate the energy system before 2030. By the end of the century, each of these two categories of reactor represents about half of the primary nuclear consumption. Only the current third generation technology of reactors is associated with the consumption of a natural resource, uranium. The 4th Generation reactors are assumed to consume nuclear waste produced by the existing technology.

In the scenarios, the consumption of uranium ore[12] reaches about 20 Mt in both scenarios (18 Mt in the baseline and 21 Mt in the 400ppm), which is above the currently estimated resources at 16 Mt (that include identified and undiscovered resources, OECD 2008). Of course different factors can extend the availability of resources: (1) depleted uranium from first enrichment can be re-enriched (increasing the amount of "reserves"); (2) additional resources may be discovered; and (3) not all future reactors will use uranium (some may use thorium for instance). However, this result still gives an indication on one possible challenge faced by the nuclear sector over the long term, that is the availability of usable ore.

In addition, increased nuclear use as observed in these scenarios also raises concerns on military security, waste management (even with the surge of a technology that would consume some waste), or civilian installation safety. Indeed, the baseline scenario implies a net increase of 1,600 GW of nuclear by 2100 (around 16 GW p.a., on top of the replacement of existing nuclear capacities), which may not be without problems.

3.3 The Development of Renewable Energies and Corresponding Land Use

The future energy supply patterns will increasingly rely on renewable energy sources: this holds both in the baseline and the 400ppm cases, and very probably in all scenarios between those two extreme cases. Because of their low surface density, harvesting such a quantity of renewable energy will therefore lead to increased use of land for energy purposes. The following section gives insights on these impacts for each of the different types of energy identified in the POLES model.

12. Contains 0.7% of U235

3.3.1 Biomass

Biomass is the most land-consuming source of energy and this energy source appear, in this modeling exercise, crucial to achieve the future strategies against climate change. However, uncertainty on the biomass availability is important and the potential has been treated as a separate scenario in this Special Issue (van Vuuren et al, 2010). This paper adopts a 200 EJ p.a. biomass potential scenario which is the medium scenario covered by van Vuuren. Such a scenario stands in the average of the global biomass potentials found in the literature (Hoogwijk et al, 2003; Hoogwijk et al, 2005 and Berndes et al, 2003).

3.3.2 Land-use Modelling

In POLES, three types of areas are available for bio-energy production, namely agricultural, forests and grassland areas. All zones which correspond to built areas, deserts and inland water bodies are assumed to be constant over time (18% of the total land surface) and are excluded from the biomass potential calculation. Total land surface amounts to 130 Mkm^2 (FAO, 2007).

- Total agricultural areas represent around 24 Mkm^2. The requested agricultural areas to satisfy global food demand are both linked to the demography and to the production yields[13]. During the first years of simulation around 15% of this surface is assumed to be available for ethanol and biodiesel production. Only 5% remains available by 2020 and 0% by 2050, mainly because of environmental and ethical concerns regarding first generation biofuels which compete on the same areas as crops for food production.
- Forest areas represent around 38 Mkm^2 and in this scenario, around 13% of the total forest areas can be exploited for energy purposes. Total forest areas are assumed to evolve smoothly according to historical trends and finally reach 42 Mkm^2 by 2100.
- Short Rotation Crops (SRC) can be grown on grassland areas which include savannas and shrublands. They include degraded and marginal lands but also more fertile areas which are not used for agricultural purposes. The grassland surface is calculated as the difference between total land area and the other land types (agricultural, forest and other areas). It accounts for almost 45 Mkm^2 in 2000 and 39 Mkm^2 in 2100. SRC are the main biomass potential for the future because of the significant amount of grassland surface and the limited competition with other land-use. In a 200 EJ p.a. biomass potential scenario, 25% of the grassland area is assumed to be available for energy crops by 2100.

13 The current world average food production per capita per day (around 4600 kcal – see UNEP 2009) is supposed to be constant and to satisfy food needs in all regions over all the period (total food production evolves with the population growth). The attached diet may evolve though, for instance towards lower consumption of meat that requires large cereal inputs per unit production. In addition, losses (in harvest, distribution and waste) could also be reduced (about 30% of total production in 2000 – UNEP 2009).

Overall, around 15 Mkm^2 are available for energy biomass production, corresponding to a potential of 200 EJ p.a.. The implemented potential reaches 60% of this total by 2100 in the baseline and 100% in the 400ppm scenario (see Table 6 below).

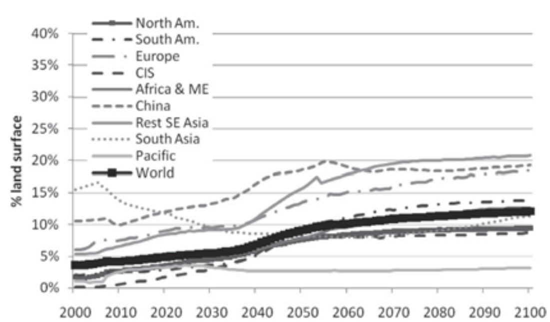
Table 6: Used Areas in the Baseline and 400ppm Scenarios

Global areas (Mkm2)	2000	2020	2050	2100	*YAGR* 2000/2020*	*YAGR* 2020/2050*	*YAGR* 2050/2100*	*YAGR* 2000/2100*
Total land	130.0	130.0	130.0	130.0				
Agricultural areas	23.8	26.4	28.0	26.3	*0.5%*	*0.2%*	*-0.1%*	*0.1%*
of which available for energy purposes	4.1	1.5	0.3	0.0	*-5.0%*	*-4.8%*	*-5.0%*	*-4.9%*
of which implemented in Baseline	0.3	0.6	0.3	0.0	*4.7%*	*-2.6%*	*-4.7%*	*-2.2%*
of which implemented in 400ppm	0.3	0.7	0.3	0.0	*5.4%*	*-2.5%*	*-5.0%*	*-2.2%*
Forest areas	38.4	39.6	38.4	41.7	*0.2%*	*-0.1%*	*0.2%*	*0.1%*
of which available for energy purposes	4.9	5.1	5.1	5.5	*0.3%*	*0.0%*	*0.1%*	*0.1%*
of which implemented in Baseline	1.7	2.1	2.4	3.3	*1.1%*	*0.5%*	*0.6%*	*0.7%*
of which implemented in 400ppm	1.7	2.3	4.1	5.5	*1.5%*	*1.9%*	*0.6%*	*1.2%*
Grassland areas	44.8	41.1	40.7	39.0	*-0.4%*	*0.0%*	*-0.1%*	*-0.1%*
of which available for energy purposes	10.0	9.6	10.0	9.8	*-0.2%*	*0.1%*	*0.0%*	*0.0%*
of which implemented in Baseline	2.7	3.0	3.8	5.4	*0.5%*	*0.8%*	*0.7%*	*0.7%*
of which implemented in 400ppm	2.7	3.3	7.3	9.8	*1.0%*	*2.7%*	*0.6%*	*1.3%*
Other land (desert, built areas, inland water)	23.1	23.1	23.1	23.1	*0.0%*	*0.0%*	*0.0%*	*0.0%*

** Yearly average growth rate*

Figure 14 shows the evolution of the surfaces dedicated to energy biomass projected by the POLES model in the 400ppm scenario (200EJ used) given the yields mentioned in Table 7. Around 12% of total World surface is used for energy biomass in this scenario, with almost 20% in China, Rest South-East Asia and Europe. Such an amount may cause problems in these regions, especially in Asia, because of the competition for land for food production and biodiversity conservation.

Figure 14. Surface Dedicated to Energy Biomass (400ppm scenario)



3.3.3 Yields Evolution

In POLES, bio-energy yields, which are differentiated by regions, are provided for each biomass type and are assumed to increase over time (Fisher, 2001). Assumptions are made on the increase rate given the total available land and the global bio-energy potential reached in this scenario (200 EJ p.a. in 2100). Yields are thus assumed to increase at the average annual increase rate of 0.35% p.a. over the whole period (i.e. +40% mean yield increase over 2000-2100).

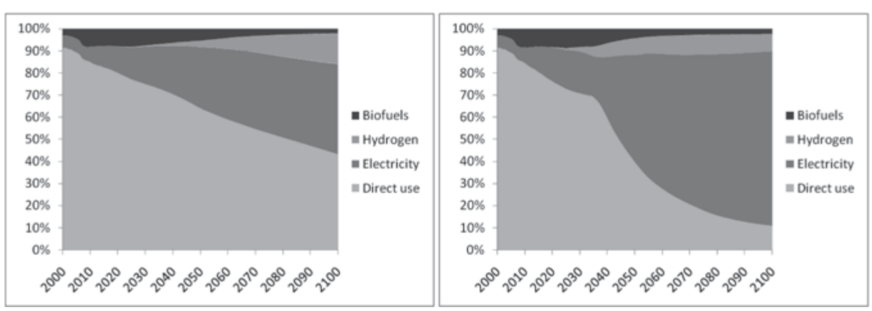
Table 7. World Mean Bio-energy Yield Evolution in the Two Scenarios

Mean world yields (ktoe/km2/yr)	2000	2020	2050	2100	*YAGR* 2000/2020*	*YAGR* 2020/2050*	*YAGR* 2050/2100*	*YAGR* 2000/2100*
Oil and sugar crops	0.130	0.148	0.172	0.189	*0.7%*	*0.5%*	*0.2%*	*0.4%*
Forest residues	0.110	0.124	0.140	0.152	*0.6%*	*0.4%*	*0.2%*	*0.3%*
Short rotation crops	0.279	0.320	0.364	0.397	*0.7%*	*0.4%*	*0.2%*	*0.4%*
					** Yearly average growth rate*			

3.3.4 Biomass Use

Biomass use depends mainly on climate policy scenarios, as shown in Figure 15. In highly constrained scenarios, biomass is utilized in the electricity sector thus providing double revenues from the electricity production sales and from a CO_2 sequestration premium. Indeed, CO_2 stored in stationary biomass power plants leads to "negative emissions" that transform the CO_2 price into some form of subsidy for the producer (provided that biomass production is carbon neutral) (van Vuuren, 2007).

Figure 15. Biomass Use in the Baseline Scenario (left) and 400ppm Scenario (right) in POLES Model



3.3.5 Other Renewables

Other renewables sources are less land-consuming, even though there are acceptability issues mostly related to visual impact. Wind production does not completely exclude other uses of the land (eg food production) and solar production occurs mostly directly on buildings and in low population density areas with high solar availability.

3.3.6 Wind

The surfaces dedicated to wind energy at World level are fairly limited: 350,000 km^2 for onshore wind farms and 150,000 km^2 for offshore wind farms by 2100. Onshore farms represent 0.02% of total land surface (1 MW per 50 km^2) but this figure varies greatly across regions from less than 1 MW per 500 km^2 in Australia to around 1 MW per 10 km^2 in many European countries. However, their visual impact can cover much wider areas; the considered average tower height is around 100m, slightly less for onshore and more for offshore, for an average capacity of 2.8 MW onshore and 6.5 MW offshore in the long term.

The installed capacities are similar in both scenarios although the constraint on emissions is far greater in the 400ppm scenario. In both cases wind appears competitive and its development is actually limited by the capacity of the grid to manage intermittency (which increases in time and with the carbon constraint) and, to a lesser extent and only in some countries, by the technical potential. In addition, it must be noted that because of increased energy efficiency the electricity demand is lower in the 400ppm than the baseline scenario. At World level, however, only 20% of onshore potential (30,000 TWh) and 10% of offshore potential (45,000TWh) is used, partly because of the mismatch of production with consuming areas. Interregional grids would certainly facilitate more wind electricity production.

The fact that the total capacity for offshore wind is lower than for onshore wind is mostly due to higher production costs. Indeed the extra-costs for both the connection to the onshore electricity networks and the operation and maintenance of turbines in a more difficult environment partly overcome the greater availability of wind and the consequent higher load factor of offshore turbines.

3.3.7 Solar

PV panels are installed on buildings. Total World PV production reaches 8000 TWh : 5000 TWh in services and 3000 TWh in the residential sector (representing an average of about 800 kWh per dwelling).

Power production from the solar power plants (concentrated solar thermal) occurs mostly in low density areas, like deserts. These production zones are located far from the main consuming areas, and because inter-connections on long distances are limited in the POLES model, this production remains far from its theoretical potential. Total production still reaches around 8000 TWh by the end of the century (10% of the total electricity production in the 400ppm scenario), and dedicated surfaces for solar power plants are limited to 50,000 km2 (versus 18 Mkm2 of deserts – FAO 2007 -, assumed to remain constant). Provided there are technically and economically feasible ways to transport such energy over very long distances and that political barriers related to national energy security (for instance because of too high dependency rates on electricity imports from other regions) are limited, potential for development could be much higher.

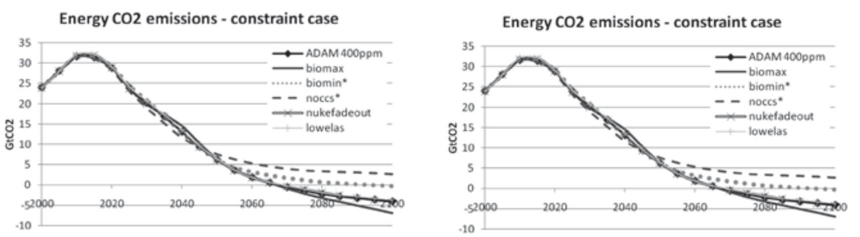
4. SENSITIVITY ANALYSIS

A sensitivity analysis has been conducted to assess the role of technological options on the emission profile and the associated abatement cost. This analysis has considered four options: (1) the role of the biomass potential; (2) the role of CCS; (3) the pace of nuclear development; and (4) energy efficiency. For each of the sensitivity cases we have produced a "no constraint" scenario and a "constraint" scenario:

- on biomass potential we have actually run two cases: one high potential of 400EJ (against 200 EJ in the scenarios presented in the previous sections), called "**biomax**"; and one low potential of 100EJ, called "**biomin**";
- in the "**noccs**" case we have excluded the CCS technology from the model;
- in the "**nukefadeout**" case, there is no construction of any new nuclear capacity and existing capacities are not replaced;
- finally, in the "**lowelas**" case, long-term price elasticities in final demand sectors have been divided by two.

Figure 16 shows that the emission levels without any carbon constraint are different from one case to another. That means that the level of abatement necessary to reach the same emission profile will be different across scenarios: similar in the 400ppm, "noccs" and "biomax"; slightly higher in "biomin"; and significantly higher in the "lowelas" and the "nukefadeout". The "nukefadeout" case is interesting in the sense that it shows the contribution of nuclear energy to emission mitigation without any carbon value (nuclear is mostly replaced by coal in the "nukefadeout" without constraint). The two scenarios "lowelas" and "nukefadeout" require cumulative reductions between the "no constraint case" and the "constraint case" by 2100 of respectively 4,200 $GtCO_2$ and 4,300 $GtCO_2$ vs. 3,900 $GtCO_2$ in the 400ppm scenario (Figure 18).

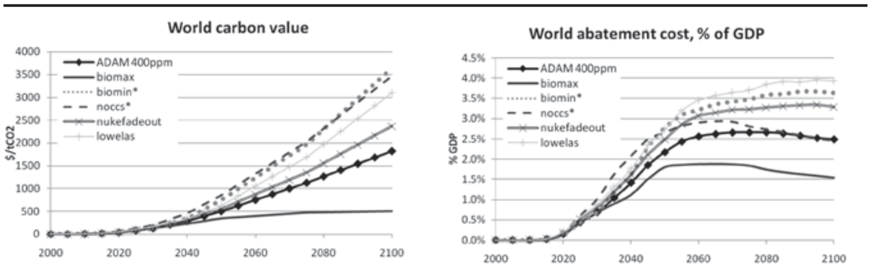
Figure 16. Sensitivity Analysis: CO_2 Emissions Without (left) and With the Constraint (right)



*In these two scenarios, the 400ppm emission profile is not reached

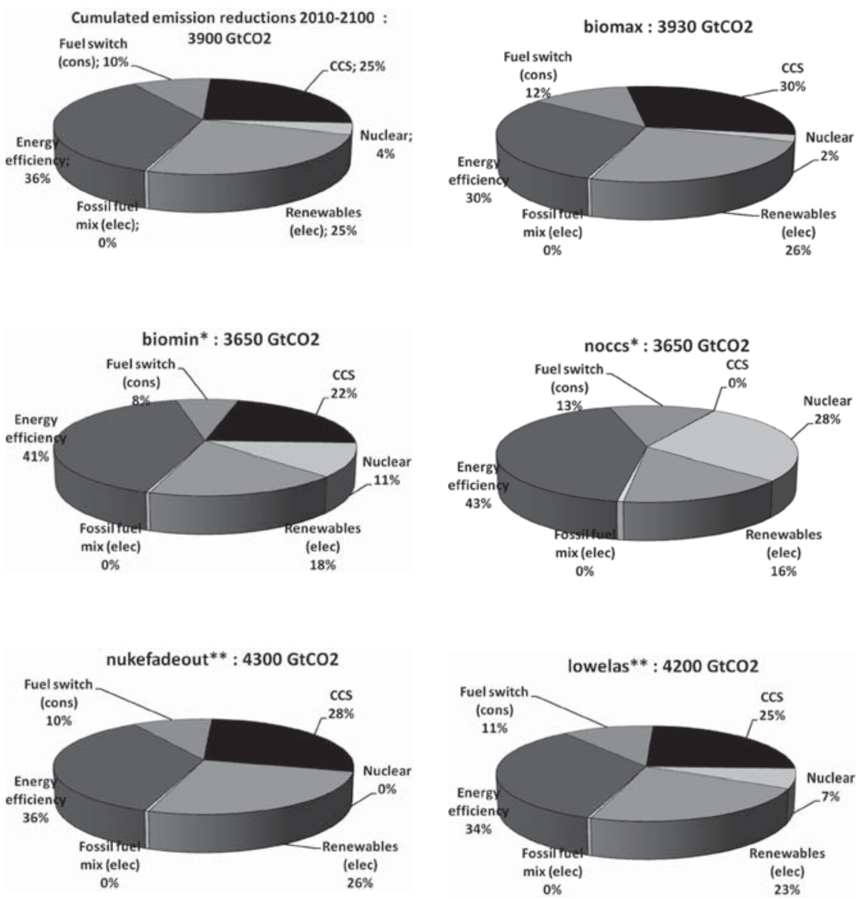
With a constraint on emissions, two cases do not reach the 400ppm emissions profile: "biomin" and "noccs", both because there are not enough stored emissions from biomass combustion. In the "noccs" case, the emissions are even kept significantly above the long-term objective (it actually lies between the 400ppm scenario and the 450ppm CO_2-eq scenario also investigated in the ADAM project but not presented in this paper). The target is reached in the three other cases, but at different marginal and abatement costs in the energy sector as shown on Figure 17. "Biomax" has an abatement cost 40% lower than the 400ppm at 1.5% GDP (and a much lower carbon value), "nukefadeout" is 30% higher (3.3% GDP), and "lowelas" (with long-term price elasticities divided by two) is 60% higher (4% of GDP). One can notice that for the "biomin", even if the target is not reached, the cost is very high - about 50% higher than in the 400ppm scenario, at more than 3.5% GDP.

Figure 17. Sensitivity Analysis: World Carbon Value (left) and Annual Abatement Cost (% GDP) (right)



*In these two scenarios, the 400ppm emission profile is not reached

Figure 18. Sensitivity Analysis: Contribution of Options to Cumulative Reductions Over 2010-2100



*In "biomin" and "noccs", the 400ppm profile is not reached (lower cumulative reductions)

**"nukefadeout" and" lowelas" require more reductions to reach the 400ppm profile due to higher baseline emissions.

The carbon value necessary to reach the emissions profile varies greatly depending on the assumptions and compared to the 400ppm scenario, from three times lower in "biomax" to twice higher in "noccs", "biomin" and "lowelas".

The contribution of the various options displayed in Figure 18 vary across the sensitivity scenarios:

- more biomass –“biomax” - leads to more CCS, more renewables in the power sector and more fuel switch in the final demand (towards biomass and electricity);
- less biomass – “biomin” - leads to the opposite;
- the absence of CCS – “noccs” – leads to a much higher contribution of nuclear, more biomass in final demand, as well more efficiency;
- the removal of nuclear induces more renewables (mostly solar and wind as biomass already reaches its potential in the 400ppm) and slightly more CCS;
- and finally the lower long-term price elasticities case(“lowelas”) leads to a similar picture as the 400ppm (more nuclear though) but at a much higher cost (as shown on Figure 17 : 4% GDP in 2100 vs 2.5% in the 400ppm).

These results show the high sensitivity of the low concentration scenario with POLES, first to biomass and CCS, and then to long-term price elasticities as regards to both the possibility of reaching such constrained emission profiles and the associated abatement cost. The absence of nuclear energy leads to higher emissions without any constraint, but it still enables the target to be reached at moderate abatement cost. However, its absence is partially compensated for by the earlier recourse to the association of biomass and CCS which, once again, underlines the dependency on these two options.

5. INSIGHTS, LIMITS AND UNCERTAINTIES

5.1 Limits and Uncertainties

When dealing with long-term energy predictions, it is of course necessary to carefully consider the quantitative results of the models. Entirely new developments in technology and socio-economic organizations and structures will occur in the coming decades, and drastically change the energy scene 50-100 years from now (Chateau 2004). One can identify three main categories of limits and uncertainties.

The first and probably most important one is related to the changes in the physical environment over the century, and to the consequent feedbacks on human activities. These changes will arise from both the growing exhaustion of resource and from the effects of climate change. As far as resources are concerned various types of conflict may arise in the competition for their control (for mineral resources, water, land and of course energy). The levels of biomass use in the energy system is one subject of concern when considering the competition with other land uses and the stability of the natural cycles. Furthermore, the availability of such resources may be considerably modified by the impact of climate change, with the consequent impacts on settlements and population movements. Because of these changes, economic growth, population dynamics or localization may differ substantially from those considered in this exercise. In this respect, the baseline scenario itself may not appear as “self-consistent”.

The second category of uncertainties concerns the technological dimension of the future. The portfolio of technologies considered is actually limited to what is currently known, already implemented or at a documented stage. However, new scientific developments could lead to dramatic changes, both regarding energy supply and energy demand technologies. Many technologies are not considered here, mostly because of a lack of information on their technical and economic performances, but they may play a significant role by 2100. On the supply side, this includes nuclear fusion, large tidal or wave energy plants, large scale electricity storage, and new applications of bio sciences. On the demand side, we are far from understanding all implications of bio and nano-technologies or understanding all applications of ICTs and their consequences on the organization of the energy systems.

The third type of uncertainty is linked to the evolution of lifestyles and social institutions in a rapidly changing environment. Deep structural changes in society and development patterns could happen regarding urbanization or organization of global and local transport systems for instance. This may occur either as a reaction to climate change or for many other endogenous reasons. Furthermore, lifestyles may evolve to adapt to a new energy system, for instance in relation to the necessary long-term development of primary renewable energies (solar, wind, ocean). All these uncertainties imply the necessity to assess the extent to which a paradigm change is needed in the ways of consuming, distributing and producing energy.

5.2 Insights

Despite the limitations exposed above, this exercise provides valuable insights on future energy policies. It shows that, in the absence of climate policies, the world energy system will be exposed to risks stemming from the increasing scarcity of conventional hydrocarbon resources. This situation may rapidly result in persistent tensions on markets, with consequent price shocks and geopolitical crises. The amounts of coal and even uranium ore used may also be a cause of concern in the longer term, i.e. in the second half of the century. In addition, of course, the levels of CO_2 emissions in the baseline case far exceed the recommendations of the IPCC and will impose major stresses to social, economic and natural systems.

It thus appears that there clearly exists a double dividend opportunity in climate change policies, in the sense that besides limiting the potentially adverse effects of an intense climate change, they also make the development of fossil energy resources more sustainable in the long term and allow limiting tensions on the international energy markets in the short and medium term. This dimension obliges us to fully consider the different categories of costs associated with the no climate policy or adaptation scenarios and is probably essential when considering the full costs and benefits of strong policies aimed at limiting the use of fossil fuels.

A key component of a long-term sustainable energy path according to the POLES model simulations (including the sensitivity analysis) appears to be the role played by the limitation of global energy consumption, both through enhanced energy efficiency triggered in all sectors by price-effects, and through the development of a new generation of very low energy and emission end-use technologies in both transport and buildings. However, low GHG emission options, such as large-scale renewable production, nuclear and carbon capture and storage will also have to be intensively developed in the very low stabilization scenarios, with an identified strong sensitivity to the recourse to energy biomass. This will raise the challenge of developing the infrastructures that will be necessary to massively and efficiently harvest renewable sources and then to transport this energy over long distances, potentially across world regions.

The massive development of renewable resources in the long term will probably rely on a complex mix of local or distributed solutions, and of large scale production and transport infrastructures. The exploration of these radically new technological systems is a key research area for the accomplishment of sustainable energy development paths in the XXI^st century.

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APPENDIX 1. SHORT DESCRIPTION OF THE POLES MODEL

The POLES model is a world simulation model for the energy sector and industrial GHG emitting activities. It works in a year-by-year recursive simulation (up to 2100) and partial equilibrium framework, with endogenous international energy prices and lagged adjustments of supply and demand by world region. Developed under different EU research programmes (JOULE, FP5, FP6, FP7), the model has been fully operational since 1997. It has been used for policy analyses by EU-DG Research (Criqui et al. 2003, Lapillonne 2007), DG Environment and DG TREN (Mima and Criqui 2006), as well as by various Europe countries Ministries and key industrial players in the energy sector (WEC 2007b).

The POLES model combines a high degree of detail on the key components of the energy systems and a strong economic consistency, as all changes in these key components are at least partly determined by relative price changes at sectoral level, regarding both demand and supply. Thus each mitigation scenario can be described as the set of consistent transformations of the initial baseline case that are induced by the introduction of a carbon constraint or carbon value/penalty.

As the model identifies 47 consuming regions of the world, with 22 energy demand sectors and about 40 energy technologies, the description of climate policy induced changes can be quite extensive. The POLES model relies on a framework of permanent inter-technology competition, with dynamically changing attributes for each technology, for which the model provides dynamic cumulative processes through the incorporation of Two Factor Learning Curves, while price induced mechanisms of technology diffusion and transformation of the energy demand are also included in the simulations.

On the supply side, the POLES model proposes a detailed description of energy supply (71 oil and gas producers with full resources discovery process) and international energy markets as well as energy transformation (full description of power and H2 capacity planning and production with load curves simulation).

The POLES model thus provides a complete system for the simulation and economic analysis of the sectoral impacts of long-term climate change mitigation strategies, even though the model does not provide the total indirect macro-economic costs of mitigation scenarios.

The model enables the production of:

- Detailed long term (2050-2100) world energy outlooks with demand, supply and price projections by country / region (47 detailed)[14]
- GHG emission abatement policy assessment (including production of Marginal Abatement Cost curves by region and/or sector), and emission trading systems analyses, under different market configurations and trading rules;[15]
- Technology improvement scenarios – with exogenous or endogenous technological change – and analyses of the value of technological progress in the context of GHG abatement policies.

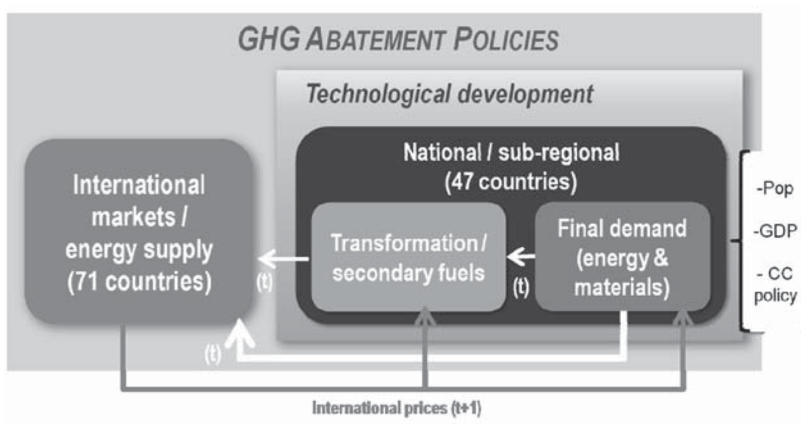
The energy balance, prices and macro-economic data for the POLES model are updated twice a year from an international energy database provided by ENERDATA, which gathers information from international and national statistics. Simulations thus usually start from data of years n-2/n-1 (eg 2007-2008 data for runs done in 2009).

In addition, technico-economic data (equipment rates, costs of energy technologies ...) are gathered from international and national statistics as well as from literature and dedicated studies by CNRS-LEPII.

Key parameters (mostly price and activity elasticities) have been calibrated within the various studies the POLES model has been used for. In addition, a substantial number of parameters are endogenously calculated by the model on historical data.

14. Examples in Criqui 2003, Lapillonne 2007, Mima et al. 2008.
15. Example in Stankeviciute et al. 2008

Figure 19. The POLES Model – A Simulation Model of the World Energy System



APPENDIX 2. REGIONAL DISAGGREGATION OF THE POLES MODEL

Table 8. Regional Disaggregation for Comprehensive Energy Balances in POLES

Large Regions	Sub-Regions	POLES countries/regions
North America		Unites States, Canada
Europe	EU-15 EU-25 EU-27	> Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, UK, (Other WE) > Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic, Baltic States, Slov-Mal-Cyp, Turkey, (Other EE)
Japan – South Pacific	South Pacific	Japan, Australia & New Zealand
CIS		Russia, Ukraine, (Other CIS)
Latin America	Central America South America	Mexico, (Other CAm) Brazil, (Other SAm)
Asia	South Asia South-East Asia	India, (Other SAs) China, South Korea, (Other SEA)
Africa / Middle-East	North Africa Sub-saharian Africa Middle-East	Egypt, Algeria-Libya, Morocco-Tunisia Sub-Saharan Africa Gulf countries, (Other ME)

Table 9. Regional Disaggregation for Detailed Oil & Gas Production in POLES

Regions	**Identified countries & residual countries aggregates**
North America	US, Canada
Europe	UK, Norway, Denmark, Netherlands Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Spain, Netherlands, Portugal, Spain, Sweden, Other Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic, Baltic States, Slov-Mal-Cyp, Turkey, Other Eastern Europe
Japan - South Pacific	Australia, Japan, Other South Pacific
CIS	Russia, Ukraine, Other CIS
South America	Argentina, Brazil, Colombia, Equador, Peru, Other South America
Central America	Mexico Other central america
South Asia	India, Rest South Asia
South-East Asia	China, South Korea, Rest South-East Asia
Africa	Algeria, Egypt, Lybia, Rest north Africa Angola, Gabon, Nigeria, Rest Sub-Saharan Africa
Middle-East	Saudi Arabia, Iran, Iraq, Kuwait, United Arab Emirates, Qatar, Rest Middle-East