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SECURE
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Long-term Storylines for Energy Scenarios in Europe

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1. Introduction

The SECURE project, carried out by 15 major European research institutions, started in 2008 and aims at building a comprehensive framework for measuring the security of energy supplies in the EU. Assessing the risks related to geopolitics, price formation and the economic and technical design of energy markets inside and outside of the EU, the SECURE project focuses on both qualitative and quantitative analyses, adopting a global as well as a sectoral approach. The models, tools and policy recommendations provided by this project will serve policy-makers to formulate energy security policies taking into account the related costs, benefits and risks.

One of the key elements of the SECURE project are various energy scenarios developed with the POLES model. The POLES model provides a tool for the simulation and economic analysis of world energy scenarios under environmental constraints. It is not a General Equilibrium, but a Partial Equilibrium Model for the energy sector, with a dynamic recursive simulation process. From the identification of the drivers and constraints in the energy system, the model allows to describe the pathways for energy development, fuel supply, greenhouse gas emissions, international and end-user prices, from today to 2050. The approach combines a high degree of detail in the key components of the energy systems and a strong economic consistency, as all changes in these key components are largely determined by relative price changes at sectoral level. The model identifies 47 regions for the world, with 22 energy demand sectors and about 40 energy technologies (including generic "very low energy" end-use technologies). Therefore, each scenario can be described as the set of economically consistent transformations of the initial Reference case (i.e. the Baseline described below) that is induced by the introduction of policy constraints.

This deliverable 3.2a has been written in addition to the previous deliverable 3.2, which was submitted jointly with deliverable 4.1 in February 2009. An additional deliverable was considered necessary, because the preliminary scenarios described in the previous submissions were developed further in the course of the SECURE project and altered sufficiently to necessitate this paper. In addition, this deliverable goes further than describing the scenario results by providing storylines aimed at putting the scenarios into various possible future global energy contexts. The aim of this paper is thus to make the scenarios better understandable by providing some key stories that lie behind them.

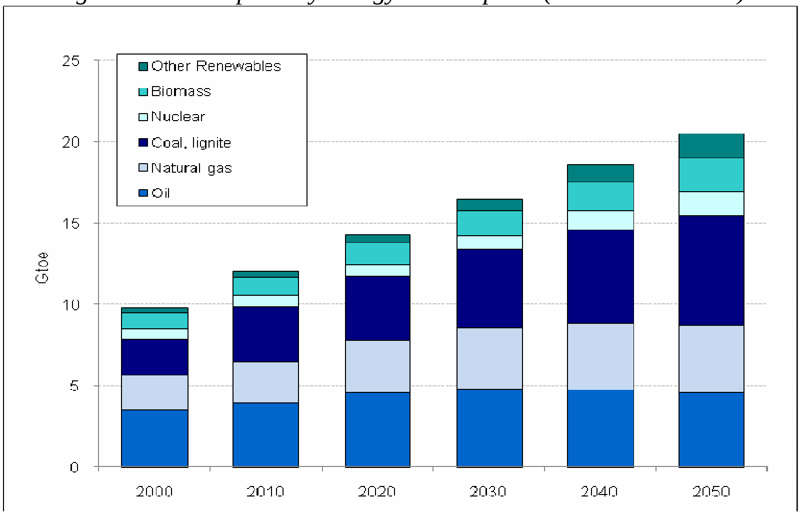
Each of the three policy scenarios will be described in the following chapters, but it was also considered necessary to describe the hypothetical case of a world without any policy intervention aimed at mitigating climate change. It is true that this baseline scenario is not only unpalatable but also unrealistic as some climate change policies, albeit largely uncoordinated and not sufficient for any sensible climate target, are already in place in many countries. However, a description of a world without climate policies allows for a good comparison of the policy scenarios with this "worst case".

For narrative reasons, all scenarios are described as if they were reality. Of course, some of the assumptions made can change quickly and reading some of the storylines in the future may lead to some confusion as to their fictional character. But it should also be noted that it lies in the very nature of scenarios and storylines to be based on various possible developments, some of which may never become reality.

2. A Hypothetical Case: The Baseline Scenario

The Baseline scenario provides a theoretical image of the development of energy systems until 2050 in the absence of climate policy. Since climate policies are a reality is should be considered merely as a reference to allow comparison with the three policy scenarios. The Baseline scenario describes a world where the human population grows from almost seven billion in 2010 to over nine billion in 2050, where global real GDP triples, and where global primary energy consumption rises by 70% (POLES model). Fossil fuels account for 83% of global primary energy consumption in 2010 but, despite continuing absolute growth, only for 76% in 2050 (see figure 1). In particular, coal consumption doubles between 2010 and 2050, oil consumption continues to increase reaching a peak around 2030, and the consumption of natural gas experiences a progressive - albeit declining - growth over the whole period. On the other hand, the share of renewables in global primary energy consumption remains modest with increases from 12% in 2010 to some 17% in 2050. As for Europe, primary energy consumption rises by some 16% between 2010 and 2050. While the share of oil decreases from 37% to 25%, the penetration of coal goes up from 17% to 25%. At the same time, the share of renewables in EU27 primary energy consumption increases to only 17% until 2050 (or 21% in terms of final energy consumption). Without a focus on domestic energy resources, the EU becomes more dependent on imports from third countries. While in 2010 the EU imported 53% of its energy consumption from abroad, this share increases to 58% in 2050.

Figure 1: Global primary energy consumption (Baseline scenario)



Source: POLES model

On the supply side, the dramatic increase in oil demand puts pressure on global oil reserves. Until 2030, oil companies continue to exploit the largest oil fields in the Middle East, those that are easy to access in North Africa, and those with the most attractive investment conditions in the North Sea. Many other areas rich in hydrocarbon resources remain unexploited because they are inaccessible to international oil companies. A radicalisation of energy nationalism in Russia and Latin America poses a threat to the required foreign investments and expertise and several oil reserves thus remain undeveloped. In addition, political instability in countries such as Iran and Iraq, as well as in Sub-Saharan Africa, reduces incentives for international companies to start new drilling (The Oil Crunch, 2008). Focusing on extracting additional volumes of petroleum from secure and well-known areas, oil companies delay their investment in non-conventional resources finding themselves unprepared to face the following oil crisis. When global oil production peaks around the year 2030, reserves start an irreversible decline leading to a 0.3% annual decrease in primary oil production between 2030 and 2050. The era of "easy oil" is once and for all over and the oil industry engages in new but more costly exploration of shale oil and tar sands in Canada, Siberia and the Arctic. Unconventional resources allow for some offsetting of the loss of capacity to depletion but the outcome is a substantial increase in oil prices to more than €110[1] per barrel in 2050.

This is a world where CO_2 emissions will more than double until 2050 (compared to 1990), pushing the concentration of CO_2 in the atmosphere to some 700 ppmv - a level which translates to a temperature increase of 5-6°C by the end of the century (IPCC, 2007). Climate change impacts would be severe, costs of damages as well as adaptation dramatic. The consequences are expected to be felt as early as 2050, and soon become irreversible. As reported by the IPCC (2007), such a dramatic increase in global temperature will eventually cause the disappearance of both Arctic and Antarctic glaciers which, in turn, will make hot extremes, heat waves, tropical cyclones and heavy precipitations more frequent and highly unpredictable. The contraction of the Greenland ice sheet contributes to rising sea levels, resulting in the number of people affected by floods to increase by 200 million until the end of the century. In addition, coastal areas in South East Asia, small islands in the Caribbean and the Pacific, as well as large coastal cities such as Tokyo, Shanghai, Hong Kong, Mumbai, Calcutta, Karachi, Buenos Aires, St Petersburg, New York, Miami and London are at risk to be wiped out (Stern, 2006).

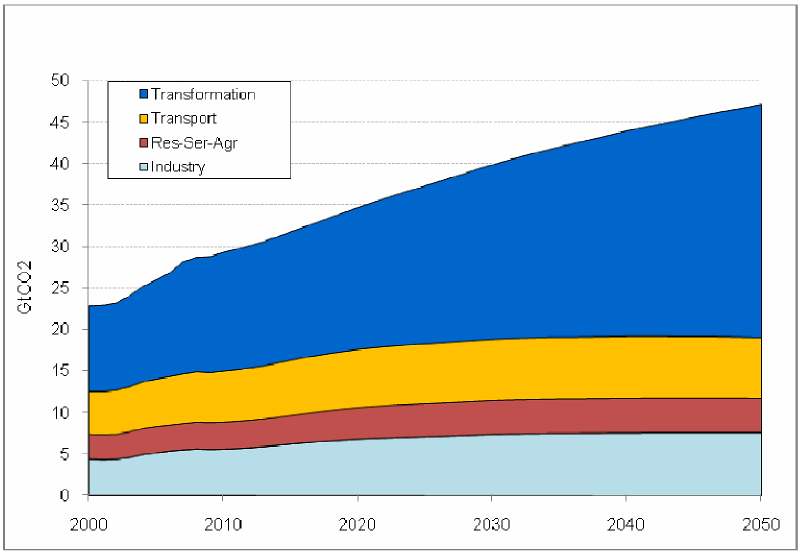
These settings match well the scenario modeled in the context of the PESETA project, which assumes a 5.4°C temperature increase in Europe until the 2080s (compared to the 1970s) accompanied by a high sea-level rise (Ciscar et al., 2009). The study estimates the combined GDP loss of five sectors of the EU economy (agriculture, river basins, coastal systems, tourism and human health) in today's terms at €65 billion, corresponding to an annual EU welfare loss of 1%, thus halving historic annual welfare growth.[2] The largest contributors to these negative economic impacts are coastal floods, followed by losses in agriculture and due to river floods. Without adaptation, around 5.5 million Europeans could be affected by coastal floods (Ciscar et al., 2009) and some European cities could even disappear under the sea level because up to 17,000 km² of land could be lost in Europe (European Commission, 2009e). The amount of people affected by river floods would double compared to the 200 million today, with annual losses reaching €15 billion (compared with an average of €6 billion today).

While northern Europe will also have to bear some severe negative consequences, such as more frequent coastal and river flooding (especially in the British Isles and central Europe), it is mainly the countries in the south, which are already economically disadvantaged, that will be most negatively affected. Some of the most severe negative impacts in the Mediterranean include prolonged periods with temperatures above the comfort zone and the accompanying effects on human health and tourism, increasing water scarcity, droughts, forest fires, desertification, decreasing agricultural

1 All financial data is quoted in Euro (2005).
2 The damages in GDP terms underestimate the actual losses. For instance, the repairing of damages to buildings due to river floods increase production (GDP), but not consumer welfare (Ciscar et al., 2009).

productivity, coastal flooding and loss of biodiversity. One of the few positive outcomes in the region will be the reduced likelihood of river flood disasters (which will be more frequent in central and eastern Europe). Thus, PESETA predicts that by the end of the century all European regions would undergo welfare losses, except northern Europe, which would experience a gain of 0.8% per year (Ciscar et al., 2009) largely due to the improvement in agricultural yields that benefit from longer and warmer growing seasons. Southern Europe could be severely affected by climate change, with annual welfare losses of around 1.4%.

Figure 2: World CO_2 emissions by sector (Baseline scenario)



Source: POLES model
Note: Res-Ser-Agr refers to the residential, service and agricultural sectors

This "reference" world is neither attractive nor politically acceptable. On the one hand, it accelerates the depletion of cheap hydrocarbon resources with all the associated consequences such as increased competition over access to these resources or rising potentials for energy shocks. On the other hand, rising GHG emissions will lead to accelerated climate change and an amplification of its impacts. The fact that global CO_2 emissions more than double between 1990 and 2050 illustrates this (see figure 2 for a sectoral breakdown of global CO_2 emissions). While these increases are lead by developments in China, India and other developing countries, industrialised countries equally fail to contribute to climate change mitigation. The EU, for example, only achieves absolute CO_2 emissions reductions after 2040, leading to a total expansion of these emissions of 9% between 1990 and 2050.

In addition to the normal scenarios, three different hypothetical events or shocks have been modelled in the SECURE scenarios. These shocks were simulated in the year 2015 and alter the outcomes of the storylines to a greater or lesser extent. The "oil and gas shock" simulates a threefold increase of oil and gas prices as a result of tensions in the market. Under the Baseline scenario, this leads to a contraction of EU primary energy consumption of 8% in the short term (2020) and 7% in the long term (2050) compared to the situation without the shock. Combining this price shock with a significant replacement of fossil based electricity with nuclear, CO_2 emissions levels in the EU could be considerably lower (-10% in 2020 and -17% in 2050) than in the absence of the shock.

Contrary to the first exercise, a shock in the form of a "nuclear accident" compels EU member states to stop building new nuclear capacities after 2015 (and to progressively phase-out existing plants). Under the Baseline scenario, the resulting nuclear production shows no significant differences in the short term (2020), but is halved in 2050. This has important implications for the EU electricity mix. A rising share of fossil fuels (coal & gas) linked with an increasing penetration of carbon capture and sequestration (CCS) technologies leads to an increase in EU CO_2 emissions of 3% by 2050, compared to the situation without a nuclear accident.

The third exercise assumes that CCS technologies fail to be deployed due to prohibitive barriers regarding their safety and cost-effectiveness. However, since CCS plays no role in the Baseline scenario, this "shock" does not alter results in the short or long term.

As noted above, the Baseline scenario represents a world without climate policy. To assess the positive and negative impacts of pro-active policy, three alternative SECURE scenarios were identified: Copenhagen Forever (Muddling Through), EU going to 30% (EU Emissions Constraint) and Johannesburg Agreement (Global Climate Regime).

3. Policy Scenario I: Copenhagen Forever (Muddling Through)

Despite decades of rhetoric on the need to take collective action to address climate change, national governments choose to focus on securing their energy supplies in the near future rather than to cooperate for a more sustainable energy system. International discussions on climate change stagnate, creating a paralysis that allows CO_2 emissions to grow continuously until 2050. The first missed opportunity for international climate change negotiations is Copenhagen 2009 when national governments – lead by a still sceptic United States Congress and some developing countries afraid of carrying a disproportional share of the costs – do not accept a significant share in reducing global GHG emissions by 50% of 1990 levels by 2050. A number of other international agreements on climate change follow, but none of them makes up for the failure experienced in Copenhagen. The latter marks the beginning of a new era of energy nationalism, opening the path towards an unsustainable global energy environment.

By 2100, CO_2 concentration stabilises at above 500 ppmv translating into a global temperature increase of 3-4°C above pre-industrial levels (IPCC, 2007). The socio-economic impacts in Europe are similar to those described in the Baseline scenario above, both in terms of type and geographical distribution. However, they are noticeably smaller in magnitude even though it should be kept in mind that the range of possible climate change effects is very wide due to various uncertainties. For example, under the above-mentioned PESETA project, a stabilisation of CO_2 concentration at 500 ppmv could result in a GDP loss of €20 billion in the studied sectors and a corresponding annual welfare loss of only 0.2% in the 2080s (Ciscar et al., 2009). Compared to today, one million Europeans would be affected by coastal floods and some 2,000 km² of land could be lost in Europe. Concerning river floods, the rise in the amount of people affected would be only one quarter of that in the Baseline scenario, with only half of the respective annual losses.

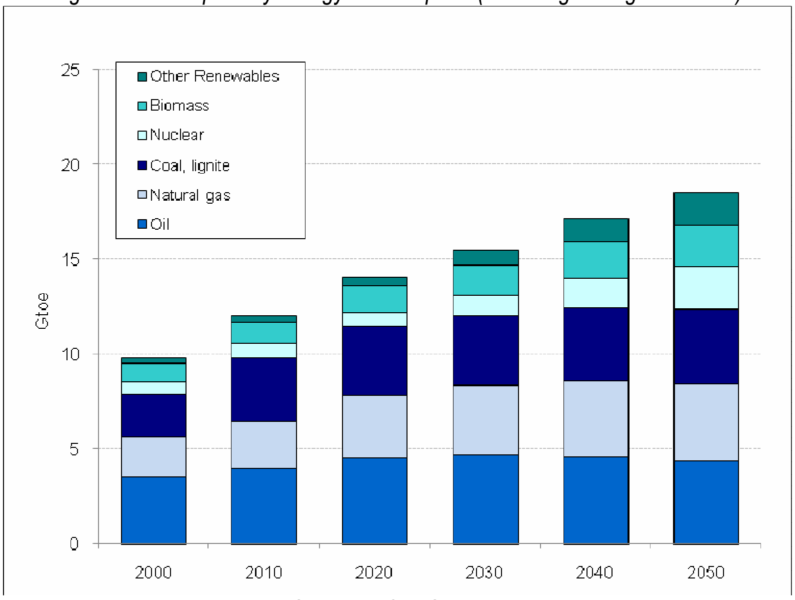
Regional differences remain within Europe. Positive impacts projected in the north include reduced demand for heating, less winter deaths, increased crop yields, longer vegetation season, extension of agricultural land areas, increased forest growth, tourism-friendly increase in the temperature of the Baltic Sea and increased hydropower potentials (Kundzewicz et al., 2009). However, health risks will increase throughout Europe due to the rising frequency of heat waves, allergy risks due to pollens, wildfires and floods. In central and eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Thus, by 2085 water runoff in Europe might decrease by some 20%. By the middle of the 21st century, extreme weather events, such as storms, hurricanes, floods, droughts and heat waves are projected to increase all over Europe. While flood risk is particularly high in eastern Europe, southern Europe is more prone to drought and heat stress to agriculture (Mechler et al. 2009).

This is a world were countries focus on their own prosperity at the expenses of a sustainable international community causing a boomerang effect of negative consequences (Shell, 2008). On the producers' side, inefficient energy systems, high energy subsidies (see e.g. Ellis, 2010; Burniaux et al., 2009) and limited development of low-carbon technologies push up domestic energy consumption and contribute to make exporting policies increasingly demanding. Due to their inefficient domestic policies, consuming countries increase their import dependence becoming politically and economically vulnerable to the decisions taken in the Middle East, the Caspian region and Africa. In turn, these dynamics affect the international discussions on climate change: while energy consuming countries would like to push for a proportional reduction of CO_2 for all regions, developing countries vindicate their right to produce more emissions than industrialised counties. The outcome is the absence of international agreements and targets which, in turn, supply a limited stimulus for national governments to push for a "green revolution".

More specifically, the failure to achieve the 2°C target is due to a generalised preference for a supply-side approach (Shell, 2008) adopted by national governments in the aftermath of the financial crisis. In order to favour a new economic boost, politicians of countries such as the United States and Japan, but also China, India and Brazil decide to limit costly and unpopular policies aimed at increasing energy efficiency and developing new clean technologies. Instead, a number of incentives for indigenous resources including coal, oil and natural gas proliferate. The result is a 22% increase in world primary production of fossil fuels between 2010 and 2030 leading to an irrational exploitation of natural resources and the achievement of a premature peak oil production level in 2030.

In a world of energy nationalism such as the in the Muddling Through scenario, the most alarming trend is a fast development of coal consumption especially in those countries where coal reserves are widely available, such as in China and the US. Partly because of a strong pressure for energy independence and partly because of relatively cheap production costs, global coal consumption increases by a fifth between 2010 and 2050 (see figure 3). This increases the risks of transport accidents via railways and via congested sea-lines. Moreover, because of relatively low long-term carbon values (€40 per ton of CO_2 in the EU and €32 in the rest of the world in 2050), CCS advances at a slow pace covering less than 10% of the electricity produced by coal in 2050. Not surprisingly, in 2050, coal is responsible for over 40% of world CO_2 emissions.

Figure 3: World primary energy consumption (muddling through scenario)



Source: POLES model

Although the increase in coal consumption is substantial, the increasing share of fossil fuels in global energy consumption is mainly due to the increase in natural gas consumption which reaches 62% between 2010 and 2050 (see figure 3). A certain share of this increase might be at the expense of further increases in coal consumption, thus benefiting CO_2 emissions. However, the application of CCS technologies in electricity production from gas is even lower than in the case of coal and gas will be responsible for about a quarter of global CO_2 emissions in 2050 (up from 18% in 2010).

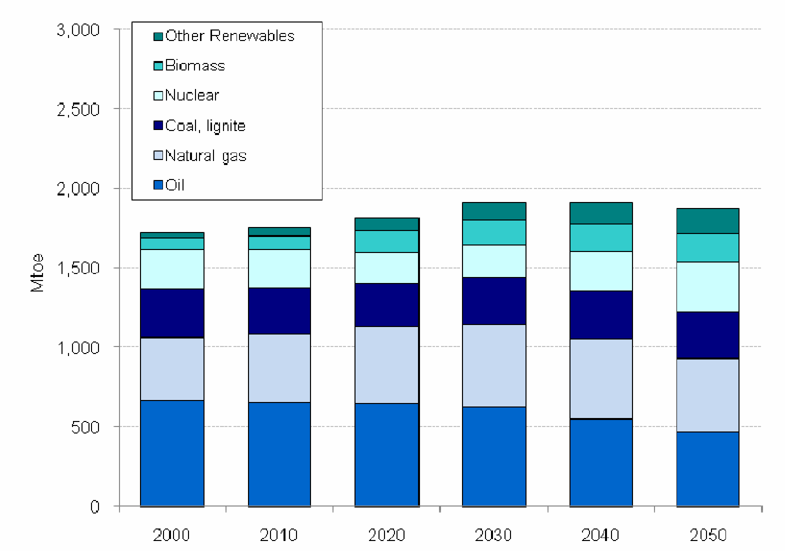
As to renewables, global primary energy production almost triples between 2010 and 2050 reaching just over 20% of total production by 2050. In terms of installed electric capacity, renewables will be able to extend their share from 24% in 2010 to 46% in 2050. The largest contribution to this increase comes from solar and biomass, but wind capacities will also be extended and will overtake the capacity of large hydro power plants by 2050. Another low-carbon energy source, nuclear energy, will see increasing capacities, especially after 2020. While production of electricity from nuclear stagnates until 2020, it more than triples between 2020 and 2050.

All in all, governments are unsuccessful in establishing GHG management schemes through carbon taxation, carbon trading and efficiency policies. Similarly, the late and half-hearted introduction of low-carbon energy sources is not able to make up for the irreversible climate change consequences caused by decades of irresponsible energy policies and no international cooperation at all. Accordingly, global CO_2 emissions rise by 67% until 2020 and 72% by 2050 as compared to 1990 levels. The slim decrease in CO_2 emissions registered between 2040 and 2050 (-3%) cannot mark a turning point in the global energy structure.

The absence of concrete international agreements on climate change and the triumph of nationalistic energy policies among major GHG emitters also have a negative impact on the implementation of EU energy and climate change policies. On the one hand, the low ambition for emission reductions worldwide keeps the carbon price within the EU low (i.e. the EU ETS allowance price) due to the availability of cheap offset credits (such as CDM) and the psychological element on the market. This makes low-carbon technologies commercially unattractive to investors, which in turn locks in any newly-built energy infrastructure and makes the cost of decarbonising the EU economy at a later stage prohibitively high. On the other hand, despite the initial commitment of European member states to stabilise global temperature at less than 2°C above pre-industrial levels, they soon realise that the overall target will not be achieved unless supported by a global agreement. The EU thus faces a hard truth: its initial efforts to support the transition towards a low-carbon energy systems were more than off-set by carbon leakage due to "free-polluting" policies of emerging economies such as China and India (see, e.g., Gros and Egenhofer, 2010). However, instead of modifying its strategy accordingly and becoming tougher in international negotiations linking energy policy to other relevant issues areas such as trade and foreign policy, the EU also adopts a nationalistic energy approach. It thus abandons its role of global leader in international energy negotiations and weakens its domestic climate policy. As described above, the outcome is an irreversible vicious circle of global inaction.

Although the EU fails to achieve its 20-20-20 targets, the initial commitment to achieve them leads to a slight improvement in the sustainability of the EU's energy systems between 2010 and 2020. Although the EU only achieves CO_2 emissions reductions of 4% in 2020 (compared to 1990), initial efforts to achieve the 20% target forced member states to limit their consumption of coal, which decreases by 7% between 2010 and 2020 (see figure 4). But the share of CCS is very slim in 2020 meaning that a quarter of CO_2 emissions in the EU in 2020 still comes from coal production. A similar downward trend is registered in oil consumption, which - although constant between 2010 and 2020 - decreases by 28% between 2020 and 2050. This is due to improvements in vehicle efficiency and bio-fuels breaking into the market. In addition, for emission abatements reasons, natural gas demand continues to grow until 2030, but declines thereafter together with total primary energy demand. The EU also fails to meet its target of sourcing 20% of final energy consumption from renewables by 2020 and only reaches it in 2050. However, there are some improvements in terms of the share of renewables in electricity production, which reaches almost 27% in 2020, reflecting an annual increase of 2.4% between 2000 and 2020. After 2020, however, the annual growth rate for renewables in electricity declines considerably. As for the third target – a 20% increase in energy efficiency – the EU is able to make some improvements by reducing the amount of energy consumed per unit of economic output by another 12% between 2010 and 2020 and by almost 40% between 2010 and 2050.

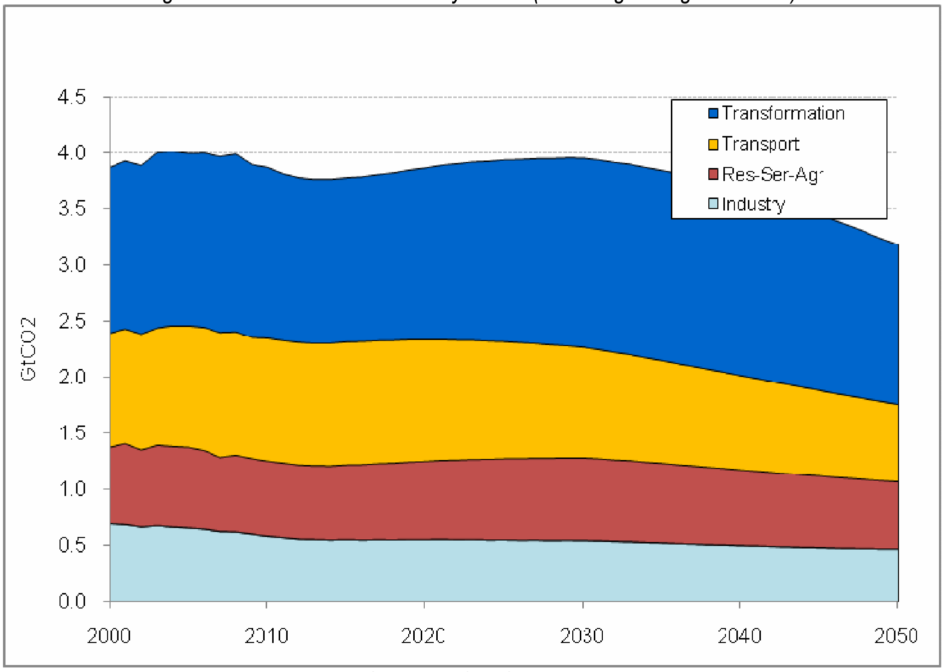
Figure 4: EU27 primary energy consumption (muddling through scenario)



Source: POLES model

Yet the picture looks slightly different after 2020 when the EU realises how marginal the impact of its Energy and Climate Change Package was on the overall level of CO_2 emissions. This event marks a turning point in EU energy policy and lines it up with the nationalist tendency already spread in the rest of the world. The most evident signal in this direction is the decision to end the EU-ETS scheme at its phase III (2013-2020), not reaching the annual 1.74% reductions planned for the phases beyond 2020. Accordingly, between 2020 and 2030, EU energy consumption increases by 0.5% annually and the increase in the share of renewable energy sources in electricity production slows down: between 2020 and 2050, their average annual increase does not go above 0.9% compared to the 2.4% of the previous period (2000-2020) Instead, electricity generation from coal rises by a third, although with a less than proportional increase in CO_2 emissions thanks to a greater diffusion of CCS technologies. In addition, starting from 2020, the share of electricity generation from nuclear goes up with the main increase registered in the period 2030-2050 (2.5% annually). The failure to support domestic low-carbon energy (electricity) sources results in a peak of EU energy import dependence of 60% in 2030. However, by 2050 the share of imports in the EU's energy mix decreases to 53%, the same level as in 2010.

Figure 5: EU27 CO_2 emissions by sector (muddling through scenario)



Source: POLES model

Note: Res-Ser-Agr refers to the residential, service and agricultural sectors

Not all the initiatives launched by the EU during the years of the 20-20-20 policy are neutralised by the new wave of nationalism of post-2020 disillusion. The investment plans undertaken by the EU before the second period continue to have positive spillovers in the following years when new nuclear power plants, CCS technologies and hybrid vehicles enter their advanced phase of production. The benefits of these spillovers are felt between 2030 and 2050 when the EU registers a decrease in CO_2 emissions of almost 20% (Figure 5). Yet the new nationalist approach adopted by European countries prevents the EU from going further than contributing to the failure of the overall objective of several past European Council Conclusions to reduce industrialised countries' GHG emissions by 80-95% by 2050 (e.g. European Council, 2009). In fact the EU only achieves emission reduction of 21% between 1990 and 2050.

Like under the Baseline scenario, three additional simulation exercises where modelled for the Copenhagen Forever scenario. The "oil and gas shock" of tripling prices in 2015 would lead to a contraction of the EU primary energy consumption by 8% in the short term (2020) and by 5% in the long term (2050) compared to the same scenario without the price shock. The shock would ultimately lead to CO_2 emission levels in the EU being lower (-10% in 2020 and -14% in 2050) than otherwise, due to the boost of nuclear in the power-generation mix.

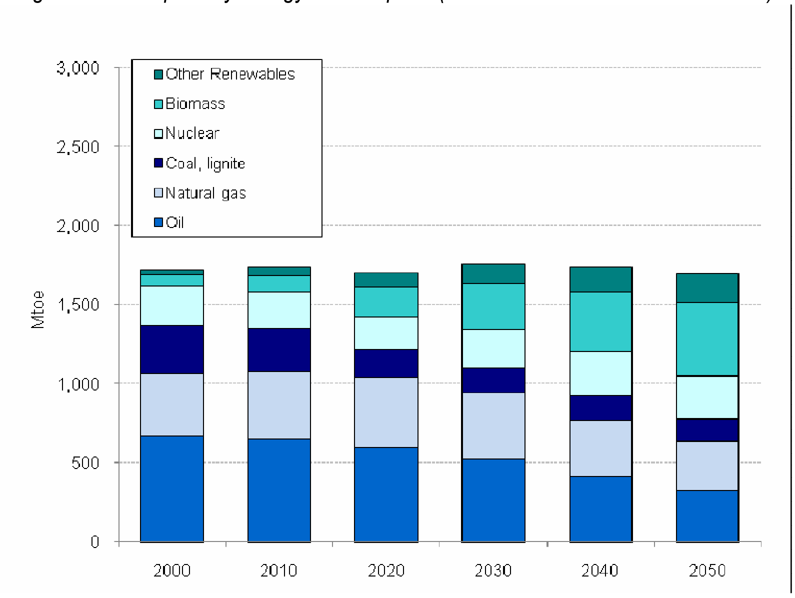
The "nuclear accident" exercise, on the other hand, would squeeze primary nuclear energy production in this scenario to less than a third of its initially projected level in 2050. The share of fossil fuels (coal & gas) including CCS would therefore be higher, resulting in the EU's total CO_2 emissions in 2050 to be 7% higher than they would be otherwise.

The third exercise, which assumes that CCS technologies fail to become deployed on a large scale, shows that although the level of electricity consumption of the EU27 would hardly change, there would be considerable shifts in the electricity mix. The use of fossil fuels would decrease, while nuclear would replace CCS with almost no impact on renewables. The result are electricity CO_2 emissions, which are 14% higher in 2050 than in the same scenario without this "CCS shock". Consequently, total CO_2 emissions in the EU would be 5% higher than otherwise in 2050.

4. Policy Scenario II: EU going to 30% (EU Emissions Constraint)

Although reaching an international agreement on climate change has not been possible, the European Union does not abandon its energy and climate change ambitions. European member states not only stick to the 20-20-20 targets by 2020 as agreed in the 2008 Energy and Climate Change Package, but they decide to go further, cutting their GHG emissions by 60% by 2050 compared to 1990 and extending the EU-ETS scheme indefinitely beyond 2020. However, in the absence of an international agreement, the overall benefits of the EU going alone and combating climate change are clearly very limited. The reduction of CO_2 emissions achieved by the EU is indeed largely off-set by the inaction of major polluting countries such as the United States, China, India and Brazil. The resulting rise in global emissions by 2050 leads to a global temperature increase and respective climate change impacts in Europe essentially identical to those in the previous scenario. The good news is that, thanks to its long-term commitment to sustainable energy policies, the EU is able to strengthen the security of its energy supplies by considerably reducing import dependence. Similarly, the EU keeps its frontrunner role in renewables, which leads to the creation of some 3 million jobs until 2020 alone, mostly in biomass, wind and hydro technologies (European Commission, 2009b). In addition, the renewables energy sector can generate a total value-added of around 1.1% of GDP until 2020, including export opportunities to countries with less developed renewables sectors.

Figure 6: EU27 primary energy consumption (EU Emissions Constraint scenario)



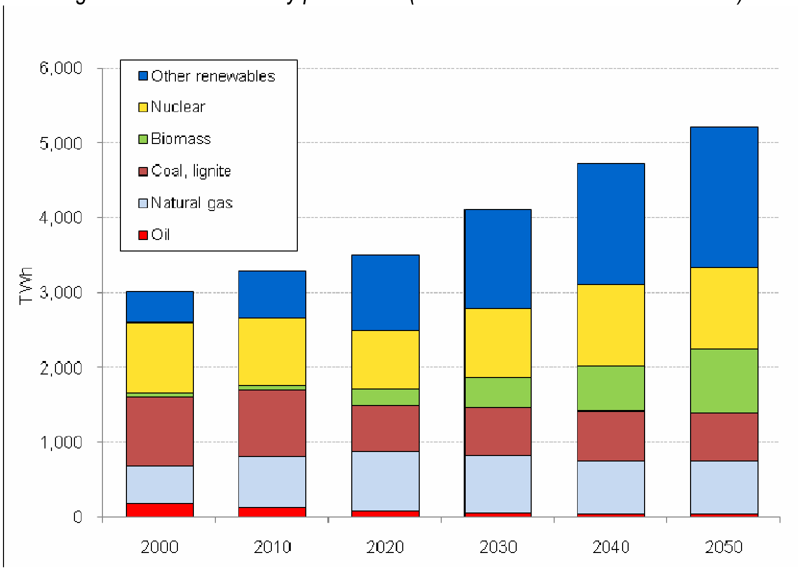
Source: POLES model

The full implementation of EU legislation on energy efficiency allows European consumers to reduce EU primary energy consumption in 2050 below 2000 levels. The biggest reduction is registered in the transport sector followed by the industrial sector. Primary demand for coal and oil declines by 48% and 50%, respectively, between 2010 and 2050 (see figure 6). However, due to rapidly decreasing domestic oil production, EU dependence on oil imports will remain at 2010 levels (i.e. when considering the percentage of oil imports in total oil consumption). The picture looks slightly different when it comes to natural gas since its role as a transition fuel does not allow for a real fall in demand any time before 2030. Thereafter, CO_2 emissions from natural gas decrease by 30% until 2050 - also due to an increasing use of CCS technologies.

Improved energy efficiency per se does not favour the penetration of renewable energy sources (European Commission, 2006a). Yet the commitment of the EU to the 20% renewable target by 2020 and to its further increase by 2050 contributes to the increase of renewables' share in the EU energy mix to some 47% in 2050. Renewable energy sources indeed account for more than a third of EU electricity generation in 2020 and for more than half in 2050 (see figure 7). The biggest growth is registered in solar energy whose contribution to electricity generation increases by a factor of 24 between 2010 and 2050. A major boost is also registered for wind power generation as well as for biomass and wastes which face a roughly fourfold increase in the same period. However, wind and biomass will supply the lion's share of renewables in electricity. Such a strong penetration of renewables helps to contain the increase of EU import dependence due to diminishing domestic production of fossil fuels thus also containing market power of oil and gas producing countries vis-à-vis Europe. Especially for natural gas, Russian threats, transit disputes and pipelines politics get less attention than they would get without such a high penetration of renewables.

It is interesting to note that despite that fact that nuclear energy is widely regarded as a low-carbon energy source, its share in EU27 electricity generation actually decreases from 27% in 2010 to 21% in 2050. This shows that the transition to a low-carbon economy is possible in the absence of a 'nuclear renaissance'.

Figure 7: EU27 Electricity production (EU Emissions Constraint scenario)



Source: POLES model

Yet the real good news for the EU is that the new energy structure leads to substantial economic benefits. Import dependence regarding all fossil fuels is reduced from 52% in 2010 to some 36% in

2050. Although this is not a security of supply benefit per se, this development reduces some of the political and technical risks in current external supplier and transit countries and thus contributes to more reliable energy supplies. Similarly, the long-term commitment of the European Union to renewable energies gives an incentive to the industry to make long-term investments in renewable-based technologies. Notwithstanding the massive start-up costs, over time economies of scales and learning by doing effects drive down the costs of electricity generation from renewables. For example, in 2030, generating electricity from wind (on-shore) power costs almost as much as electricity from coal with CCS (€24-56 per MWh vis-à-vis €36-48 per MWh); in the same year, geothermal and large hydro are able to produce electricity at cheaper costs than regular power plants (IEA, 2007).

Modelling the three simulation exercises into the scenario alters the results slightly, in line with the results of these three exercises in the previous scenario. The "oil and gas shock" of tripling prices in 2015 scenario would thus cause a contraction of the EU primary energy consumption by 6% in the short term (2020) and only by 3% in the long term (2050) compared to a situation without the shock. As expected, the price shock would ultimately lead CO_2 emission levels in the EU to be lower (-8% in 2020 and -6% in 2050) than otherwise, due to the boost of nuclear in the power-generation mix.

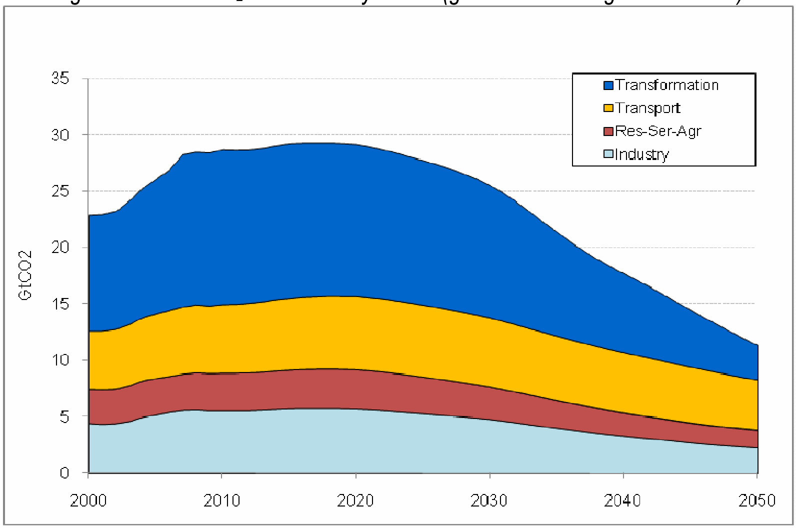
The results of the "nuclear accident" simulation exercise are also in line with those of the previous scenario, showing a long term reduction of the share of nuclear energy in the energy mix. The increasing use of fossil fuels, which serve as a substitute for some of the nuclear energy, leads to increases in long term CO_2 emissions despite available CCS technologies.

Without the availability of CCS technologies, i.e. in the context of the third simulation exercise, nuclear energy becomes more prominent in the EU's electricity mix at the expense of fossil fuels. However, because the CO_2 emissions of the remaining fossil fuels are unabated, electricity CO_2 emissions will be 43% higher in 2050 than initially projected. Consequently, total CO_2 emissions in the EU would be 11% higher than otherwise in 2050.

5. Policy Scenario III: Johannesburg Agreement (Global Climate Regime)

There is an emerging international consensus to tackle climate change globally in order to limit average global warming to no more than 2°C above pre-industrial levels. In Johannesburg in December 2011, the world has decided by 2050 to reduce global GHG emissions by 50% compared to 1990 levels. This ambitious reduction target is achieved in the Global Climate Regime scenario of POLES, where global CO_2 emissions peak around 2020 and decrease considerably thereafter (see figure 8). As a result of global climate change mitigation efforts, CO_2 concentrations are stabilised at around 400 ppmv, which translates into a 50:50 chance of limiting global average temperature increase to 2°C by the end of the century (IPCC, 2007).

Figure 8: World CO_2 emissions by sector (global climate regime scenario)



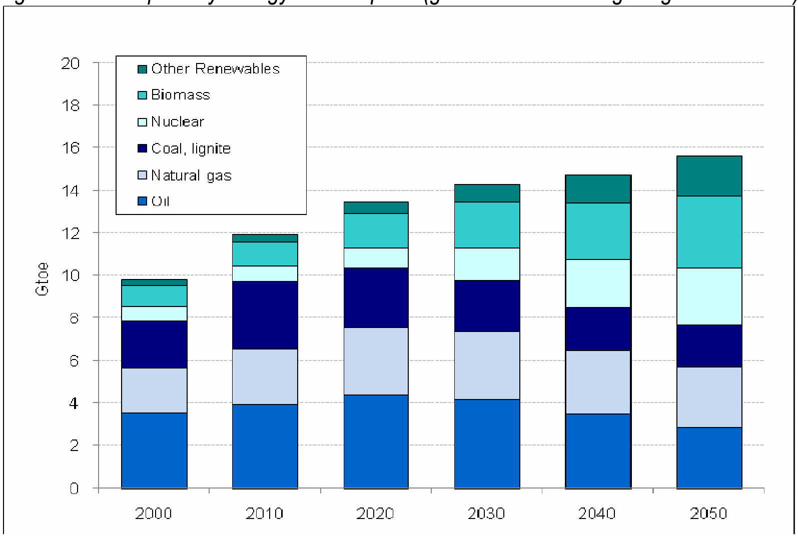
Source: POLES model
Note: Res-Ser-Agr refers to the residential, service and agricultural sectors

There are still serious climate change impacts but overall, they seem to be manageable. According to the IPCC (2007), global impacts of climate change still include Greenland ice sheet melting and accelerating sea level rise leading to frequent coastal flooding. However, the risk of these events and the intensity of weather events may be lower, leading to fewer extremes than under other scenarios (Kundzewicz et al., 2009). Large-scale transformation of ecosystems and degradation of coral reefs may also be avoided, but 100% of Arctic sea ice would likely still be lost. In addition, fewer people may be affected by climate change impacts.

At such low temperature increases the net economic impacts in Europe are likely to be positive in the 2050s, considering agricultural yields and tourism, among others. For example, fewer weeks with good conditions for skiing each year (Kundzewicz et al., 2009) could be outweighed by increased demand for non-winter tourism (Ciscar et al., 2009). By 2085, water runoff in Europe might decrease by around 10%. Neverheless, precipitation intensity will increase also for Europe, with extremes becoming more frequent than in the past.

Notwithstanding these dramatic impacts which are the consequences of human behaviours of last centuries, the world is actually better off in the Global Climate Regime than in the other scenarios. Public opinion, from Europe to Asia, has put pressure on governments to engage in sustainable energy policies for the good of present and future generations (Shell, 2008). A radical change in world energy systems based on a substantial shift from fossil fuels to low-carbon fuels is the bottom line of the 4.5% annual per capita CO_2 emissions reduction between 2030 and 2050 in this scenario. Together with only moderate global population increase in that period, this translates into global CO_2 emissions reductions of almost 4% yearly. In particular, more efficient use of energy and behavioural changes in energy consumption are the most important factors leading to a more sustainable world. In addition, the introduction of a CO_2 pricing mechanism which spreads the role-model of the EU ETS around the world, including China and the US, becomes a major incentive for modifying the structure of the global energy mix without facing major economic consequences (Shell, 2008). In this scenario description we assume two global markets for CO_2 emissions allowances, one for Annex I countries (i.e. industrialised countries) and one for non-Annex I countries (i.e. developing countries). However, in the POLES model, a global climate regime with one global market has also been modelled.

Figure 9: World primary energy consumption (global climate change regime scenario)

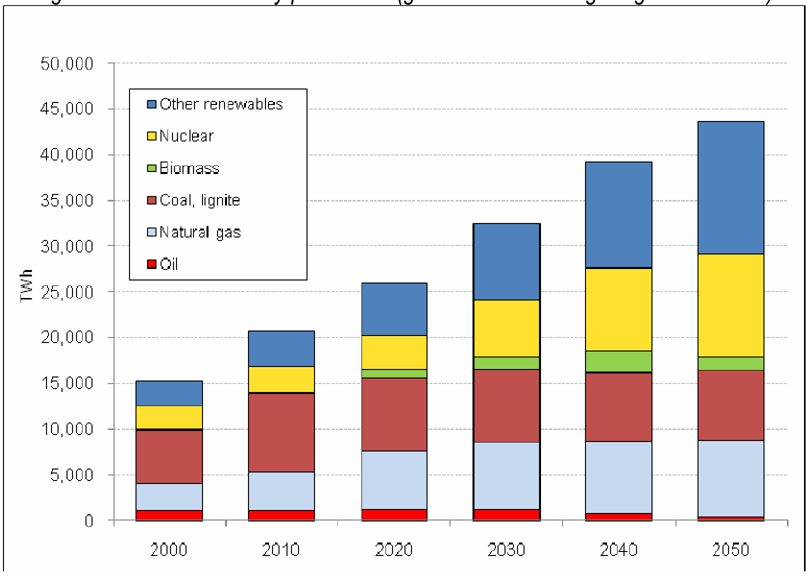


Source: POLES model

Governments of developing countries such as China and India, which have become the biggest contributors to CO_2 emissions in the world, supply incentives for electric vehicles leading to major emissions savings, given that electricity is increasingly produced with low carbon energy sources. New car technologies developed in Europe also contribute, both through exports and local use, to make the transport sector more environmentally friendly. After the peak of 2020, these initiatives translate into a world oil demand reduction of 27% by 2050 (compared to 2010 levels) leading to a reduction of the international oil price to some €58 per barrel in 2050. The real good news is the drastic reduction in coal starting from 2010 unless associated with carbon abatement technologies (Figure 9). Thanks to a high carbon price (€180 per tonne of CO_2 in 2030 and €392 in 2050 for Annex 1 countries, and €43 in 2030 and €257 in 2050 for non-Annex 1 countries), investment in carbon capture and storage becomes profitable and its use skyrockets after 2030. In fact, by 2050, some

90% of electricity generated from coal will be based on CCS technologies. Accordingly, despite the stagnation in world coal consumption after 2040, CO_2 emissions produced by burning coal fall substantially. As for natural gas, it remains an important energy source and demand only decreases slightly after 2030. But CCS will also play an increasing role, leading to some further CO_2 emissions savings.

Figure 10: World electricity production (global climate change regime scenario)

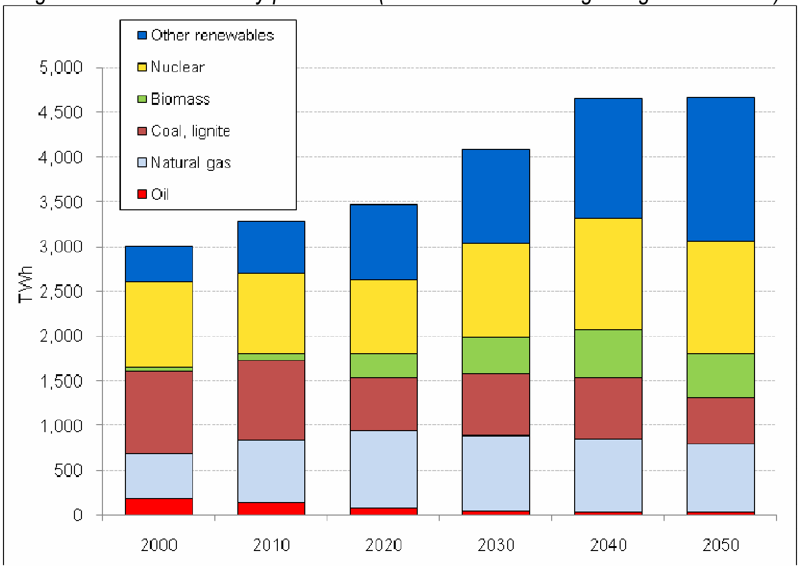


Source: POLES model

The decline of fossil fuel production and consumption is complemented by an accelerated development of non-carbon sources. In 2030, over 30% of electricity is produced from renewables and the share increases to over 40% in 2050 (see figure 10). The biggest increase is in electricity produced from solar and biomass, which expand by a factor of 161 and 34, respectively, between 2010 and 2050. Electricity generated from wind also increases significantly but by 2050 biomass overtakes wind as the second most important renewable electricity source, second only to hydro power. The role played by the two global CO_2 trading schemes is crucial in this regard: European countries and the US are allowed to compensate for some of their CO_2 emissions by exporting and installing their clean energy technologies in developing countries. The solar sector in the southern Mediterranean, for example, benefits from this. Besides renewable energies, an expansion of electricity generation from nuclear power can be expected. This development is not surprising given an increasing CO_2 price and the related increase in the competitiveness of low-carbon electricity from nuclear power plants. On top of this, international cooperation in the field of nuclear energy and non-proliferation contributes to engage countries which have been initially reluctant to agree to restrict their right to build nuclear capabilities, namely North Korea and Iran.

The commitment of major energy consuming countries - China, the US, India - to cut GHG emissions gives a further incentive to the European Union to pursue its climate policy objectives of reducing EU GHG emissions by almost 80% until 2050 compared to 1990. The largest single instrument to achieve this objective is certainly the EU Emissions Trading System (EU ETS), which was introduced in 2005 (Phase 1), improved in subsequent phases and which served as a role model for the two global trading markets (i.e. one for Annex I countries and one for non-Annex I countries). Two additional elements compose the strategy to achieve a low carbon society in the EU: improved energy efficiency and the increasing penetration of renewable in the EU energy mix (European Commission, 2009a). The former enables a stabilisation of primary energy consumption slightly below 2010 levels. In addition, fuel switch to no or low carbon fuels reduces CO_2 emissions significantly. The 80% reduction in CO_2 emissions by 2050 (compared to 1990) is thus closely related to an increase of the share of renewables in final energy consumption to some 47% in 2050. The shift towards renewable energies is particularly significant in electricity generation: in 2050, more than half of the electricity produced in the EU comes form renewables, 23% from nuclear and only 22% from fossil fuels (see figure 11). This increase in indigenous energy sources in the European energy mix means that import dependency will be considerably reduced. In fact, while in 2010 more than half of primary energy consumption originates from foreign sources, this percentage will be reduced to 31% in 2050.

Figure 11: EU27 electricity production (Global Climate Change Regime Scenario)



Source: POLES model

The substantial structural changes in the EU energy mix are achieved by policies which exploit the potential for significant cost reductions and economies of scale for renewable energy sources. These include the common development of the most promising RES technologies such as offshore wind energy, biomass and solar energy, as well as cooperation mechanisms in support of renewables. Technology-specific support policies for renewables and further major efforts in R&D will also play a major role. As for energy efficiency, a mixed basket of policies adopted by the EU includes mandatory minimum standards and labels for industrial cross-cutting technologies, energy efficiency funds to promote energy management schemes and investment in energy efficient technologies and in material efficiency, mandatory energy audits, minimum energy performance standards, top runner schemes, labeling and removal of tax exemptions (Neufeldt at al., 2009).

Although the European Commission enforces energy efficiency and renewable legislation for all member states, several measures at the national level are also implemented according to specific policy traditions and public values and cultures, which differ between member states. Respecting these differences allows for policy development at the appropriate levels and ensures best integration of all levels of society, not least the private sector, consumers and financial institutions. In addition, the success of EU climate and energy policies is linked to the adoption of both short-term (2020) and long-term targets avoiding a lock-in into unsustainable technologies and providing the necessary incentives and security for investing in technological change. Long-term predictability of policy decisions has been key to allocating further investments to decarbonise the EU economy (Neufeldt at al., 2009).

As for transport, emissions decrease by almost 4% annually in the period 2030-2050, thereby contributing significantly to European CO_2 emissions reduction efforts. A successful transport policy package composed of incentives and regulations is the main driving force. The strongest reduction of GHG emissions is for urban transport, for which hybrid vehicles, fuel efficient city cars, electric vehicles as well as public transport, slow modes, and car-sharing systems favour a radical change of the transport system. In addition, to foster the shift to low carbon technologies, the EU introduces GHG emissions limits for cars, taxation based on GHG emissions, efficiency labelling, city tolls and subsidies for market entry of new technologies. Other elements are incentives for efficiency improvements and modal-shift from road towards railways (e.g. road user charges, railway capacity increase and interoperability), the inclusion of air transport and ship transport into the EU-ETS and the increased usage of biofuels for heavy trucks and planes (Neufeldt at al., 2009).

The decarbonisation of the European socio-economic system favours the abatement of GHG emissions but also contributes to limiting the EU's energy import dependence. Given that the share of oil in primary energy consumption decreases from 37% in 2010 to 15% in 2050 and that the share of gas decreases from 25% to 16% in the same time period, total import dependence of European energy systems decreases considerably. While in 2010 some 53% of primary energy consumption depends on imports, this share decreases to 31% in the year 2050. Without the parallel depletion of hydrocarbon resources in the North Sea and in the rest of Europe, this decrease would be even more pronounced. The latter results in Europe's gas import dependency to increase from 69% in 2010 to 96% in 2050. The good news, however, is that the political risks related to this increase in import dependency – such as energy nationalism and the use of energy as a political weapon – tend to disappear. The international regime of cooperation for reducing GHG emission incentivises most of energy producing countries which used to be perceived as a threat in Europe, namely Russia, to adopt milder exporting policies in exchange for technology transfers in the field of green energy.

As in the other scenarios, three energy shocks were modelled to assess their impacts in a world governed by a global climate regime. Given that CCS technologies and nuclear energy play a substantial role in this low-carbon energy scenario, both the non-deployment of CCS and a nuclear accident in the year 2015 have larger impacts on CO_2 emissions than in the previous two scenarios. On the other hand, due to a lower dependence on fossil fuels, an oil price shock has less impact on long-run demand for oil and gas than in previous scenarios.

6. Conclusions

Given an unattractive and politically unacceptable (and unrealistic) reference scenario characterised by unsustainable energy systems and unmanageable environmental damages, the POLES model identifies three alternative policy scenarios – Copenhagen Forever (Muddling Through), EU going to 30% (EU Emissions Constraint) and Johannesburg Agreement (Global Climate Regime). Each of them highlights the possible long-term consequences of different policy choices in Europe and in the rest of the world.

The Copenhagen Forever scenario (Muddling Through) is the harshest one. It describes a world where no global agreement on climate change is ever reached neither in Copenhagen, Johannesburg nor afterwards. Instead, national governments choose to follow a nationalistic approach, looking at the perceived security of their own energy supply rather than at the sustainability of their energy policies. The absence of a global commitment to reduce GHG emissions also pushes the EU to abandon its energy and climate change ambitions initially adopted with the Energy and Climate Change package. Neither the EU's binding 2020 targets are reached nor its long-term targets for 2050. The outcome is a world where energy systems are highly inefficient, CO_2 emissions increase starkly and energy competition becomes a security issue for all energy importing countries, especially after 2020.

The overall energy and climate change trends of the EU going to 30% scenario (EU Emissions Constraint scenario) are similar to those of the Copenhagen Forever scenario. There is no collective action to address climate change while inward looking and competitive energy policies generally prevail. Only the EU is not deterred in pursuing its climate change ambitions, not only up to 2020 but also afterwards, when a new set of policies allows the EU to go further than the 20-20-20 targets. However, in this scenario the overall benefits of the EU "going alone" and combating climate change are very slim although European member states strengthen their security of energy supplies reaping some economic benefits from their "green" approach.

The Johannesburg Agreement scenario (Global Climate Regime) is the most promising scenario. Thanks to pressures of world public opinion, national governments are obliged to undertake sustainable energy policies. The result is an international agreement reached in Johannesburg in December 2011 to reduce global GHG emissions by about 50% by 2050. This ambitious commitment triggers radical changes in world energy systems including a shift from fossil fuels to low-carbon fuels, more efficient use of energy and other resources and behavioural changes in energy consumption. The EU is the leader of this "green revolution" and is therefore the first to benefit from reduced energy dependency and reduced competition for natural resources. The success of international cooperation on climate change, although not able to prevent an increase in global temperature of 2°C, makes the impacts of climate change still manageable.

The latter scenario is therefore the objective which the EU and the world as a whole should aim for. Instead, a world where the EU "goes alone" as well as a context in which no measures at all are taken to limit global CO_2 emissions look highly unsustainable.

For each of these scenarios, three possible energy shocks were simulated in the year 2015. An increase in the price of oil and gas by a factor of three leads to a contraction of EU oil and gas consumption of around 10-20% in the short term (2020), but to diminishing impacts in the longer term (2050). High prices for fossil fuels promote the application of nuclear energy with a positive effect on long term CO_2 emissions.

The second shock is a nuclear accident in the year 2015, which leads to a moratorium on new nuclear power plants after 2015 and a progressive phase-out of existing plants. Until 2020 this has no significant effects on nuclear production in Europe, but reduces nuclear production significantly until 2050. An increase in the share of fossil fuels leads to increasing CO_2 emissions in the long term, as compared to a situation without a preceding nuclear accident.

The third shock takes into account that deployment of CCS may never occur due to barriers to safe and cost effective deployment. Although this will decrease the use of fossil fuels (and increase nuclear production), CO_2 emissions are expected to increase in the long-term because they are not abated in the absence of CCS.

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