European Union post-Kyoto scenarios: benefits from accelerated technology progress

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Abstract: This paper addresses the issue of the potential benefits from technological change in post Kyoto CO_2 emission reduction scenarios for the EU energy system. The first section provides an assessment, based on the PRIMES model results, of the changes that will occur in a post Kyoto context for the EU energy system. The second section considers the contribution and the benefits of accelerating the progress of key energy technologies (six alternative technology clusters formulated and examined) in the post Kyoto context. Finally, the paper concludes with the comparison of the alternative scenarios and the corresponding benefits from technology change. The result obtained clearly indicate that any acceleration in improving low-carbon generation technologies and demand side technologies can lead to significant reductions of the compliance costs for the emission reduction scenarios.

Keywords: CO_2 emission reduction to 2030; marginal abatement costs; technological breakthrough; power generation technologies; value of technology change; European Union.

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1 Introduction

The purpose of this paper is to examine the potential impact of technological innovation in the period after 2010 for the European Union energy system. Given the longevity of most energy using equipment and capital stock, it is, in fact, after 2010 that the full impact of technological progress can be most appreciated.

To assess the benefits from accelerating energy technology progress, it is assumed that effort is undertaken in the EU to meet stringent climate change targets not only for 2010 but also beyond. A 'post Kyoto' scenario is constructed in which emissions over the period to 2030 are targeted to be significantly below their level under baseline assumptions. It is within such an emissions constrained scenario that the role of technology in the period beyond 2010 can best be evaluated.

It is also assumed that a similar effort is undertaken at a World level and therefore the EU coordinates actions with the rest of the World. To model this process, the PRIMES-based scenarios for the EU are coordinated with similar scenarios constructed with the POLES world energy model [1].

The analysis with PRIMES first refers to a post-Kyoto carbon dioxide limitation scenario coordinated with a similar world scenario in which regional permit allocations satisfying some elementary criteria of feasibility and equity are introduced. The post-Kyoto scenario is considered as a benchmark to evaluate a set of alternative cases in which technology progress improves faster. These cases are named 'technology stories' (elaborate alternative technological development scenarios) and serve for evaluating the impact of technological innovation in particular as a means of dealing with the global warming problem.

2 Technology progress and regional markets for energy technology under CO_2 reduction constraints

2.1 Impacts of the post-Kyoto scenario to the European energy system

A CO_2 emission reduction scenario for the European Union has been constructed by using the PRIMES model in order to estimate the likely degree of difficulty and possible energy system impacts of imposing restrictions to the amount of CO_2 emissions that the EU energy system will be allowed to emit in 2030 [2].

The emission target for the EU energy system under this scenario is 2605 $MtCO_2$ in 2030 representing, an emission reduction of 463 $MtCO_2$ or 15.1% from 1990 levels.

In accordance with the results for the same scenario obtained from the POLES model at the world level, a permit price of 178 Eur'90 per ton of Carbon avoided has been used for the EU post-Kyoto scenario to synchronize to the trading at world level [3].

As compared to the 2010 targets, the 'post-Kyoto' scenario involves post 2010 intensification of emission limitation. World level trading of emissions allows for a rather moderate increase of marginal abatement cost, as compared to the results for 2010 in which only Annex B countries were participating in the trading.

Table 1 Baseline and post-Kyoto emissions 1990, 2010,2030

	1990	2010		2030	
		Baseline	Post-Kyoto	Baseline	Post-Kyoto
CO_2 Emissions (Mtn CO_2)	3068	3245	2738	3597	2905
Change from Baseline (Mtn CO_2)			-507		-692
% of 1990 level		105.8	89.2	117.2	94.7

Source: PRIMES

Table 1 summarises the results of the post-Kyoto scenario and compares them with those of the baseline for 2010 and 2030 [4]. It is assumed that the economic agents fully anticipate that the emission limitation effort will intensify beyond 2010. Therefore they undertake even before 2010 emission reduction actions that are more intensive than in the case of Kyoto scenarios for 2010. In other words the agents perceive that they have continuously to buy emission permits at a constant high level as the one estimated to be necessary for the world level to reach the 2030 target. For the EU this anticipation needs an emission reduction of 11% in 2010 as compared to 1990, which is higher than the Kyoto target. This indicates that stronger effort is required in the short term to get closer to the long run post-Kyoto target in more economical terms. Since the Kyoto target for EU in 2010 is an 8% reduction from 1990 levels, the EU energy system can become an exporter of pollution permits in 2010, in fact being able to export permits for about 90 $MtCO_2$. However, in 2030 the EU energy system reduces CO_2 emissions by only 5.3% in comparison to 1990 levels and, in order to satisfy the post-Kyoto target, purchasing of pollution permits equivalent to 300 $MtCO_2$ is required.

The EU energy system adjusts by changing both the energy and the carbon intensities. The reduction in primary energy demand accounts for about half of the overall emission reduction achieved in 2010 under the post-Kyoto scenario (see Table 2). In the long run it becomes more difficult for the European energy system to further reduce primary energy needs than to modify the fuel-mix and hence reduce carbon intensity. As a result, in 2030 emissions are about 19% less than in the baseline while primary energy demand declines by only 8% from its baseline level.

Table 2 Primary fuels and CO_2 emissions, 2010, 2030

	1990	2010			2030		
		Baseline	Post-Kyoto	%Difference from baseline	Baseline	Post-Kyoto	%Difference from baseline
Gross Inland Consumption (Mtoe	**1313**	**1524**	**1397**	**-8.4%**	**1550**	**1425**	**-8.0%**
Solid Fuels	301	191	139	-27.3%	300	123	-59.0%
Liquid Fuels	543	633	551	-13.0%	602	578	-4.0%
Natural Gas	222	394	373	-5.4%	412	445	7.9%
Nuclear	181	216	227	5.2%	117	151	28.3%
Electricity	2	2	2	-6.5%	2	2	-7.4%
Renewable Energy Sources	64	88	106	19.5%	116	126	9.1%
Total CO_2 (Mtn CO_2)	**3068**	**3245**	**2738**	**-15.6%**	**3597**	**2905**	**-19.2%**

Source: PRIMES

The key factor for the 2030 drop of emissions is the big decrease in the use of solids, -59% from baseline, in combination with a significant increase of nuclear energy, +29% compared to baseline. The period beyond 2015 involves considering the decommissioning of the bulk of nuclear energy plants put in place in the 70s and 80s in Europe. In the baseline scenario it is projected that for economic reasons few of the decommissioned nuclear plants will be replaced again by nuclear. The post-Kyoto scenario, however, introduces an economic context leading to full reconstruction of the nuclear park. Under baseline assumptions, a significant comeback of solids was projected to take place beyond 2015 in power and steam generation. This was the effect of rising prices of gas. Under the carbon constraint scenarios, the implicit cost of carbon results in a significant increase in the relative price of solids and their come back does not take place. Shifts towards the use of renewable energy forms and, secondarily, natural gas also occur.

In terms of changes in final consumption, the reduction in demand accounts for about 70% of the overall reduction in emissions originating from adjustments in final energy in 2010, increasing to 72.5% in 2030 (see Table 3). The improvement of energy intensity indicators for the different demand sectors is given in Table 4.

Table 3 Impact on final demand by sector, 2010, 2030

	1990	2010			2030		
		Baseline	Post-Kyoto	%Difference from baseline	Baseline	Post-Kyoto	%Difference from baseline
Total Energy (Mtoe)	**852**	**1037**	**942**	**-9.2%**	**1085**	**1002**	**-7.6%**
Industry	257	281	263	-6.4%	279	263	-5.5%
Tertiary	110	152	126	-17.6%	187	163	-13.0%
Households	232	263	243	-7.7%	287	271	-5.4%
Transports	253	341	310	-8.9%	333	305	-8.3%
CO_2 Emissions (Mtn CO_2)	**1800**	**2001**	**1740**	**-13.1%**	**1875**	**1676**	**-10.6%**
Industry	424	376	324	-13.9%	301	262	-12.8%
Tertiary	193	212	144	-32.2%	188	149	-20.5%
Households	447	429	376	-12.2%	423	383	-9.6%
Transports	735	984	896	-9.0%	963	881	-8.4%

Source: PRIMES

Table 4 Energy intensity improvement in the demand side, 2010, 2030

indicator (1995=100)	1995	2010		2030	
		Baseline	Post-Kyoto	Baseline	Post-Kyoto
Industry (production related)					
iron and steel	100.0	88.5	80.6	59.5	51.7
non ferrous metals	100.0	83.0	82.1	64.5	61.1
chemicals	100.0	82.2	77.5	66.8	63.4
building materials	100.0	98.0	96.1	83.6	81.2
paper and pulp	100.0	94.1	91.1	76.4	74.8
food drink tobacco	100.0	97.6	94.0	86.7	84.8
engineering	100.0	96.9	92.2	81.8	79.3
textiles	100.0	97.5	93.6	86.3	84.0
other	100.0	97.1	93.3	84.6	82.0
Tertiary (value added related)	100.0	82.3	67.8	69.5	60.5
Households (income related)	100.0	78.4	72.4	60.5	57.2
Transports					
passenger (income related)	100.0	89.0	81.9	59.5	55.3
goods (GDP related)	100.0	84.6	75.3	62.9	56.0

Source: PRIMES

Demand sectors act in different ways to the introduction of emission reduction constraints. In industry and households, while in 2010 the contribution of energy and carbon intensity improvement is almost equally split, in 2030 the potential for further decrease of demand becomes limited and changes in the fuel mix become more important. In the tertiary sector improvement in energy intensity is the dominant factor for emission reduction, accounting for 55% of sectoral emission reduction in 2010 and rising to 64% in 2030. In transport the reduction in demand accounts for almost 100% of emissions reduction over the whole time horizon of the study.

As discussed in [5], the power and steam generation system of the EU appears to be the sector that can adjust in the most cost-effective way to emission reductions. The projections from the post-Kyoto scenario further justify this property of electricity and steam generation system for the long run (see Table 5).

Table 5 Impacts on power and steam generation, energy and emissions, 2010, 2030

		2010			**2030**		
	1995	**Baseline**	**Post-Kyoto**	**%Difference from baseline**	**Baseline**	**Post-Kyoto**	**%Difference from baseline**
Electricity and steam output (TWh)	**3376**	**4289**	**4133**	**-3.6%**	**5310**	**5059**	**-4.7%**
Nuclear	810	851	895	5%	456	585	28%
Hydro and Renewables	294	353	425	20%	523	494	-5%
Total CO_2 (Mtn CO_2)	**1220**	**1244**	**998**	**-19.8%**	**1721**	**1228**	**-28.6%**
Electricity and steam	1162	1201	959	-20.1%	1695	1204	-29.0%
Energy sector	59	43	39	-9.9%	26	24	-7.1%
Fossil fuel inputs in electricity and steam generation	**365**	**416**	**360**	**-13.5%**	**557**	**469**	**-15.8%**
of which	**%**						
Solids	47%	34%	29%		50%	23%	
Gas	23%	40%	47%		32%	48%	
Biomass/Waste	6%	8%	11%		8%	12%	
Efficiency rates of Electricity and steam generation	0.54	0.64	0.68		0.67	0.74	
% of CHP in steam generation	45.7%	62.5%	62.5%		80.0%	76.9%	
% of total CO_2 reduction by Electricity and steam			48%			71%	

Source: PRIMES

In the post-Kyoto scenario, for every one per cent reduction in generation output there is a six-fold decline in CO_2 emissions in 2030. Consequently, electricity and steam generation systems of the EU contribute more than 70% of the overall system reduction in emissions achieved in 2030 in comparison to baseline. The return of nuclear energy to the detriment of solids is the main contributor for this result. The increase in nuclear energy production also affects that from renewable energy forms, mainly wind energy and a 5% decrease in comparison to baseline is projected. However, the contribution of renewable energy forms to electricity and steam production remains rather unaffected. The average efficiency rate of electricity and steam generators improves by 7% from 0.67% in the baseline to 0.74% in the post-Kyoto scenario.

Table 6 Impacts on main energy system indicators, 2010, 2030

	1995	2010			2030		
		Baseline	Post-Kyoto	%Difference from baseline	Baseline	Post-Kyoto	%Difference from baseline
Energy intensity (toe/MEUR90)	240.2	186.1	170.5	-8.4%	133.7	122.9	-8.0%
Carbon intensity (tn CO_2/toe)	2.2	2.1	2.0	-7.9%	2.3	2.0	-12.2%
Import dependency (%)	46.4	54.8	49.0	-5.8%	69.5	64.7	-4.8%

Source: PRIMES

The improvement of energy intensity in the European energy system increases by 8% in 2030 in comparison to baseline (8.4% in 2010) while that of carbon intensity increases in the long run by more than 12% in 2030 (see Table 6). The decrease in energy demand leads to an improvement of the EU import dependency.

Table 7 summarises the way in which the post-Kyoto emission reduction target is achieved by the EU energy system in 2030 and the corresponding costs.

Table 7 Cost of achieving the post-Kyoto target for EU energy system, 2030

		1990	Post-Kyoto target	2030	
				Baseline	Post-Kyoto
Carbon value (EUR'90/tn of Carbon avoided)					178
CO_2 Emissions (Mtn CO_2)		3068	2605	3597	2905
of which	abated in 2030 within EU				-692
	traded from other countries				-300
Cost (MEUR'90) of	abated emissions				17228
	traded emissions				14579
	Total Cost				**31808**
	as % of GDP				0.274%

Source: PRIMES

About 70% of the CO_2 emission reduction required to satisfy the post-Kyoto target in 2030 is achieved through emission abatement within the European energy system. The corresponding cost reaches 17230 MEur'90. The remaining 30% of emission reduction required, or some 300 $MtCO_2$, is achieved through the purchase of pollution permits at a price of 178 Eur'90 per ton of Carbon traded. The total cost of achieving the post-Kyoto target reaches 31810 MEur'90 or 0.274% of EU gross domestic product in 2030.

3 Technology stories and benefits from technology change

3.1 Introduction

This section explores the implications for the European Union of accelerating the progress of key energy technologies in the demand and supply sectors over the period 2010-2030.

Each technology story is implemented as a scenario involving acceleration of technology progress and a goal about meeting the post-Kyoto emission reduction targets. It is also assumed that trade of pollution permits to the rest of the world remains unchanged at the levels of the post-Kyoto scenario. The results provide an insight for each technology story's potential and the cost savings resulting from the corresponding technological breakthrough.

3.2 The nuclear story

In this scenario, it is assumed that there is significant improvement in the technical-economic characteristics of the conventional nuclear technology, as well as the emergence of a new nuclear design.

In particular:

- For a standard large LWR, it is assumed that, whereas in the baseline case the capital cost was slightly increasing over time, in the nuclear story the cost of capital becomes about 30 % cheaper by 2030. Furthermore, fixed operation and maintenance costs were assumed to become about 35 % lower; and
- A new evolutionary nuclear design with inherent safety characteristics is introduced after 2020 with capital cost about 13 % less cheaper and operating costs about 25 % less than the LWR. This type of plant was assumed to be 30 % cheaper to construct and 50 % less cheaper to operate than in the baseline case.

The above changes make nuclear plants more competitive in terms of generating costs. The higher penetration of nuclear plants makes it easier for the energy system to achieve the CO_2 emissions abatement of the post-Kyoto scenario. The required marginal abatement cost under the nuclear story drops to 116 Eur'90 per ton of Carbon avoided, or 65% of that of the post-Kyoto scenario. Consequently, fuel costs (as perceived by the economic agents) also decrease for both the demand and the supply side.

The additional constructions of nuclear plants in 2010-30 reach 92 GW as compared to the post-Kyoto scenario. The penetration of nuclear is effected to the detriment of GTCC plants (-121 GW) and fuel cells (-51 GW). As nuclear energy facilitates meeting the emission target, the perceived cost of using fossil energy lowers in comparison to the case with no technology progress in nuclear. Therefore, some coal technologies become more competitive than using coal and represent less environmental charges than in the no technology progress case. This explains that a side effect of the nuclear story is that supercritical coal plants become relatively more competitive and their capacity reaches 191 GW in 2030 (260 GW in the baseline scenario, 95 GW in the post-Kyoto scenario). Capacities of renewable energy forms and of other plant types remain almost unchanged from the post-Kyoto scenario.

Increased investments in nuclear and supercritical coal plants, which involve centralised production, lead to smaller level of decentralisation of electricity and steam generation and to smaller share of co-generation of electricity and steam. The share of utilities in terms of electricity production increases from 77.5% in the post-Kyoto scenario to 82% in the nuclear story, while electricity produced from CHP units decreases by 5% compared to the post-Kyoto scenario. Emissions from the power and steam generation decrease by 4.5%, counterbalanced by an equal increase in the demand side.

Finally, the nuclear story leads to a reduction of average power and steam generation costs by about 15% in 2030 compared to the post-Kyoto scenario.

3.3 The clean coal story

For the purpose of this scenario three new clean coal technologies have been retained as candidates for accelerated technology improvement:

- Supercritical coal having a rate of efficiency of 51% by 2030, improve in terms of average specific capital cost (863 ECU/kW instead of 1114 ECU/kW in Baseline) and fixed maintenance costs (20 ECU/kW);
- IGCC plants improve in terms of thermal efficiency reaching by 2030 a rate of 54% (50 % in Baseline), and capital costs (1003 ECU/kW instead of 1333 ECU/kW in Baseline); and
- PFBC plants also improve in terms of capital costs (780 ECU/kW instead of 1040 ECU/kW in Baseline) and thermal efficiency reaching a rate of 47 % by 2030.

These improvements, combined with low coal prices, make clean coal technologies very attractive in comparison to natural gas plants when used mainly for base load operation. The winner within the family of clean coal technologies seems to be PFBC, to the detriment of supercritical coal plants, the capacity expansion of which decreases in comparison to the post-Kyoto scenario. In total, the clean coal story involves the construction of about 30 GW of clean coal on top of the post-Kyoto scenario in 2010-30. These also displace some of the candidate GTCC plants. The substitution of base load GTCC plants (which present a rather limited interest for cogeneration) by clean coal technologies facilitate further development of capacities related to industrial sectors, especially in 2020-30. Industries also invest in fuel cells (+23.5 GW) so as to more cover their needs for electricity and steam economically. The clean coal story induces higher penetration of co-generation, than the post-Kyoto scenario (18 GW more), implying also a higher degree of production decentralisation. Small gas plants, renewable energy forms and nuclear are not affected.

However, the evolution within the clean coal story has substantial adverse effects on CO_2 emissions. To obtain CO_2 emissions similar to the post-Kyoto scenario levels it is necessary to face a marginal carbon abatement cost of 210 Eur’90 per ton of Carbon avoided, which is 18% higher than in the post-Kyoto scenario. Although electricity and steam demand decrease by 0.5% and 0.25% in 2030, CO_2 emissions emitted by the power and steam generation system increase by 3% indicating that it is necessary to commit a much higher effort in the demand side for the achievement of the CO_2 emission reduction target.

3.4 The gas & fuel cells story

GTCC is a mature technology and investment in this type of plant is widespread around the world. In this scenario, it is assumed that there is a significant improvement of this technology over time, both in terms of thermal efficiency (64 % in 2030 compared to 60 % in Baseline) and capital cost (430 ECU/kW instead of 490 ECU/kW in Baseline). In addition, fixed operating and variable operating costs decrease by up to 55% and 20% respectively when compared to Baseline in 2030.

- The technological progress in fuel cells technology is enabled through the development of SOFC (Solid Oxide Fuel Cells), which allows for high ratios of heat to power generation. Important improvement of the technical and economic characteristics of fuel cells is assumed in the scenario: The electrical efficiency of fuel cells rises up to 70 % by 2030 (65 % by 2015);

- Capital cost becomes 25 % less than in the Baseline case;
- O&M costs are 66.7 % lower in this story.

Similar assumptions regarding capital and O&M costs are made for Fuel Cell technologies used in the demand side (transport sector).

The gas & fuel cells scenario also assumes abundance of natural gas supplies, which is reflected in lower gas prices than in the baseline and further facilitates the penetration of GTCC and smaller gas machines, as well as fuel cells. For the latter it is assumed that reforming of natural gas will be used as the main fuel source of fuel cells, in the absence of massive development of hydrogen and biofuels.

The combination of these changes provides high potential to GTCC and fuel cell plants for power generation and power and steam co-generation.

The considerable improvement of gas-based generating technologies contributes to narrow the gap in generation cost terms between large utilities and small producers. Independent producers penetrate more easily in the market, leading to significantly higher decentralisation of generation (35% in 2030 compared to 22.5% in the post-Kyoto scenario).

Up to 2020 the system is based on GTCC plants, which represent about 32% of total installed capacity. The evolution of technology over time is such that fuel cells start to be competitive after 2020. Their market shares increase substantially and reach up to 35% of total installed capacity in 2030(10% in 2020). More than 185 additional GW of fuel cells are constructed in the period 2010-2030, compared to the post-Kyoto scenario.

All other technologies, except renewable energy forms in which investment also increase (+15GW), are negatively affected. Investment in GTCC plants and clean coal technologies decrease by 73 GW and 50 GW in comparison to the post-Kyoto scenario. There is also a significant decrease in small gas turbine plants, 26 GW less, and nuclear plants, 20 GW less, comparised to the post-Kyoto scenario.

Consequently, a spectacular improvement in average thermal efficiency of both power generation and co-generation is observed. Efficiency of electricity production improves by 7.5% in 2030, while the percentage of electricity production from CHP plants reaches 39% from 22% in the post-Kyoto scenario.

As regards the demand side, the penetration of fuel cell technologies in transport, especially private cars, increases substantially in comparison to the post-Kyoto scenario (+85% in terms of passenger-km driven in 2030). However, their average market share remains small in the time horizon studied.

The gas and fuel cells story is very efficient in terms of CO_2 emissions and significantly less effort is needed to achieve the post-Kyoto target. In order to abate, within the EU energy system, the same quantity of CO_2 emissions in 2030 as in the post-Kyoto scenario, the marginal abatement cost halves reaching 93 Eur'90 as opposed to 178 Eur'90 per ton of Carbon avoided (in the post-Kyoto scenario).

Lower carbon abatement costs also lead to lower charges in using energy and fossil fuels. In conjunction with lower capital costs associated with fuel cell and other gas technologies and the lower price of natural gas, the scenario shows a significant drop of average generation costs (-20%) as compared to the post-Kyoto scenario. This further leads to increased demand for electricity and steam (+5% and +6.5% in 2030 in comparison to the post-Kyoto scenario) which, in turn, further facilitates the penetration of fuel cells and other gas technologies as enabling further economies of scale. The demand side effects, although smaller than the gains in the supply side, evidently act against limiting carbon dioxide emissions.

3.5 The renewable story

The renewable story involves considerable technological progress in intermittent power production technologies and a decrease of costs associated with the use of biomass. In particular:

- For wind turbines the capital cost decreases from 985 ECU/kW (in the baseline scenario) to 412 ECU/kW in 2030;
- For photovoltaic technologies used in buildings, the capital cost reaches 950 ECU/kW, compared to 1910 ECU/kW in the Baseline scenario for 2030;
- For small hydro plants the capital cost is reduced to 1115 ECU/kW (2060 ECU/kW in the baseline scenario);
- For tidal-ocean technologies capital costs decrease from 1831 ECU/kW (in the baseline scenario) to 990 ECU/kW; and
- For geothermal plants capital costs become 1042 ECU/kW (1928 ECU/kW in the Baseline scenario).

The O&M costs of the above technologies also lower in this story (by 50%), as compared to the Baseline scenario.

Biomass gasification is also assumed to improve in terms of capital cost (from 946 ECU/kW in the Baseline scenario to 514 ECU/kW in 2030) and O&M costs (from 29.7 ECU/kW to 19.8 ECU/kW).

The above technology improvements are enough to make renewable power plants considerably more attractive. The scenario involves additional constructions of about 130 GW of renewable technologies. About 32 GW of the above capacity expansion concerns investment in biomass gasification plants. The share of renewable energy forms reaches 28% of power and steam generation in 2030 (compared to 15% in 2000 and 20.5% in 2030 in the post-Kyoto scenario).

As a result of these developments, the power and steam production system becomes more efficient and less carbon intensive. To abate carbon dioxide emissions and reach the level of the post-Kyoto scenario, it is necessary to face marginal carbon abatement costs of 153 Eur’90 per ton of Carbon avoided, which are 14% lower than in the post-Kyoto scenario. The average production cost of electricity and steam is reduced by 7.5%.

More than two thirds of the additional investment in intermittent renewable energy forms occurs at the level of end use sectors and independent small-size generators. This development operates to the detriment of GTCC (-42 GW in comparison to the post-Kyoto scenario) and fuel cell plants (-44 GW). The shift of industrial and other small generators towards electricity production through renewable energy forms results in smaller penetration of co-generation (-3% in comparison to the post-Kyoto scenario).

Centralised utilities face a shrinking market and have to construct more for backing the system and especially the base load. In these circumstances it is more economical to increase investment in supercritical coal plants (+47 GW in comparison to the post-Kyoto scenario). However, despite the increased demand for electricity (+1.5% in 2030 compared to the post-Kyoto scenario) and steam (+1%) and the adverse effects from the reduction of gas use, CO_2 emissions from power and steam generation decrease by 2.5% compared to the post-Kyoto scenario.

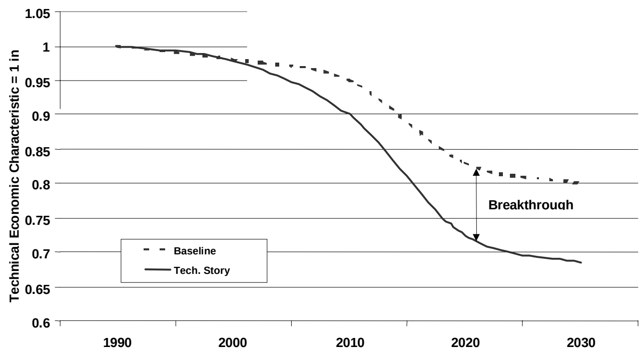
3.6 The demand side story

Demand side technologies are explicitly considered in the PRIMES model in all end use sectors. Three stylised technology generations are considered for each type, namely ordinary, improved (roughly corresponding to those best available technologies that start becoming commercially mature) and advanced (promising but not yet commercially mature technologies). The model represents each demand sector individually and formulates economic selection of technologies.

The demand side technology story, as described below, assumes that the performance of demand side technology generations evolve more rapidly than under baseline conditions. The scenario assumes that improved and advanced technology generations become available over time at more favourable terms as compared to ordinary end use techniques as they might have evolved over the same period of time.

Technology progress is formulated in cost and efficiency terms and begins from 2000, accelerates between 2010-2020 and reaches maturity by 2030. The generic time pattern of the assumed evolution of technology is shown in the following figure.

Figure 1 Pattern of technology



The demand side story is defined in a rather simple way. It is assumed that all the new technologies in end uses become 35% cheaper when compared to the baseline. This occurs gradually over time, allowing for a more rapid penetration of improved and advanced technologies. However, none of the new generation technologies ever becomes cheaper than the ordinary technology as this also dynamically evolves though capital turnover. The assumption is that the gap between improved-advanced technologies and ordinary technologies at any point in time becomes smaller than in baseline scenario. This of course facilitates the frequency of adopting improved or advanced technologies when making new investment, in particular when for example carbon emission is constrained.

The fact that future technologies are becoming cheaper and their penetration is becoming faster, has multiple indirect effects. First, through learning by doing and market maturity mechanisms, the technology that starts penetrating receives an additional boost. Secondly, because of the differentiated structure of technology mix in different energy uses and sub-sectors, substitutions between uses and sub-sectors occur. Those sub-sectors that decline experience a slowdown in technical progress along with the slowdown in capital replacement schedule. The sub-sectors that develop more rapidly benefit from accelerated capital turnover and the embedded technological improvement.

The demand side sectors are also affected by an indirect effect coming from the supply-side. Efficiency gains in demand side induce changes in the demand for electricity and steam addressed to the supply-side. The adjustment of the supply sectors also implies changes in emissions, fuel mix and selling prices. The latter influence the choices of fuel mix in the demand side.

The following table shows the improvement of energy efficiency through energy intensity indicators at the level of the different demand sub-sectors (negative values indicate improvement):

Table 8 Energy efficiency change in the demand side, 2010, 2030

Demand side story					
	% Difference from Post Kyoto			% Difference from Post Kyoto	
	2010	2030		2010	2030
Industry					
integrated steelworks	-1.4%	0.3%	cement	-0.9%	-3.5%
electric processing	-0.7%	-3.7%	ceramics	-1.5%	-3.9%
primary aluminium	-0.9%	-9.4%	glass	-1.0%	-3.1%
secondary aluminium	-0.9%	-4.0%	glass recycled	-1.2%	-4.2%
copper	-1.2%	-3.9%	other building materials	-1.3%	-3.5%
zinc	-1.6%	-4.1%	pulp	-1.3%	-4.4%
lead	-1.4%	-3.7%	paper	-1.4%	-5.0%
other non ferrous products	-0.9%	-3.9%	food, drink, tobacco	-0.9%	-4.9%
fertilisers	-1.0%	-5.0%	engineering	0.0%	-4.4%
petrochemical	-2.2%	-5.1%	textiles	-0.7%	-4.7%
inorganic chemicals	-0.3%	-4.2%	other industries	-0.1%	-4.1%
low energy chemicals	-1.0%	-5.2%			
tertiary	3.1%	-8.2%	households	-1.4%	-7.6%
passenger transports (income related)	3.0%	-9.8%	goods transports (GDP related)	4.2%	-3.3%
Vehicle efficiency					
passenger transports (toe/Mpkm)	2.3%	-10.4%	goods transports (toe/Mtkm)	2.4%	-4.8%
Gross Inl Cons / GDP (toe/1990MECU)	1.5%	-4.1%			

Source: PRIMES

The demand side technology progress, as defined in this scenario, induces significant (but not dramatic) energy efficiency improvements, in comparison to the post-Kyoto scenario. The effects are more pronounced in the domestic sector (households and tertiary) and in transport and in particular over the long-run.

High efficiency improvement as observed in the demand side leads to a significant decrease of the effort needed to achieve the post-Kyoto target in 2030. The corresponding marginal carbon abatement cost drops to 79 Eur'90 per ton of carbon avoided, or 45% of that required in the post-Kyoto scenario. Demand side CO_2 emissions in 2030 decrease by 7.7% allowing the supply side for undertaking less emission reduction effort.

The introduction of improved technologies in the demand side results in a decrease of electricity (-10% in 2030 compared to the post-Kyoto scenario) and steam demand (-2.5%), leading to a further decrease of overall investment requirements in 2010-30 by 91 GW. The reduction in electricity and steam demand affects mainly industrial and other small electricity and steam generators. The system becomes more centralised (+5% in terms of electricity production). The share of electricity production from CHP plants drops by around 8 percentage units in 2030 compared to the post-Kyoto scenario (from 22% to 14.3%).

As a consequence, investment in GTCC and fuel cell plants decrease between 2010 and 2030 by 128 GW and 86 GW respectively. The supply sector facing less emission reduction restrictions and corresponding charges on fossil fuels render supercritical coal plants to become more competitive, and their capacity increases (+102 GW). For other reasons (related to load management) renewable energy forms find more room to develop (+15 GW). Other power technologies, like nuclear and peak load plants, are not affected.

3.7 The 'all technologies' story

The 'all technologies' story is a rather unrealistic scenario, which assumes that technological breakthrough will, occur simultaneously in all the different clusters of technologies examined above. The reason for running this scenario is that it helps to evaluate the role of each cluster of technologies in the presence of a general improvement in technology.

Demand side technologies seem to be the dominant factor among the technology clusters, at least when examining the demand side sectors. Consequently one should place high importance on demand side technology progress for achieving the post-Kyoto emission reduction target within the EU. Table 9 summarises the improvement of energy efficiency indicators (through energy intensity indicators for which negative values show improvement) at the level of the different demand sub-sectors for 2030, and compares to the corresponding improvement under the demand side story.

In some cases, such as the tertiary and households sectors, the improvement under 'all technology progress' is lower than when technology progress takes place only in demand side. This can be explained by the price-adjusting electricity demand in these sectors. In the 'all technology progress' case, supply-side technology progress eases the supply of electricity and facilitates higher demand for electricity in these sectors. This counteracts the direct effects of demand side progress enabling electricity saving.

Carbon dioxide emissions from demand sectors fall by about 7% in comparison to the post-Kyoto scenario, reflecting the importance of demand side technology improvement.

The high efficiency improvement observed in the demand side, combined with the availability of improved technologies in the supply side, greatly ease the meeting of emission limitation targets. The marginal carbon abatement cost needed to achieve the post-Kyoto target becomes only 40 Eur'90 per ton of Carbon in 2030, the lowest among all scenarios examined.

Technological improvement in the demand side leads to a decrease of electricity demand by 2.5% in 2030 compared to the post-Kyoto scenario, while steam demand remains rather unaffected. The demand side savings overcompensate the supply-side effects that because of technology improvement lower costs and push demand upwards.

As in the case of the demand side story, there is higher centralisation and lower contribution of CHP, +4.5% and –4.5% respectively in terms of electricity production. Investment requirements decrease by 33 GW in 2010-30.

Nuclear energy (+31 GW), PFBC clean coal technology (+66 GW) and fuel cells (+27 GW) exhibit gains in terms of capacity expansion. This occurs to the detriment of supercritical coal plants (-71 GW), GTCC plants (-60 GW) and small size gas turbines (-29 GW). Renewables (+4 GW) and conventional thermal plants (-1 GW) remain rather unaffected. Power and steam generation emits more CO_2 emissions under this scenario than in the post-Kyoto scenario (+7.5%). These additional CO_2 emissions are counter-balanced in the demand side and therefore the same emission reduction target as in the post-Kyoto scenario is met.

Table 9 Energy efficiency improvement in the demand side, 2010, 2030

Demand side technologies in All technology story versus Demand side story					
	% Difference from Post Kyoto in 2030			% Difference from Post Kyoto in 2030	
	Demand side	All technology		Demand side	All technology
Industry					
integrated steelworks	0.3%	3.7%	cement	-3.5%	-3.0%
electric prossesing	-3.7%	-3.4%	ceramics	-3.9%	-3.2%
primary aluminium	-9.4%	-9.3%	glass	-3.1%	-2.3%
secondary aluminium	-4.0%	-3.3%	glass recycled	-4.2%	-3.5%
copper	-3.9%	-3.1%	other building materials	-3.5%	-2.7%
zinc	-4.1%	-3.4%	pulp	-4.4%	-3.8%
lead	-3.7%	-3.1%	paper	-5.0%	-4.5%
other non ferrous products	-3.9%	-3.0%	food, drink, tobacco	-4.9%	-4.3%
fertilisers	-5.0%	-4.1%	engineering	-4.4%	-3.4%
petrochemical	-5.1%	-4.9%	textiles	-4.7%	-4.0%
inorganic chemicals	-4.2%	-3.4%	other industries	-4.1%	-3.3%
low energy chemicals	-5.2%	-4.6%			
tertiary	-8.2%	-3.4%	households	-7.6%	-5.4%
passenger transports (income related)	-9.8%	-8.6%	goods transports (GDP related)	-3.3%	-1.3%
Vehicle efficiency					
passenger transports (toe/Mpkm)	-10.4%	-9.4%	goods transports (toe/Mtkm)	-4.8%	-3.5%
Gross Inl Cons / GDP (toe/1990MECU)	-4.1%	-2.1%			

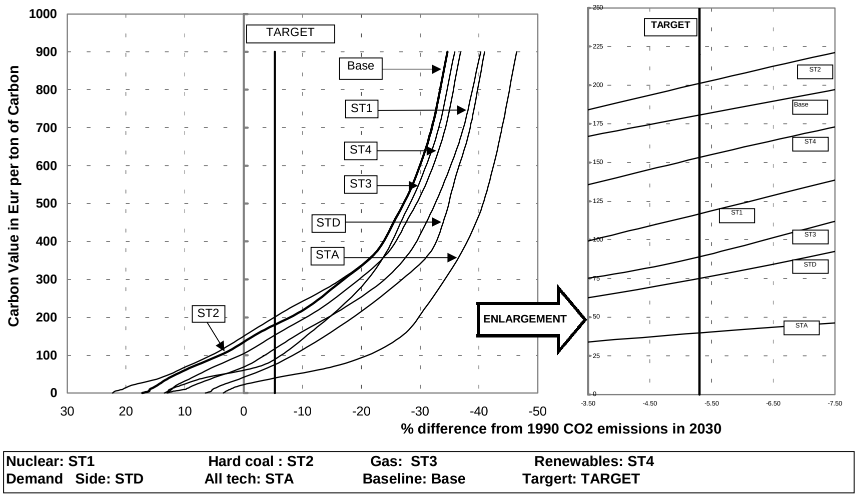
Source: PRIMES

4 Comparison of the alternative technology stories and evaluation of benefits from technology change

The marginal abatement cost curves for the different technology stories are illustrated in Figure 2.

As mentioned before the effort of meeting an emission reduction target is eased when a technology progresses more than under baseline conditions. In other terms, the cost of meeting a target becomes lower because of the technology progress. This cost saving represents some of the benefits gained from the technology progress and is termed ‘value of technology change’. Evidently this definition makes reference to the climate change objectives, while in real society other targets and issues might be of equal or higher concern. Therefore in this paper the term ‘value of technology change’ is used relatively to climate change compliance costs.

Figure 2 Marginal abatement cost curves of technology stories, 2030



Source: PRIMES

To meet the emissions target (-5.3% in comparison to baseline for 2030) a technology story involves less total costs than the post-Kyoto scenario, which is derived from baseline technology progress assumptions. The corresponding cost savings are estimated as the area below the marginal abatement cost curves and is defined as the value of technology change associated with the corresponding technology story in relation to climate change objectives (see Table 10).

Table 10 Value of technology change in achieving the post-Kyoto target under alternative technology stories, 2030

	Post Kyoto	Nuclear Story	Hard coal story	Gas and fuel cells story	Renewables story	Demand side story	All technologies stories
Required carbon value (EUR'90 per tn of carbon avoided)	178	116	210	93	153	79	40
Cost of abating CO_2 emissions within the EU energy system (MEUR'90)	17228	7153	20642	7261	12140	4264	1740
as % of GDP	0.15%	0.06%	0.18%	0.06%	0.10%	0.04%	0.02%
Value of technology change (MEUR'90)		10075	-3413	9967	5088	12965	15488
as % of GDP		0.09%	-0.03%	0.09%	0.04%	0.11%	0.13%

Source: PRIMES

The value of technology change is positive in all cases except the clean coal story where technology change acts as a missed opportunity involving a negative value of technology change (-0.03% of European Union GDP in 2030). The highest value of technology change is observed, as expected, in the ‘all technologies’ story (0.13%), followed by the demand side story (0.11%). The significant emission and cost gains in the supply side, resulting from the improvement in the demand side, explain why these scenarios involve high benefits from technology progress. The nuclear and the gas and fuel cells stories involve benefits from technology progress that are of the same order of magnitude, representing about 0.09% of European Union GDP in 2030. Finally, the value of technology change in the renewable energy story is rather limited (0.04% of GDP). This is due to the high penetration of renewable energy forms in the post-Kyoto scenario, in combination with the limitations imposed regarding the availability of renewable energy.

In terms of capacity expansion under the different technology stories and in comparison to the post-Kyoto scenario, one of the most interesting findings is the observed higher investment in clean coal technologies to the detriment, mainly, of GTCC plants. The driving force of this result is the perception of lower environmental charges associated with fossil fuels when technology progresses faster than in baseline. In a context that seems to be easier for the achievement of the post-Kyoto target, clean coal technologies become more competitive compared to baseline technologies as under the post-Kyoto scenario. This is of course an adverse effect with respect to emission targets, which reduces the gains from technology progress in terms of compliance cost savings.

The highest additional investment requirements are found in the renewables story reflecting the intermittent character of renewable energy forms. It must be mentioned here that biomass gasification plants are grouped within conventional thermal technologies (+32 GW in renewables story). In general, renewable energy forms seem to gain market shares within the context of almost all different technology stories, which is not the case for any of the other plant types.

Table 12 summarises the results for some key indicators of the EU energy system for the different technology stories. The different technology stories are generally beneficial for all energy policy objectives, other than emission reduction for climate change. For example security of supply is improved, as far as measured by an overall import dependency indicator, except in the case of the gas story. The energy policy objective related to economic competitiveness is positively addressed in case of technology progress, except in the case of clean coal development.

Table 11 Changes in capacity expansion compared to the post-Kyoto scenario, 2010-30

	Nuclear story	Hard coal story	Gas and fuel cells story	Renewables story	Demand side story	All technology stories
Nuclear	72	0	-20	0	0	31
Conv. Thermal	6	-3	-3	32	5	-1
Clean Coal	0	45	-4	-7	0	66
Supercritical coal	96	-16	-46	47	106	-71
GTCC	-121	-59	-73	-42	-128	-60
Small size Gas plants	11	3	-26	9	-2	-29
Fuel Cells	-51	23	185	-44	-86	27
Hydro-Renewables	6	-1	15	97	13	4
TOTAL	17	-8	28	92	-91	-33

Source: PRIMES

Table 12 Key indicators of the EU energy system for the different technology stories, indexed to 100 for the post-Kyoto scenario in 2030

	Post Kyoto	Nuclear story	Hard coal story	Gas and fuel cells story	Renewables story	Demand side story	All technology stories
Import dependency	100.0	90.4	99.2	104.8	97.4	95.2	96.9
Energy intensity	100.0	106.2	99.2	99.0	100.6	95.9	97.9
Carbon intensity	100.0	94.2	100.9	101.4	99.0	104.3	102.2
Average electricity and steam production cost	100.0	85.9	102.4	79.8	92.5	84.2	69.8
Change in cumulative CO_2 emissions 2010-2030 (Mtn CO_2)		1085	-950	1813	646	403	584

Source: PRIMES

References and Notes

1 Kouvaritakis, N., Criqui, P. and Thonet, C. (2000) 'World post-Kyoto scenarios: benefits from accelerated technology progress', *Int. J. Global Energy Issues,* Vol. 14, Nos. 1-4, pp. 184-203.

2 The following formulae was used in order to derive the CO_2 emissions target for the EU for 2030 under the assumed emission reduction scenario in the post Kyoto period:

$$Target_{2030} = (Target_{2010})^2 \; / \; Emissions_{1990}$$

3 The difference between the PRIMES model and the permit price resulting from the POLES model led to a redefinition of carbon values (permit prices) used in PRIMES. For a more detailed discussion of the issue, see also [6].

4 Capros, P. and Mantzos, L. (2000) 'The European energy outlook to 2010 and 2030', *Int. J. Global Energy Issues,* Vol. 14, Nos. 1-4, pp. 137-154.

5 Capros, P. and Mantzos, L. (2000) 'Kyoto and technology at the European Union: costs of emission reduction under flexibility mechanisms and technology progress', *Int. J. Global Energy Issues,* Vol. 14, Nos. 1-4, pp. 169-183.

6 Capros, P. and Mantzos, L. (1999) *Energy system implications of reducing CO_2 emissions: analysis for EU sectors and member-states by using the PRIMES ver.2 energy system model*, final report to Directorate General for Environment (DG-XI) of the European Commission.

Bibliography

1 Capros, P. *et al.* (1998) *The PRIMES energy system model – reference manual*, National Technical University of Athens, document as peer reviewed by the European Commission, Directorate General for Research.

2 Capros, P., Mantzos, L., Criqui, P., Kouvaritakis, N., Soria, A., Schrattenholzer, L. and Vouyoukas, E.L. (1999) *Climate technology strategies 1. Controlling greenhouse gases. Policy and technology options*, Springer-Verlag, Berlin.

3 Capros, P., Georgakopoulos, P., van Regemorter, D., Proost, S., Schmidt, T.F.N., Koschel, H., Conrad, K. and Vouyoukas, E.L. (1999) *Climate technology strategies 2. The macro-economic cost and benefit of reducing greenhouse gas emissions in the European Union*, Springer-Verlag, Berlin.

4 Capros, P., Mantzos, L., Vouyoukas, E.L. and Petrellis, D. (1999) 'European energy and CO_2 emission trends to 2020', *The Bulletin of Science Technology and Society*, Vol. 19, No. 6, Sage Publications Inc., Thousand Oaks, California, USA.

5 Capros, P. *et al.* (1999) 'European Union energy outlook to 2020', European Commission, Directorate General for Energy DG-XVII, special issue of *Energy in Europe*, catalogue number CS-24-99-130-EN-C, ISBN 92-828-7533-4.

6 Criqui, P., Cattier, F., Kouvaritakis, N. and Thonet, C. (1998) *Technological scenarios, climate change and emission trading: EC-IEA study on energy technology and climate change simulations using the POLES world model*, IPTS, Seville.

7 Criqui, P. and Viguier, L. (2000) 'Kyoto and technology at world level: costs of CO_2 reduction under flexibility mechanisms and technical progress', *Int. J. Global Energy Issues*, Vol. 14, Nos. 1-4, pp. 155-168.

8 Ellerman, A.D., Jacoby, H.D. and Decaux, A. (1998) 'The effects on developing countries of the Kyoto Protocol and CO_2 emission trading', *MIT Joint Program on the Science and Policy of Global Change*, Report No. 41, Cambridge, MA.

9 European Commission (1995) *The PRIMES project*, DG-XI, publication of the European Commission, EUR 16713 EN, August.

10 US Energy Information Administration, Department of Energy, (1998) Scenario of US carbon reductions-potential impacts of energy-efficient and low-carbon technologies by 2010 and beyond, Five Labs study.

11 Grubb, M. and Edmonds, J. (1998) 'The cost of limiting fossil-fuel CO_2 emissions, a survey and analysis', *Annual Review of Energy and Environment* 18.

12 Parry, I.W.H. (1997a) 'Pollution regulation and the efficiency gains from technological innovation', *Resources for the future*, Discussion paper 98-04, Washington, DC.

13 US Energy Information Administration, Department of Energy, (1997) *Technology opportunities to reduce GHGs*, October

14 US Energy Information Administration, Department of Energy, (1998) *Impacts of the Kyoto Protocol on US energy markets and economic activity,* October.

15 Ybema, J.R., Lako, P., Kok, I., Schol, E., Gielen, D.J. and Kram, T (1997) *Scenarios for Western Europe on long term abatement of CO_2 emissions*, ECN, December.