European Energy and CO_2 Emissions Trends to 2020: PRIMES model v.2

P. Capros
L. Mantzos
National Technical University of Athens

L. Vouyoukas
Independent Consultant

D. Petrellis
National Technical University of Athens

The purpose of this article is to present a summary of a consistent European Union (EU) energy and energy-related emissions outlook for the period to 2020. The material presented here is based on quantitative analysis and on a process of communication with and feedback from a number of energy experts and organizations. All the results presented for EU energy trends are based on the PRIMES partial equilibrium model for the European energy system, version 2. The PRIMES model provides simulation of the energy system and the decisions of the agents and the markets, covering in detail several sectors, uses, and technologies. The results of this analysis indicate that the EU will not meet the obligations for greenhouse gas emissions reductions it undertook at Kyoto unless it introduces policy initiatives for the abatement of energy-related emissions. Although the industrial, tertiary, household, and transportation sectors can all make significant contributions to CO_2 emissions reductions, the electricity- and steam-generation sector appears to offer the greatest potential because of its relative flexibility in terms of technology and fuel choice. Finally, when the only criterion for emissions reductions is economic efficiency, our analysis indicates that reduction levels differ significantly among EU countries.

Key words: *Energy analysis, energy forecasting, energy market, environment, European Union*

Key Assumptions

European Union (EU) population is projected to increase by only 12 million people in the period to 2010 and to be effectively stable after that. Economic growth in the EU is expected to be just under 3% in the short run, but it is assumed that, despite the generally favorable overall international context, the EU growth rate after 2000 will decelerate to levels that are consistent with long-run historical trends. In the period 2000-2010, the annual economic expansion is projected to be around 2.4%, whereas in the period after 2010, it is limited to less than 1.8%.

The long-established trend of restructuring EU economies away from the primary and secondary sectors and toward services and high-value-added products (less material- and energy-intensive products) is assumed to continue, although the pace of change is expected to decelerate in the long run.

The baseline scenario is based on the assumption that EU policies currently in place will remain unchanged. These include the further development of the liberalized electricity and gas markets in the EU, further improvement of energy technologies in both the demand and supply sides, the continuation of support of renewables and cogeneration, the extension of

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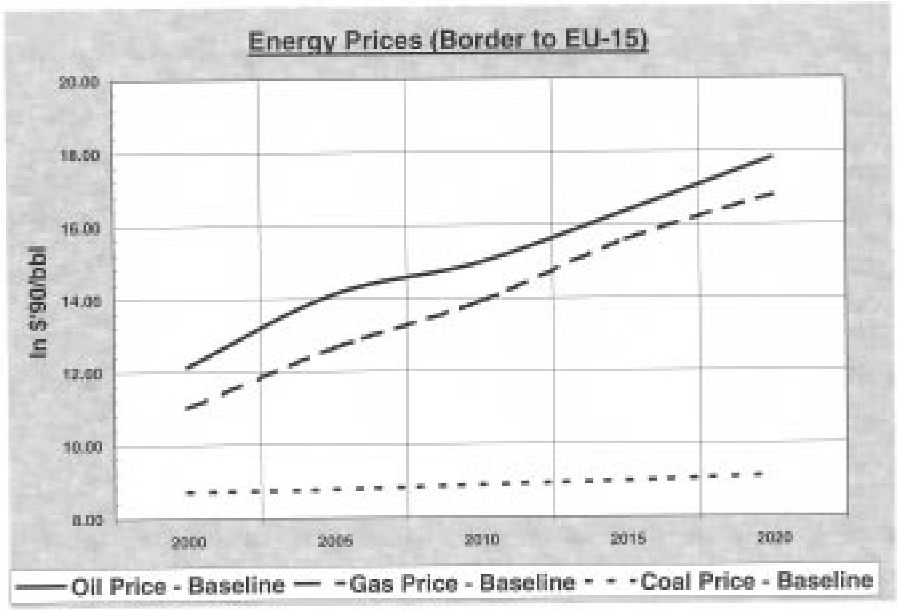

Figure 1. Primary Fuel Price Assumptions

natural gas supply infrastructure, and stringent regulation of acid rain pollutants. The baseline scenario does not include any policies that specifically address the climate change issue.

Crude oil prices (at the EU border) by 2020 are projected to be close to 18 Eur'98/bbl, which is less than their level of 1990 (in real terms) but above their level in recent years. Gas prices in Europe are assumed to rise significantly faster, by around 50% from their current levels, mostly in the medium to longer term. The price of hard coal imported in the EU is expected to remain relatively stable (see Figure 1).

EU Primary Energy Supply and Demand

Production of fossil primary energy within the EU is expected to continue to decline throughout the period to 2020, after peaking in the period 2000-2005. Production of all fossil primary fuels is expected to decline, in particular in the longer run, except that of renewable sources of energy, which are likely to receive a significant boost as a result of policy and technology progress. The decline of EU indigenous solids and oil is especially noticeable.

Despite the evidence of some saturation for some energy uses in the EU, energy demand is expected to continue to grow throughout the outlook period even though at rates significantly smaller than in history. The growth rate in primary energy consumption is expected to continue to be close to 1% over the period to 2010 and then to decelerate to just 0.4% until 2020. Figure 2 shows the relative change of some key indicators of the energy system compared to their 1995 level arbitrarily set at 100.

The implied energy intensity improvement is gradually expected to improve and to reach an annual rate of more than 1.5% toward the end of the projection period (see Table 1). Structural change in the demand side mainly explains this change. The role of energy technology is also important.

The EU energy system remains dominated by fossil fuels over the next 25 years, and their share rises marginally from its level of just under 80% in 1995. Nearly two thirds of overall energy requirements in the EU will be imported by 2020, compared to less than half in 1995. Import dependency will gradually increase for

experts from member countries, responsibility for the content of this article and the views expressed rests solely with the authors. The development of the PRIMES model would not have been possible without the multiyear support of the European Commission DG XII services, and especially P. Valette who led the F1 unit that financed and inspired the model development research. A special acknowledgment is due to Eurostat, the only source for European Union energy data that has been used in the Shared Analysis Project. Other Eurostat data has also been used. We are indebted to P. Tavoularidis and other officers of Eurostat and to M. Lecloux of DGXVII for their support related to data and information.

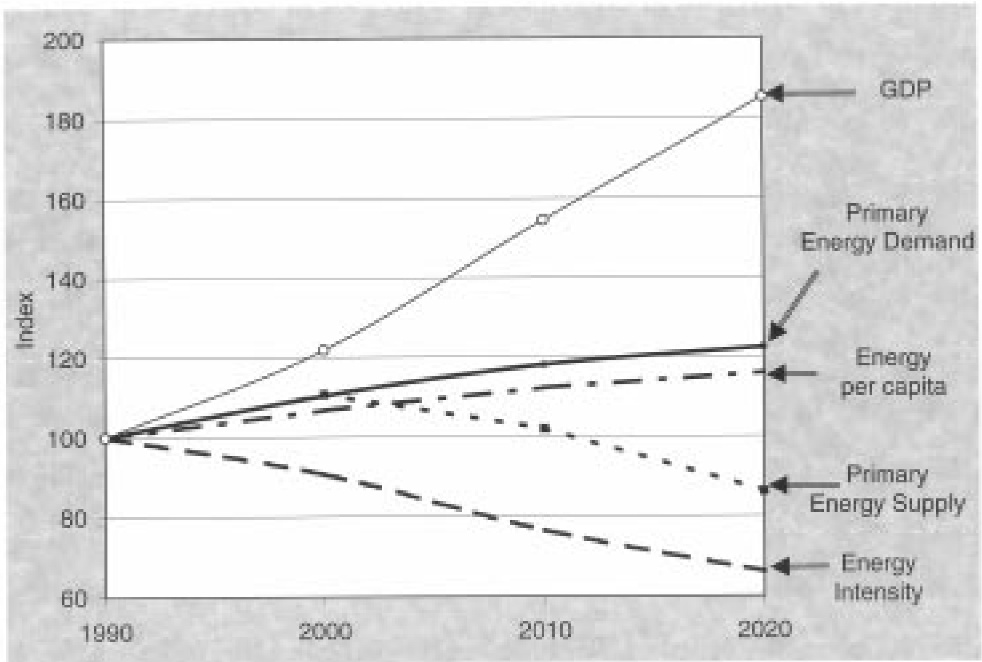

Figure 2. European Union Primary Energy Indicators, 1995-2020
Source: PRIMES.

Table 1. Primary Energy Demand, EU15

	Mtoe				Percentage Annual Growth Rates			Shares, Percentage		
	1995	**2000**	**2010**	**2020**	**1995/2010**	**2010/2020**	**1995/2020**	**1995**	**2010**	**2020**
Total	1,368	1,454	1,556	1,612	0.9	0.4	0.7			
Solid fuels	238	207	182	218	–1.8	1.8	–0.3	17.4	11.7	13.5
Liquid fuels	578	606	655	663	0.8	0.1	0.5	42.2	42.1	41.1
Natural gas	274	338	401	431	2.6	0.7	1.8	20.0	25.8	26.7
Nuclear	205	223	227	199	0.7	–1.3	–0.1	15.0	14.6	12.3
Electricity	1	1	2	3	2.7	1.2	2.1	0.1	0.1	0.2
Renewable energy sources	72	79	88	100	1.4	1.2	1.3	5.3	5.7	6.2
Energy intensity (toe/MEur'90)	241	225	190	164	–1.6	–1.4	–1.5			
Energy per capita (toe/cap)	3.7	3.9	4.1	4.2	0.7	0.3	0.5			

Source: PRIMES.
Note: Mtoe = million tons of equivalent.

all fossil fuels and is likely to reach very high values in the longer run.

The use of solid fuels is expected to continue falling until 2010 both in absolute terms and as a proportion of total energy demand. Beyond 2015, however, due to the power-generation problems that will ensue from the decommissioning of a number of nuclear plants, and the loss of competitiveness of gas-based generation, due to higher natural gas import prices, the demand for solid fuels is projected to increase modestly.

Spurred by its very rapid penetration in new power generation plants and cogeneration, gas is by far the fastest growing primary fuel. Its share in primary energy consumption is projected to increase further to 26% by 2010. The projection shows, however, stabilization at that level beyond 2010.

Table 2. Final Energy Demand by Sector and by Fuel, EU15

	Mtoe				Percentage Annual Growth Rates			Shares, Percentage		
	1995	2000	2010	2020	1995/2010	2010/2020	1995/2020	1995	2010	2020
Total	888	957	1,056	1,111	1.2	0.5	0.9			
By sector										
Industry	247	259	283	291	0.9	0.3	0.7	27.8	26.8	26.2
Residential	241	257	268	282	0.7	0.5	0.6	27.1	25.4	25.4
Tertiary	124	140	159	177	1.7	1.1	1.4	14.0	15.1	15.9
Transports	276	301	346	360	1.5	0.4	1.1	31.1	32.8	32.4
By fuel										
Solid fuels	44	36	27	20	–3.2	–2.7	–3.0	4.9	2.5	1.8
Liquid fuels	405	437	479	489	1.1	0.2	0.8	45.6	45.3	44.0
Natural gas	178	198	212	213	1.2	0.0	0.7	20.0	20.1	19.1
Steam	70	74	89	102	1.6	1.3	1.5	7.9	8.5	9.1
Electricity	170	190	227	266	1.9	1.6	1.8	19.1	21.5	23.9
Hydrogen	0	0	0	0	—	18.3	—	0.0	0.0	0.0
Methanol-ethanol	0	0	0	0	—	8.5	—	0.0	0.0	0.0
Renewable energy sources	22	22	22	21	–0.1	–0.4	–0.3	2.5	2.1	1.9
Biomass	22	21	21	20	–0.2	–0.6	–0.4	97.4	96.3	94.6
Other	1	0	1	1	2.2	3.5	2.7	2.6	3.7	5.4

Source: PRIMES.
Note: Mtoe = million tons of equivalent.

The share of oil in primary consumption is projected to be relatively stable over the period to 2020, and its annual growth rate is projected to decelerate from 1% in the period to 2010 to 0.1% during 2010-2020.

Under baseline technology assumptions, novel energy forms, such as hydrogen and methanol, do not make significant inroads, primarily due to cost considerations.

Final Energy Demand in the EU

Final energy demand is expected to grow marginally faster than primary energy (because of improved rates of conversion efficiency in power generation), rising by 1.2% and 0.5% in the 1995-2010 and 2010-2020 periods, respectively. As can be seen from Table 2, there are relatively modest changes in fuel shares over the next 25 years. The only notable change is the increase by nearly 4 points in the share of electricity. However, even by 2020, electricity continues to account for less than a quarter of final energy consumption. The penetration of more efficient electrical technologies (such as heat pumps, advanced lighting, and improved electrical appliances) is noticeable.

Energy demand in the tertiary sector is the fastest growing segment of final demand, reflecting the expected restructuring of the economy toward services. The modest growth in residential energy demand reflects the lack of growth in EU population and the small increase in the number of households. By 2020, transportation accounts for almost a third of EU final energy consumption, followed by industry and the residential sector, which account for 26% of consumption each.

Oil becomes almost exclusively a fuel for transportation and petrochemicals. The increase in transportation energy demand is actually greater than the increase in the demand for liquid fuels over the 1995-2020 period, implying a decline in oil consumption in the other sectors.

Figure 3 illustrates the different trends observed in the evolution of final energy demand when associated with the evolution of gross domestic product (GDP).

Power Generation in the EU

Under baseline assumptions, the technology of electricity and steam generation improves, leading to higher thermal efficiency, lower capital costs, and greater market availability of new generation technologies. The assumed improvement, however, is not spectacular and no technological breakthrough occurs during the projection period in the baseline scenario.

The use of electricity is expected to expand by 1.7% over the projection period, and its growth is expected

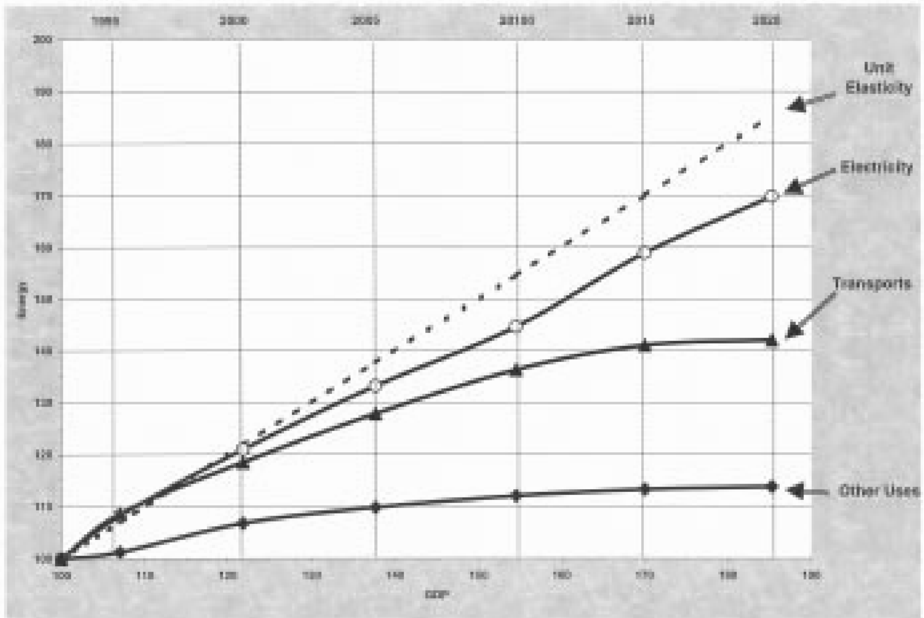

Figure 3. Energy as a Function of Gross Domestic Product (Index 100 in 1990), 1995-2020
Source: PRIMES.

Table 3. Power Generation Capacity by Type of Plant, GW, European Union

	GW			Percentage Annual Growth Rates			Shares, Percentage		
	1995	2010	2020	1995/2010	2010/2020	1995/2020	1995	2010	2020
Nuclear	131.9	135.1	117.2	0.2	–1.4	–0.5	23.1	18.8	13.4
Coal and lignite	179.7	101.1	36.9	–3.8	–9.6	–6.1	31.5	14.1	4.2
Open cycle multifired	65.7	60.2	122.3	–0.6	7.3	2.5	11.5	8.4	14.0
Open cycle of IPP	32.8	25.0	20.5	–1.8	–2.0	–1.9	5.8	3.5	2.4
GTCC and small GT	46.3	253.9	384.2	12.0	4.2	8.8	8.1	35.4	44.1
Clean coal and lignite	0.5	3.4	26.6	14.5	22.7	17.7	0.1	0.5	3.1
Biomass-waste of utilities	3.9	4.7	6.0	1.2	2.5	1.7	0.7	0.7	0.7
Fuel cells	0.0	0.0	0.0				0.0	0.0	0.0
Hydro-renewables	109.3	133.7	158.0	1.3	1.7	1.5	19.2	18.6	18.1
Total capacities	570.2	717.0	871.6	1.5	2.0	1.7			

Source: PRIMES.

to be especially rapid in the tertiary and in the transportation sector. Steam demand is projected to grow by 1.3% in the period to 2010 and by slightly below 1% in the following decade. The industrial sector is projected to remain the dominant user of steam.

Table 3 demonstrates that total power capacity requirements for the EU increase by some 300 GW in the 1995-2020 period and a similar amount of new capacity will be required for the replacement of decommissioned plants. Thus, the EU is projected to build 594 GW of new plants over the 1995-2020 period to cover its growing needs and replace the decommissioned plants.

The use of traditional coal and oil plants declines very rapidly. Due to the decommissioning of older plants, there is a modest decline in the capacity of nuclear plants, whereas nearly half of the thermal plants currently used by independent producers is also expected to be scrapped. These declines in capacity are more than made up in the dramatic increase in gas turbine combine cycle plants and small gas turbines. Their capacity increases by nearly 10 times over the projection period to exceed 380 GW, or almost 45% of the total installed capacity by 2020.

Significant growth in generation by clean coal plants and biomass generation is also expected to

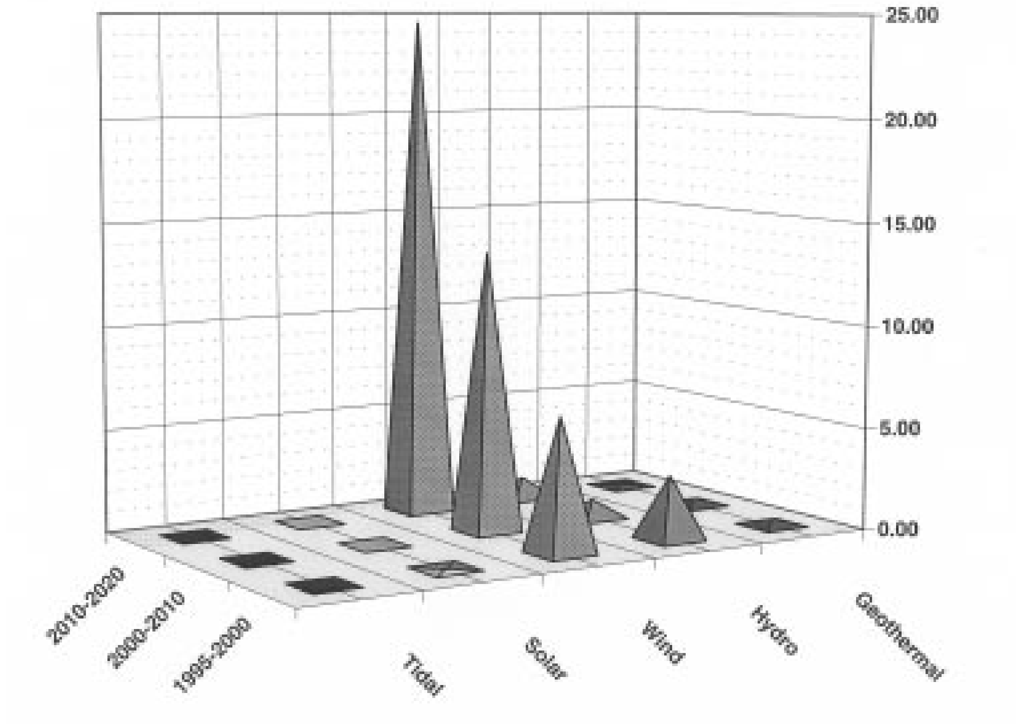

Figure 4. Capacity Expansions in Renewable Energy Forms, GW
Source: PRIMES.

occur over the next 20 years, in particular toward the end of the projection period. However, these forms of power generation will still only account for less than 5% of total generation capacity by 2020.

Growth in hydroelectricity and other renewable forms of generation is projected to be modest, but at more than 50 GW of new capacity, the increase in these capacities will make a significant contribution. The additions mostly concern wind power (see Figure 4).

Technological advances and changes in market structure will reduce the dominance of utilities in electricity generation. This trend is clearly related to the widespread use of gas turbines in that with this form of generation, economies of scale are very limited above a rather modest size of a turbine. The use of gas turbines in combined cycle mode will also greatly encourage the more widespread use of steam, especially by independent producers. Small-scale producers are projected to get close to a fifth of the electricity market by 2020 (see Figure 5).

A significant improvement is expected to occur in the efficiency of power generation (see Table 4). The efficiency of the overall power and steam generation system is expected to increase by around 12 percentage points and to reach 66% by 2020. The efficiency of generation of electricity excluding steam improves from 34% to 45% between 1995 and 2020. This is the combined effect of adopting more efficient technologies (like Greater-Than-Class-C [GTCC]) and cogeneration.

The use of coal and lignite declines quite dramatically between 1995 and 2010, but after that it recovers to reach, and marginally exceed (after 2020), its 1990 level. This is due to the increased decommissioning after 2010-2015 of nuclear plants and the progressive rise of the relative price of natural gas.

Economic Implications

The above energy trends have significant implications for the financial requirements of the EU energy system. At the primary supply level, the significant growth in the demand for gas in the EU will make necessary the importation of gas from a number of distant fields in Russia and other countries. This will require the financing of a number of new expensive pipeline projects.

The further lightening of the consumed barrel of oil products, together with the required "cleaning" of a number of oil products, may require significant invest-

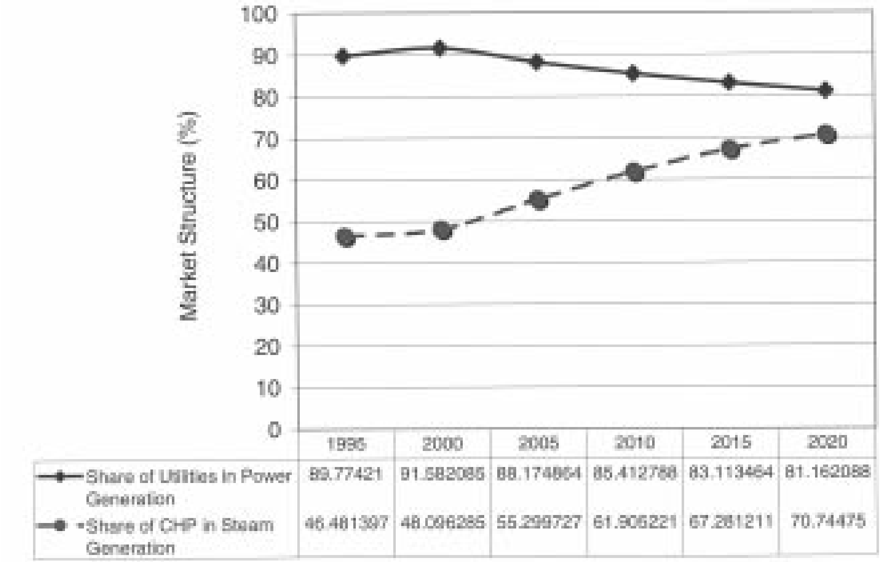

Figure 5. Share of Utilities in Generation and the Share of Cogeneration
Source: PRIMES.

Table 4. Power Generation Efficiency, European Union

	Indicator			Percentage Annual Change		
	1995	2010	2020	1995/2010	2010/2020	1995/2020
For total electricity and steam	0.54	0.64	0.66	1.1	0.4	0.8
For electricity including CHP	0.41	0.54	0.58	1.9	0.7	1.4
For electricity excluding steam	0.34	0.42	0.45	1.4	0.7	1.1
Normalized for electricity only	0.35	0.44	0.47	1.4	0.7	1.1
Normalized for steam only	1.31	1.68	1.99	1.6	1.7	1.7

ments for the upgrading of the refining system of the EU or increased heavy product trading with the United States.

The power-generation sector will continue to be one of the most important investment outlets in the EU economies. However, due to the relative slow growth in electricity demand, the sector's financial requirements will decline significantly as a share in gross fixed capital investment.

The structure of the financial requirements of the power- and steam-generation sector will change as the relative importance of capital requirements declines quite significantly while that of fuel spending increases. This is almost exclusively due to the penetration of GTCC and small gas units whose capital cost is significantly lower than that of conventional technologies.

Because of technological progress, throughout the energy system the cost of energy for the consumer stabilizes and in some cases decreases, despite the continuous rises of imported oil and gas prices. Also, facilitated by liberalization, the average electricity tariff is projected to decrease in 2010-2020 to a range of 15% to 20% below the current level. The share of energy costs in total production costs (for firms) or in total income (for households) continuously decreases.

Environmental Implications

In view of the relative size of the increase in emissions from developing countries, it is clear that any action to reduce emissions from the EU alone will only have a limited impact on long-run CO_2 concentrations.

The rising share of fossil fuels will lead to an increase in the carbon intensity of the EU energy system. Together with the modest increase in energy demand, this will lead to an increase in CO_2 and other

Table 5. CO_2 Emissions by Sector

	Mt CO_2				Percentage Annual Growth Rates		Shares Percentage		
	1990	1995	2010	2020	1995/2010	2010/2020	1995	2010	2020
Total	3,079	3,037	3,298	3,508	0.6	0.6			
Industry	430	382	379	355	0.0	–0.7	12.6	11.5	10.1
Tertiary	193	203	221	203	0.6	–0.8	6.7	6.7	5.8
Households	449	428	445	450	0.3	0.1	14.1	13.5	12.8
Transports	738	804	999	1,038	1.5	0.4	26.5	30.3	29.6
Electricity-steam production	1,213	1,162	1,202	1,419	0.2	1.7	38.3	36.5	40.5
Biofuels production	0	0	0	0	—	—	0.0	0.0	0.0
Hydrogen production	0	0	0	1	—	18.3	0.0	0.0	0.0
Energy branch	57	59	52	43	–0.9	–1.9	1.9	1.6	1.2
CO_2 emission index									
Total	100.0	98.7	107.1	114.0					
Industry	100.0	88.8	88.3	82.7					
Tertiary	100.0	105.2	114.3	105.1					
Households	100.0	95.4	99.2	100.2					
Transports	100.0	108.9	135.4	140.6					
Electricity-steam production	100.0	95.8	99.2	117.1					
Biofuels production	—	–	—	—					
Hydrogen production	—	–	—	—					
Energy branch	100.0	103.6	90.7	75.1					

Source: PRIMES.

energy-related emissions. CO_2 emissions are projected to increase annually by 0.6% in the 1995-2020 period (see Table 5).

In absolute terms, the increase in emissions originated from combustion of natural gas more than make up for the sharp decline in emissions that results from the decline in the use of solid fuels. Energy intensity improvements act in favor of moderating the rise of CO_2 emissions. The carbon intensity does not improve.

In the period to 2010, the sectors with the fastest increase in emissions are those where energy demand is expected to grow fastest, namely, the tertiary and transportation sectors. However, in terms of their absolute contribution to the increase in emissions, it is the transportation sector that accounts for nearly two thirds of the overall increase in emissions between 1995 and 2010. Beyond 2010, it is the electricity and steam generation that is almost solely responsible for the increase in CO_2 emissions.

Emissions of SO_2 and NO_x from the whole energy system and especially from the power-generation system are expected to decline quite rapidly over the outlook period. By 2020, NO_x emissions from power and steam generation (large combustion plants) will be nearly at half their level of 1995, whereas SO_2 emissions will be only a quarter of their 1995 level.

Longer Run Trends

While the analysis carried out formally covers only the period to 2020, a number of trends and issues that are important for policy analysis become apparent for the period beyond 2020. The significance of discussing these emerging longer term trends lies in that, often, policy must take a very long horizon for its effectiveness and economic efficiency to be optimized.

Energy import dependency problems will become very acute in the period beyond 2020 in the absence of breakthroughs in supply technologies or of new and unexpected large discoveries of oil and gas. The latter is not considered very likely.

Imports of gas will have to take place from increasingly distant places in Russia and the Middle East, with potentially negative cost implications. Following the decommissioning of a large number of nuclear plants in the period around 2020, there is much uncertainty on the means through which these plants will be replaced.

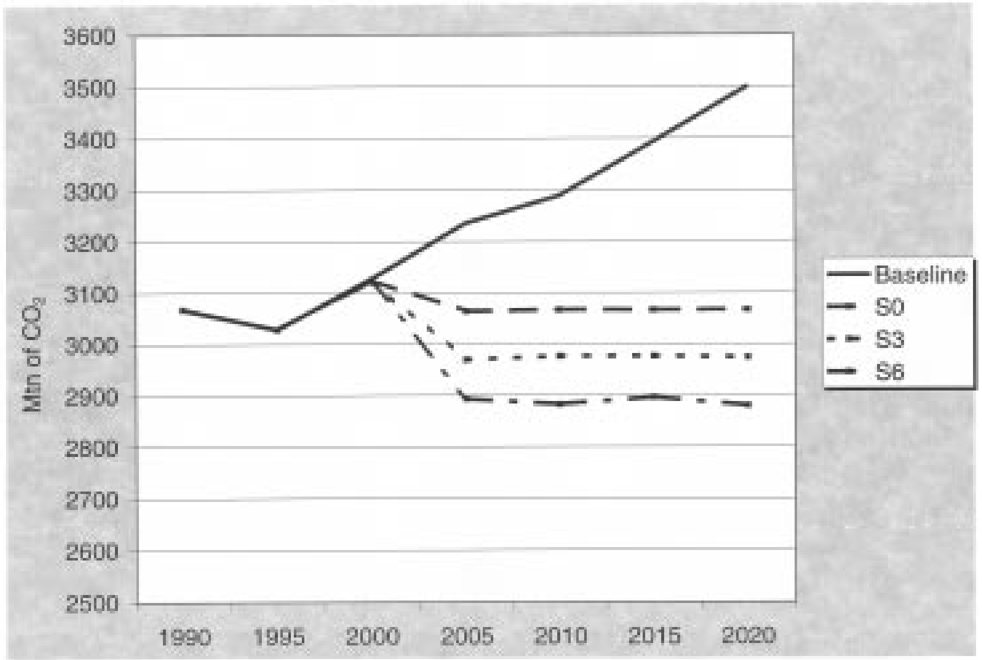

Figure 6. European Union Emissions Under Baseline and the Three Scenarios
Source: PRIMES.

The potential of new technological breakthroughs becomes very large both for alleviating the import dependency of the EU and for tackling emissions problems. This is particularly challenging for the power-generation sector, which beyond 2020 will face major strategic technology and fuel choice dilemmas affecting the overall energy policy and European geopolitics.

A key uncertainty for the period beyond 2020 is the means by which the large number of decommissioned nuclear plants will be replaced. More than 100 GW of nuclear capacity will be retired between 2015 and 2030. Whether this capacity is replaced by nuclear plants or by plants using fossil fuels will make a significant difference to both the emissions and energy outlook of the EU.

Emissions Reduction Scenarios

Definition

Three CO_2 emissions–reduction scenarios have been run with PRIMES 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 2010 and beyond.

As can be seen from Figure 6 and Table 6, the three new scenarios analytically examined and presented in this section are as follows:

- S0 scenario: Under this scenario, CO_2 emissions remain at their 1990 level throughout the projection period (at around 3068 Mt CO_2). In absolute emissions of CO_2, this scenario results in 222 less Mt CO_2 by 2010 and 430 Mt CO_2 less by 2020 than the baseline.
- S3 scenario: Under this scenario, CO_2 emissions in 2010 and beyond amount to just under 3000 Mt CO_2, reflecting a reduction of around 3% from the level of emissions in 1990 and a reduction of nearly 10%, or around 300 Mt CO_2, when compared to the baseline emissions in 2010. By 2020, the difference in CO_2 emissions between this scenario and the baseline exceeds 500 Mt CO_2.
- S6 scenario: Under this scenario, CO_2 emissions after 2010 amount to around 2880 Mt CO_2, reflecting a reduction of around 6% from the level of emissions in 1990 and a reduction of just over 13%, or around 450 Mt CO_2, compared to the baseline emissions in 2010. The difference in emissions by 2020 amounts to over 600 Mt CO_2, when compared to the baseline.

Table 6. Baseline and Sensitivities Emissions 1990, 2010, 2020

		2010				2020			
	1990	**Baseline**	**S0**	**S3**	**S6**	**Baseline**	**S0**	**S3**	**S6**
CO_2 emissions ($Mt\ CO_2$)	3,068	3,289	3,067	2,977	2,883	3,500	3,067	2,974	2,880
Reduction from baseline ($Mt\ CO_2$)			–222	–312	–406		–432	–525	–619
Percentage of 1990 level			100	97	94		100	97	94
Carbon value (Eur'90/tn carbon avoided)		0	50	78	102	0	59	81	115

Source: PRIMES.

The selection of the range of emissions span by the above scenarios was designed so as to include the emission-reduction target that is likely to be eventually accepted for the energy system of the EU, once the possibilities from non-CO_2 greenhouse gases and other flexibility instruments of the Kyoto protocol have been allowed for. The analysis assumes full flexibility adjustment within the EU member states. The carbon constraints have been applied as global constraints treating the EU energy system as one economic system without any a priori allocation of emissions reductions to any sector, fuel, or country.

Carbon constraints were imposed globally on the EU energy system without any limits on the amount of emissions reduction that would originate from one country or one sector. The only criterion used was that of economic efficiency. The methodology adopted was similar to that of an EU-wide carbon permit trading scheme. As can be seen from Table 6, the stabilization of emissions that is achieved in scenario S0 requires a carbon value of 50 Eur in 2010 and 59 Eur in 2020 (all carbon values are given in terms of 1990 Eur per ton of carbon avoided). The carbon values for scenario S3 for 2010 and 2020 are 78 Eur and 81 Eur, respectively, whereas the corresponding carbon values for S6 are 102 Eur and 115 Eur. These figures indicate that holding emissions at the same level beyond 2010 requires only a relatively small increment in the carbon value. This is despite the fact that emissions without the carbon constraint would tend to increase as underlying energy demand and carbon intensity would increase under baseline assumptions. For example, stabilization of emissions in 2020 requires the reduction of an additional 200 Mt CO_2 that would occur between 2010 and 2020. This is achieved with "only" an additional 9 Eur of carbon value to its level in 2010. Similarly, the additional required reduction in emissions between 2010 and 2020, which is around 200 Mt CO_2, in the S3 and S6 scenarios is achieved with a relatively modest increase in the carbon value between 2010 and 2020. This tendency is likely to reflect the fact that as we move further into the future, technological improvements make a reduction in emissions relatively easier than it is with present technologies.

There is also a tendency for the degree of difficulty of reducing emission, as represented by the level of carbon value, to increase nonlinearly as the required level of emissions reduction increases (see Figure 7).

The issue of nonlinear costs in incremental reductions in CO_2 emissions has been discussed in Capros and Mantzos (1999) in greater detail and for a far greater range of carbon values. It was concluded that there is a tendency for carbon values to increase nonlinearly as the emissions target becomes more severe (see Figure 7). In other words, beyond a certain level of emissions reduction, for each additional ton of carbon reduction, the cost increases disproportionately. It was also observed that for the range of emissions reductions likely to be required for reaching the Kyoto target, the degree of difficulty for the EU energy system remains within manageable levels.

Energy System Impacts

The economic system can respond to the imposition of the carbon constraint, while assumed to maintain the same level of GDP, by reducing the energy intensity and/or by changing the fuel mix to reduce the carbon intensity. For the period to 2010, in all three scenarios under consideration, nearly half of the overall reduction in emissions is achieved through a reduction in energy consumption. An even greater proportion of emissions reduction takes place through substitution

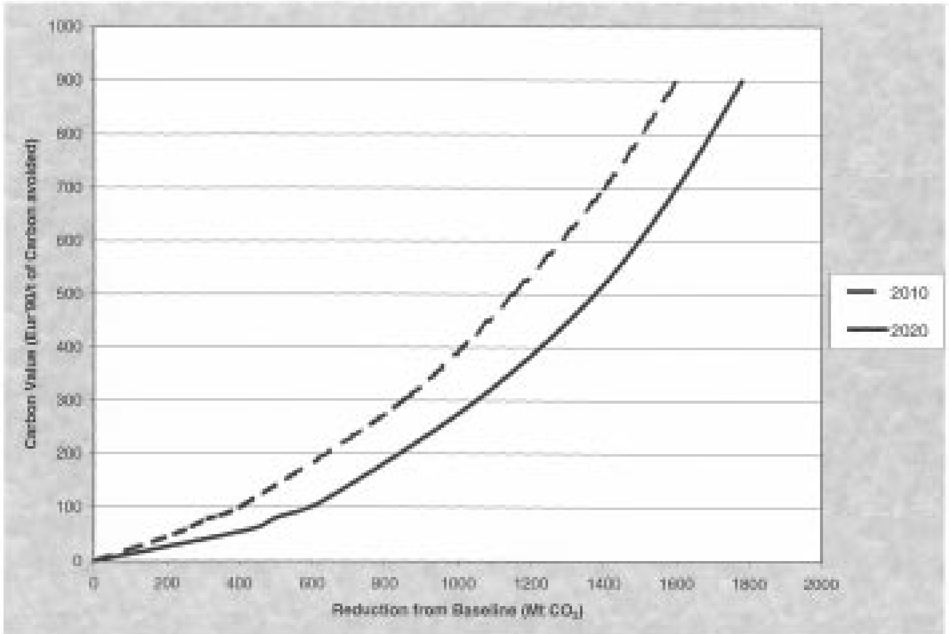

Figure 7. Carbon Values and CO_2 Emissions Avoided Compared to Baseline 2010, 2020
Source: PRIMES.

Table 7. Primary Fuels and CO_2 Emissions in the Four Scenarios

		2010	Percentage Difference From Baseline in 2010			2020	Percentage Difference From Baseline in 2020		
	1990	Baseline	S0	S3	S6	Baseline	S0	S3	S6
Gross inland consumption (Mtoe)	1,314	1,552	–3	–4	–6	1,609	–4	–5	–6
Solid fuels	301	182	–23	–31	–40	218	–53	–62	–67
Liquid fuels	544	653	–4	–6	–8	660	–3	–4	–7
Natural gas	222	400	3	3	5	430	9	10	10
Nuclear	181	227	–1	0	–1	199	12	12	12
Electricity	2	2	–2	–3	–4	2	–3	–4	–5
Renewable energy sources	64	88	9	15	21	100	17	22	27
Total CO_2 (Mt CO_2)	3,068	3,289	–7	–9	–12	3,500	–12	–15	–18

Source: PRIMES.
Note: Mtoe = million tons of equivalent.

in 2020. This effectively means that as we move further into the future, the economic system finds substitution among fuels (i.e., reducing the carbon intensity) much more cost effective than reducing overall energy use (i.e., reducing the energy intensity).

Table 7 presents these two effects for each of the three carbon constraints examined for the EU as a whole and for the period to 2010. It can be seen that for the period to 2010, in all three scenarios under consideration, nearly half of the overall reduction in emissions is achieved through a reduction in energy consumption. For example, under the S3 scenario, emissions are about 9.5% less than in the baseline, whereas primary energy demand has declined by only 4.5% from its baseline level. Thus, for the level of adjustment difficulties implied by the three scenarios, it seems that at the margin it is as difficult for the system to reduce overall energy demand as it is to change the mix in primary fuels. The latter effect is, of course, somewhat weakened by the assumption that nuclear

Table 8. Impact on Final Demand by Sector

		2010	Percentage Difference From Baseline in 2010			2020	Percentage Difference From Baseline in 2020		
	1990	Baseline	S0	S3	S6	Baseline	S0	S3	S6
Total energy (Mtoe)	852	1,053	–3	–4	–6	1,108	–3	–5	–6
Industry	257	282	–2	–3	–4	290	–3	–4	–5
Tertiary	110	159	–7	–10	–12	177	–6	–8	–10
Households	232	267	–2	–4	–5	282	–2	–4	–5
Transports	253	344	–2	–4	–5	359	–3	–4	–5
CO_2 emissions									
(Mt CO_2)	1,800	2,036	–4	–6	–8	2,038	–4	–6	–8
Industry	424	378	–5	–7	–8	354	–5	–6	–10
Tertiary	193	220	–12	–16	–20	203	–11	–14	–18
Households	447	444	–4	–6	–8	448	–4	–6	–8
Transports	735	994	–2	–4	–5	1,033	–3	–4	–5

Source: PRIMES.
Note: Mtoe = million tons of equivalent.

power generation will not be allowed to increase beyond the level assumed in the baseline, irrespective of any carbon constraint imposed on the system.

The picture is somewhat altered when the figures for 2020 are considered. It can be seen from the table that, compared to baseline results, the reduction in primary energy in 2020 is similar to that for 2010, whereas the reduction in emissions is significantly increased. For example, under the S0 scenario, the fall in primary energy consumption is very similar when compared to the baseline for both 2010 and 2020. The required overall reduction in emissions, however, at 12.4% is nearly double in 2020 from its level of 6.7% in 2010. This effectively means that as we move further into the future, the economic system finds substitution among fuels (i.e., reducing the carbon intensity) much more cost effective than reducing overall energy use (i.e., reducing the energy intensity).

By far the most significant effect in terms of primary energy fuels is the decline of solid fuel consumption, which falls not only because of the overall fall in energy consumption but also because their use is replaced by less carbon intensive fuels. The reverse effect operates on gas and renewables, both of which increase by 2010 and 2020, compared to their consumption level under baseline assumptions. The modest negative effect on liquid fuels is due mostly to a small reduction in overall demand rather than to substitution.

In terms of changes in final consumption, the reduction in demand accounts for about two thirds of the overall reduction in emissions originating from adjustments in final energy (see Table 8).

In industry, most of emissions reduction comes from restructuring industrial processes (e.g., more electric arc processing, more recycling of materials, etc.). Improved electrical technologies and heat pumps seem to be attractive and cost-effective options. In general, the degree of flexibility available to industry for reducing emissions is limited.

The tertiary and household sectors seem to have large possibilities for emissions reduction both through adopting more efficient electric appliances and through reducing their thermal needs by improving buildings.

The most noticeable changes in the transport sector concern trains and aircraft. In both cases, the average efficiency progresses, but trains gain market share while air transports lose. The effects in the road sector mainly concern behavioral changes in car purchasing and use rather than in car technology itself. High emissions reduction constraints are necessary to enable significant technology change in the transport sector.

Table 9 illustrates the reduction potential indicators for annual CO_2 emissions in the EU (from baseline 2010 projections) associated with different average cost ranges (based on currently available data).

In general, as illustrated in Table 10, the rate of adoption of best available technologies is low in the emissions reduction scenarios examined.

Sensitivity analysis, on the other hand, shows much potential from greater adoption of best available technologies. As discussed in Capros and Mantzos (1999), once the carbon value exceeds a certain level and the adoption of more energy-efficient technologies becomes marginally cost effective, their market pene-

Table 9. Potential Emissions Reduction in Mt CO_2

Sector/Measures	Average Cost < 50 Eur'90/ t. CO_2	Of Which Average Cost < 25 Eur'90/ t. CO_2	Of Which Average Cost < 5 Eur'90/ t. CO_2
Industry (direct energy uses)	80	40	5
Transport			
Under conventional technology	130	60	10
Under ACEA Agreement (2)	170	170	80
Tertiary and households (energy efficiency and insulation)	230	140	35
Cogeneration (in industry and district heating)	70	40	15
Renewables in power generation	160	80	30
Fuel switching and efficiency in power generation	150	140	50
EU total	820 to 860	500 to 610	145 to 215

Table 10. Percentage Decomposition of CO_2 Reductions by Effect in Final Energy Demand

	2010			2020		
	S0	S3	S6	S0	S3	S6
Structural change and behavioral effects	18.8	19.7	19.2	9.7	10.7	12.5
Technological improvement	23.1	23.7	23.0	15.1	17.7	18.9
Change of fuel mix	2.5	2.5	2.3	1.2	1.4	1.5
Change of emission factor of electricity and steam (supply effect)	55.6	54.2	55.5	74.0	70.3	67.1

Source: PRIMES.

tration develops a strong momentum leading to the decline in the additional capital charges involved in the use of the new technology. In other words, the more a new technology is used, the greater the reduction in its costs. In all sectors, the additional costs from paying for carbon emissions are largely offset by cost savings due to the adoption of improved technologies.

The increasing importance of new, more energy efficient technologies is illustrated in Figure 8, in which the effects responsible for the emissions reductions are considered, arranged in four categories. There, the share of technological improvements rises almost continuously with higher levels of carbon value, ultimately accounting for around half of total emissions reduction. Consequently, there may be large scope for policy to promote best available technologies.

Effectively, substitution at the primary level is rather easier to achieve than at the level of final energy demand. As the carbon constraint increases, final demand accounts for an increasing share in the reduction of emissions from their baseline levels. Structural changes and behavioral effects in the demand side contribute by 20% to total emissions reduction.

The bulk of the change in carbon intensity of the EU energy system is due to the electricity- and steam-generation system. For the period to 2010, nearly 60% (see Table 10) of the overall reduction in emissions is achieved through adjustments in the power- and steam-generation sector. By 2020, this proportion rises up to more than 70%. Higher use of nonfossil energy forms accounts for 35%, whereas technological improvement as such accounts for the rest (see Table 11).

The power- and steam-generation system of the EU appears to be the sector that can adjust in the most cost-effective way to emissions reductions. It is partly because the power- and steam-generation system is more flexible in the reduction of emissions that its output does not decline as sharply as that of other forms of final energy. Electricity and steam consumption

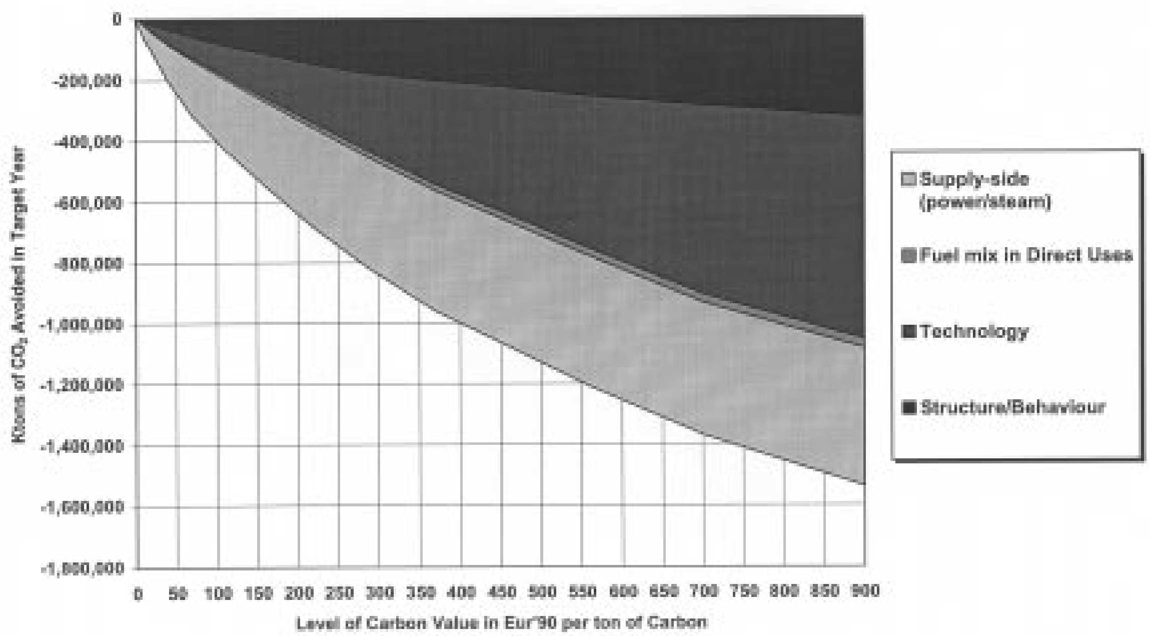

Figure 8. Decomposition of CO_2 Emissions Reduction Into Four Categories for 2010
Source: PRIMES.

Table 11. Percentage Decomposition of CO_2 Reductions by Effect in Electricity and Steam Generation

	2010			2020		
	S0	**S3**	**S6**	**S0**	**S3**	**S6**
Change of demand	10.9	10.5	9.5	8.7	9.9	10.1
Production from nonfossil fuels	23.4	29.9	29.6	37.3	36.2	36.0
Change of fuel mix and technological improvement of fossil fuel plants	65.7	59.6	60.9	54.0	53.9	53.9

Source: PRIMES.

decline by less than half the amount of reduction in other fuels in scenarios S0 to S6. There are many reasons for this flexibility of the generation system. First, because nearly half of electricity generation takes place through the use of carbon-free primary fuels, such as hydro and nuclear, a 1% reduction in emissions in the system can take place with only half as much reduction in output—only the generation through fossil fuels needs to be reduced. Second, the generation through carbon-free fuels can actually increase, although this is not allowed to a significant extent, by assumption, in the case of nuclear power. Third, the system can respond by increasing its overall efficiency of generation through fossil fuels. This can be achieved either by adopting improvements in the technology used for any given fuel (this effect is limited for 2010) or through alternative combinations of technologies and fuels, such as the use of combined cycle gas turbined plants as opposed to thermal coal plant, or through changes in the allocation of the available plants in the merit order. Finally, the generation system can improve its overall efficiency by increasing the degree of cogeneration of steam and electricity.

The operation of at least some of the above mechanisms can be seen in Table 12, where a sharp difference can be seen to exist between the decline in the system's output and fossil fuel inputs. In all three scenarios examined, the decline in inputs is close to 4 times the corresponding decline in electricity and steam output for 2010. For example, in S6, electricity and steam

Table 12. Impacts on the Transformation Sector Energy and Emissions, 2010, 2020

		2010	Percentage Difference From Baseline in 2010			2020	Percentage Difference From Baseline in 2020		
	1990	Baseline	S0	S3	S6	Baseline	S0	S3	S6
Total fuel inputs (Mtoe)	419	481	–5	–7	–8	550	–11	–13	–14
Fossil fuel inputs in electric and steam generation	364	418	–6	–7	–9	487	–12	–13	–15
Energy sector	56	64	–3	–4	–6	63	–4	–5	–7
Electricity and steam output (TWh)	3,159	4,320	–1	–2	–2	4,952	–2	–3	–4
Total CO_2 (Mt CO_2)	1,269	1,253	–11	–15	–20	1,461	–24	–28	–31
Electricity and steam	1,212	1,201	–11	–15	–20	1,418	–24	–28	–32
Energy sector	57	52	–3	–5	–6	43	–3	–5	–7
Percentage of total CO_2 reduction by electricity and steam			60	59	60		80	77	73

Source: PRIMES.
Note: Mtoe = million tons of equivalent.

generation in 2010 is 2.3% below its level in the baseline scenario, whereas the corresponding generation inputs are 8% below their baseline level. This effect is similar in magnitude for 2020.

The flexibility of the power- and steam-generation sector to respond to carbon constraints is shown most dramatically by the changes achieved in emissions. On average, for every 1% reduction in generation output, there is a sevenfold decline in CO_2 emissions. Thus, in the stabilization scenario, by reducing electricity and steam generation by just 1.3%, the generation system reduces its emissions by 11%, and this accounts for two thirds of the overall system reduction in emissions to reach the carbon constraint. Since, as was seen above, around half of this reduction is achieved through improved efficiency and an increase in nonfossil fuels, nearly half of the overall reduction in emissions is achieved through changes in the generation fuel mix. This effect seems to become even stronger in 2020. In the S0 scenario, 2020 electricity output is reduced by 2.4% when compared to the baseline. The resulting decline in emissions is 10 times higher.

One of the reasons for the growing scope of relatively cost-effective substitution in the power and steam sector after 2010 is that under baseline assumptions, a large comeback of solids was projected to take place. This was on the basis of rising prices of gas. Under the carbon constraint scenarios, the impact of the increased relative price of gas is negated by the implicit cost of carbon, which results in a significant increase of the relative price of solids. Consequently, the power- and steam-generation system continues along its path to 2010, which involved that the bulk of new generation capacity would use gas as a fuel.

Renewable energies and nuclear also expand as a result of the imposition of the carbon constraints. The use of nuclear expands substantially while the effect of renewables is rather limited. Similarly, the improvement in efficiency of generation in the three scenarios only accounts for a modest part of the reduction in emissions, whereas the share of cogenerated electricity from thermal plants increases modestly.

Although the role of the electricity and steam sector remains dominant in meeting the carbon constraint, there are indications that the relative difficulties increase as the constraint becomes tighter. Effectively, at low levels of the carbon constraint, the flexibility of the generation system and the available fuel switch options make it a convenient and cost-effective means to achieve emissions reductions. As the constraint gets tighter, the options within the generation system become relatively more difficult and final demand is required to make a more substantial contribution (see Figure 8).

Figure 9 illustrates the effects responsible for the emissions reductions in power and steam generation arranged in four categories. The contribution of pro-

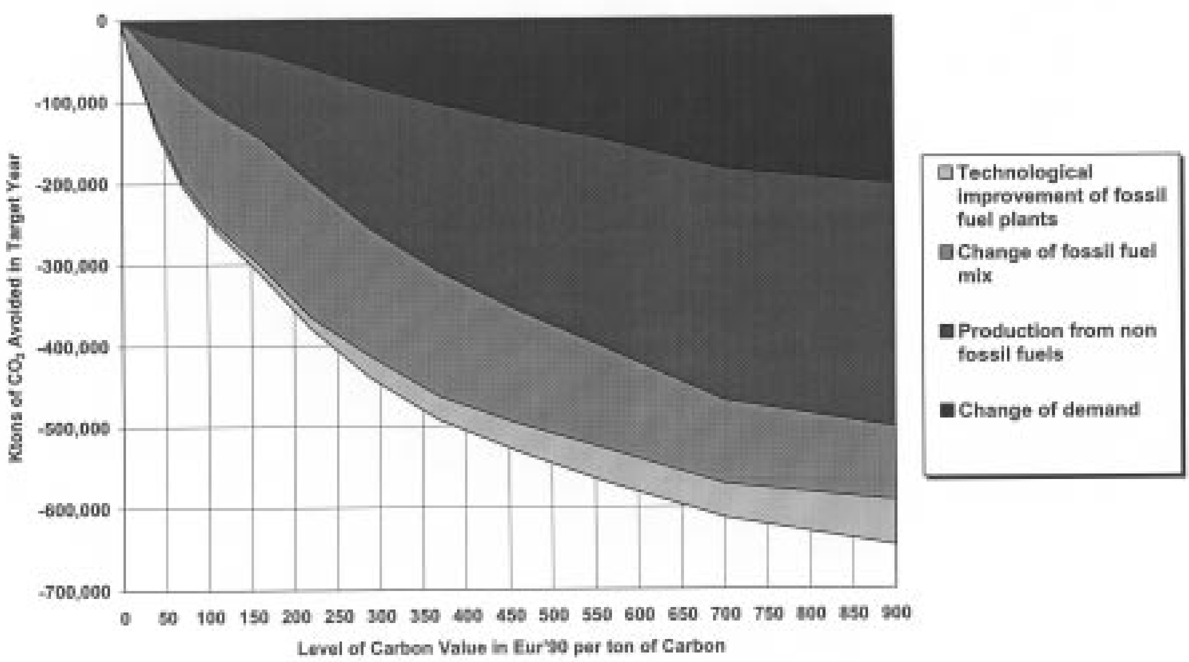

Figure 9. Decomposition of Changes in Power- and Steam-Generation Sector Into Four Categories for 2010

duction from nonfossil fuels rises almost continuously with higher levels of carbon value, ultimately accounting for around half of total emissions reductions.

Economic Implications

The analysis shows that the cost of CO_2 emissions reduction differs substantially across the EU member states. This is because there are large differences among member states in the structure of power and steam generation, in the fuel mix and technology choices, and in base year emissions.

The restructuring processes (in some member states acting in favor of reducing emissions and in some others acting to the detriment of emissions) ongoing in the member states for reasons other than climate change also greatly differ. Thus, there is a tendency for countries with high energy intensities and high carbon intensities in their power-generation system to contribute more to the required emissions reduction than their share in baseline emissions in 2010 would warrant.

Table 13 presents, in absolute terms, the level of emissions avoided under the three scenarios in 2010 when compared to the level of emissions for the same year under baseline assumptions. The table also shows the percentage change in emissions in each country, when compared to 1990, as well as the share of its country in 2010 emissions. It can be seen that in this representation of the scenario impacts, there are huge differences among EU countries. For example, in the S6 scenario, 2010 emissions are nearly 24% below their level in 1990 in Germany and 11% in the United Kingdom, whereas they are higher than they are in 1990 by more than 30% in Greece and Portugal. These differences reflect to a large extent the different dynamics in each country's energy system and industrial restructuring. The carbon intensity of the power-generation system also plays a key role in the ease with which a country can adjust to the imposition of a carbon constraint.

The total energy system cost of reaching the emissions targets under the three scenarios for the EU in 2010 is equal to between 0.02% and 0.07% of GDP. One of the most interesting results of the analysis presented here is that of the relatively modest cost of meeting the carbon constraints considered.

One of the main factors limiting the costs is the relatively low cost of switching between gas and coal in the electricity- and steam-generation sector, which accounts for the bulk of the reduction in emissions in all scenarios relevant to the Kyoto target.

Table 13. Change of CO_2 Emissions in 2010 Compared to 1990 and to Baseline Levels in 2010 and Distribution of Emissions by Country in 2020

	Percentage Change 2010-1990				Mt of CO_2 Avoided in 2010 Compared to Baseline			Percentage Share in 2010 Emissions			
	Baseline	S0	S3	S6	S0	S3	S6	Baseline	S0	S3	S6
AU	–0.4	–8.0	–8.7	–11.6	–4.2	–4.6	–6.2	1.7	1.6	1.7	1.7
BE	18.4	12.7	9.6	7.5	–5.9	–9.2	–11.3	3.8	3.8	3.9	3.9
DK	4.3	–4.6	–9.9	–14.0	–4.7	–7.4	–9.6	1.7	1.6	1.6	1.6
FI	43.3	29.4	21.1	18.1	–7.2	–11.4	–12.9	2.2	2.2	2.1	2.1
FR	10.6	5.4	2.9	0.7	–18.2	–27.2	–34.7	11.8	12.1	12.2	12.3
GE	–13.0	–18.1	–20.6	–24.3	–48.4	–71.7	–106.8	25.2	25.4	25.4	25.0
GR	54.3	35.6	33.6	31.4	–13.3	–14.7	–16.3	3.3	3.1	3.2	3.2
IR	42.6	31.8	26.2	23.7	–3.2	–4.9	–5.7	1.3	1.3	1.3	1.3
IT	10.8	2.7	–0.4	–3.4	–31.4	–43.4	–55.1	13.1	13.0	13.0	13.0
NL	34.3	24.8	22.1	19.6	–14.6	–18.7	–22.6	6.2	6.2	6.3	6.3
PO	70.2	57.1	54.6	37.0	–5.1	–6.1	–13.0	2.0	2.0	2.0	1.9
SP	35.8	25.6	19.4	16.4	–20.5	–33.0	–39.1	8.3	8.3	8.1	8.2
SV	26.5	17.1	13.5	11.3	–4.8	–6.6	–7.7	1.9	1.9	1.9	2.0
UK	0.9	–6.2	–8.5	–10.5	–40.3	–53.4	–64.9	17.4	17.3	17.4	17.6
EU14	7.2	0.0	–3.0	–6.0	–221.8	–312.4	–405.9	100.0	100.0	100.0	100.0

Although changes in the pattern of electricity and steam supply are the main contributor to the emissions reductions at relatively low carbon values, their importance gradually diminishes with rising carbon values. Structural changes, such as the restructuring of industrial production toward less energy intensive (higher value added) processes and changes in consumer behavior toward more energy conservation increase in importance, although moderately, at relatively low levels of carbon value and stabilize at about one fifth of total emissions reductions at higher levels of carbon value. Finally, the contribution of fuel mix changes in final energy demand is limited to almost 2% for all levels of carbon value.

The various economic sectors are affected differently by the imposition of the carbon constraint in 2010. The costs differ among sectors depending on energy intensiveness. Thus, energy-intensive industrial sectors tend to be the most severely affected, although even there overall sector costs only increase by a maximum of a few percentage points even under the S6 scenario. The costs incurred by the power- and steam-generation sector relate to higher capital expenditures (more expensive plant technology), the costs induced from stranded capital, and the high fuel costs needed for fuel switching. The average generation cost increases by up to 18%, including the cost of paying for carbon emissions, whereas investment expenditures for power and steam generation also rise by up to 10%. Electricity tariffs under the S6 scenario increase by just over 20% in industry and by close to 10% in the tertiary and household sectors. All figures are generally somewhat higher in 2020, reflecting the higher carbon value for that year.

Uncertainties

The outlook for nuclear power is one of the key uncertainties of this outlook. Nuclear can play a very significant role in reducing emissions beyond 2010. Its impact will depend on whether the massive amount of nuclear plants that are due to be decommissioned between 2015 and 2030 will be replaced by nuclear plants or by fossil fuel plants. Despite the restrictions imposed on the expansion of nuclear power, it was shown, under the high oil and gas price sensitivity, that the role of nuclear power could be very significant.

Under the nuclear sensitivity, it was shown that under an emissions constraint and without any restrictions on the scope of nuclear power within the countries that use this form of energy, nuclear capacity is projected to increase to 181 GW by 2020 and to 212 GW by 2030. This is quite a dramatic expansion of nuclear power and is only comparable with what has taken place between 1960 and 1990. In view of the large decommissioning due between 2015 and 2030, in terms of new capacity under the assumptions of the high nuclear sensitivity, almost 200 GW of new nuclear capacity will have to be built between 2015 and 2020. The impact of this sensitivity on the EU energy economy is quite significant.

Under the assumptions of the high oil and gas sensitivity, it was shown that even a modest increase in the cost of gas in the longer term is sufficient to increase the use of solids significantly. In fact, if the use of nuclear power was not simultaneously stimulated as a result of the increased price of gas, the resulting expansion in the use of solids and in emissions would be substantially higher.

The role of transportation is critical for the future increase in oil import dependency and significant for the future growth in emissions. Under a sensitivity that included the implementation of a recent voluntary agreement between the EU and the auto manufacturers association, it was shown that 2010 oil demand is reduced by 28 Mtoe (or more than half a million barrels per day) in the EU, which is equivalent to more than 4% of EU oil demand. The 2020 impact on oil demand is about double and is equivalent to a reduction in the required oil imports of the EU by more than 9%. The impact of the agreement on emissions is more limited than on oil demand but very significant nevertheless. By 2020, CO_2 emissions in the EU decline by 4.6% when compared to the baseline.

The contribution of factors related to technology progress in the demand-side is also expected to increase significantly with the level of the emission constraint in the longer run. In other words, the impact of more efficient technologies would be significantly greater beyond 2020 as more of the capital stock would be replaced and as the market of the new technologies would develop a critical mass, which is necessary for the reduction in the price of new technologies.

Policy Implications

It was shown that under reasonable assumptions for the period to 2010 (the baseline scenario), it is unlikely that the EU will meet its Kyoto undertakings, at least through energy-related CO_2 emissions. Instead of the 8% reduction in emissions by 2010, a 7% increase is projected for 2010 when compared to the level of CO_2 emissions in 1990. Depending on the outlook and policy measures for non-CO_2 greenhouse gases, such as CH_4, it is clear that a number of policy initiatives will have to be undertaken for the abatement of energy-related emissions.

Using as the sole criterion that of economic efficiency, the impacts that were discussed under scenarios S0, S3, and S6 were based on what would be cost effective, irrespective of any national or industrial political considerations. It was seen that under the three additional scenarios, CO_2 emissions could decline by between 222 and 406 Mt CO_2. Whether these reductions are sufficient for the EU to meet its target will clearly depend on what measures are taken for emissions from sectors other than that of energy.

The sensitivity analysis that was carried out earlier showed that a number of measures, other than the imposition of a global restriction on CO_2 emissions, can also be effective. However, many of these affect mostly the period beyond 2010. The one significant effect examined that is relevant for the Kyoto period is the potential contribution to emissions reduction from improvements in the efficiency of transportation. It was seen that the implementation of the 1998 voluntary agreement between the EU and the auto manufacturers association could result in more than 80 Mt CO_2 reduction by 2010, a very significant contribution.

The decrease of demand for energy, the fuel mix shifts toward gas, and the changes in power and steam generation in favor of nonfossil fuels contribute to considerable reductions in the emissions of acid rain pollutants, under the three additional scenarios examined. The 2010 reduction in SO_2 emissions, when compared to the baseline, ranges from 23% to 33%, and those of NO_x range from 6% to 10%.

The imposition of emissions reduction targets would also affect the ongoing process aiming at market liberalization of electricity. The cases of small to medium emissions reduction targets could have adverse effects on market liberalization in the sense that independent producers will see their position threatened in competitiveness terms.

One of the major conclusions to emerge from this work is the crucial role that the electricity- and steam-generation sector may be called to play in reducing emissions. Orchestrating this role may prove quite difficult in the circumstances of liberalized, mostly privately owned and competitive markets. It is important to recall that the reduction in emissions from the sector are not only due to market forces, such as the relative price of gas and coal, but also due to a number of other factors many of which are influenced by policy. These include any nonfossil fuel obligations, subsidies for renewables (or other measures in support of renewables), difficulties of insurance for nuclear plants, fair tariffs for cogeneration, research and development support for promising generation technologies, and so on. Thus, the task of the regulator becomes even more important in monitoring and ensuring the implementation of a number of potential policy initiatives related to the sector.

Under the carbon constraint scenarios as well as under the nuclear and high price sensitivities, long-term security of supply improves for the EU but it remains a potential concern. Dependence on imported oil is not affected much by any of the alternative assumptions examined and remains close to its level in 2020.

The imposition of carbon constraints does indeed lead to a further penetration of renewables. This is due to their relative price becoming more attractive once fossil fuels have to carry the cost implied by the carbon value. However, their share in total primary energy remains below 8.4%, even under the S6 scenario for 2020. In general, the current EU target for renewables seems very difficult to reach. The cost gap between renewables and fossil fuels remains large, even by the end of the projection period. The reduction in the costs of renewable energy forms needs to be much more substantial than those suggested by the alternative scenarios examined here. Alternatively, technological progress must be much more rapid than assumed here.

Reference

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P. Capros is a professor of energy economics and operation research in the Department of Electrical and Computer Engineering of National Technical University of Athens. He is a member of the board of directors of the Greek Public Corporation. Professor Capros holds an engineering degree from NTUA; three DEAs in economics, informatics and operations research from ENSAE, University of Dauphine, Paris; and a doctorat d'état in mathematical economics from University Pierre et Marie Curie, Paris. He has widely published (more than 100 publications) and conducted research programs in the areas of energy modeling, macroeconomics, operations research, and mathematical programming. He has built and used a variety of large-scale mathematical models. He has more than 15 years professional experience of consultancy in the domain of energy and economic policy.

L. Mantzos is a graduate from National Technical University of Athens, Department of Electrical Engineering. He did postgraduate studies in energy economics and modeling and obtained a Ph.D. degree. He has 10 years experience in energy modeling, in particular in the construction and running of the MIDAS energy model for all European countries and the market equilibrium energy model PRIMES. He participated as a main researcher in several energy analysis projects of the European Commission.

L. Vouyoukas studied economics and econometrics at the Universities of Essex and Southampton in the United Kingdom and at Queen's University in Canada. He worked as a senior consultant at Commodities Research Unit, London, during the 1984-1986 period, carrying out macroeconomic country analysis and industrial modeling. Between 1986 and 1990, he worked as a senior economist in the Corporate Planning Department at British Petroleum Plc, London, where he worked on a large number of issues relating to the oil market. Between 1990 and 1996, he worked as a senior economist and then as head of the Economic Analysis Division, International Energy Agency, Paris. Since leaving IEA, he has worked as a freelance consultant on a variety of energy and economic issues. His clients have included the Organization for Economic Cooperation and Development, the French Ministry of Industry, the IEA, and the European Union.

D. Petrellis studied geology at the University of Athens and has specialized in energy analysis and policy. He is a research assistant at the National Technical University of Athens.