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Post Kyoto Options for Belgium, 2012-2050

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SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY (**SPSD II**)

Post Kyoto Options for Belgium, 2012-2050

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Abstract

This report examines possible post-Kyoto options for Belgium. Climate change is coming up again at the top of the policy agenda with the decision of the European Commission to reduce its GHG emissions by 20% by 2020. The analysis is done with the MARKAL/TIMES model, a partial equilibrium model for the energy system. It is a technico-economic model, which assembles in a simple but economic consistent way technological information (conversion-efficiency, investment- and variable costs, emissions, etc.) for the entire energy system. Two CO2 reduction scenarios for Belgium are analysed up to the horizon 2050, with and without the possibility of nuclear and carbon capture technologies. The scenarios analysed show that it is possible to attain very stringent CO_2 reductions in Belgium. The welfare cost remains limited in the case of a -22.5% reduction in 2050 compared to 1990. The cost is 0.7% of GDP on an annual base but it can become more expensive and reaches up to 1.3% of GDP on an annual base, when the reduction is -52%. These costs are the costs within the energy system without considering any potential side benefits (reduction of other air pollutants and energy security) and assuming a CO_2 tax or a permit system as policy instrument for achieving the CO_2 reduction target, i.e. an efficient instrument.

Keywords: climate change, energy system modelling, post-Kyoto

BELGIAN SCIENCE POLICY

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I. INTRODUCTION

The objective of this report is to examine possible post-Kyoto options for Belgium. Climate change is coming up again at the top of the policy agenda with the decision of the European Commission to reduce its GHG emissions by 20% by 2020. It is therefore important for each country to evaluate what are its costs to reach this target and what are the most promising technologies.

The analysis presented in this report is done with the MARKAL/TIMES model, a partial equilibrium model for the energy system. MARKAL/TIMES is a technico-economic model, which assembles in a simple but economic consistent way technological information (conversion-efficiency, investment- and variable costs, emissions, etc.) for the entire energy system. It can represent all the energy demand and supply activities and technologies for a country over a horizon of 40/80 years, with their associated emissions and the damages generated by these emissions. Compared to ad-hoc models that are more specific to a country or a sector and use another modelling technique, it presents three important advantages:

- due to its transparency it promotes the communication between experts with different sectoral or technological background (it is the place where engineers and economists understand each other),
- it is easily verifiable: its results can be related to assumptions regarding technological data and economic parameters,
- it is comparable at an international level: as many countries use the same model, its results can be immediately compared with results from other countries.

The model is developed within an IEA Implementing agreement, ETSAP, in which Belgium participates. The Belgian version of the model was developed by CES-KULeuven and VITO with the financing of the Belgian Science Policy Office. The work presented here is based on the results of the project 'MARKAL/TIMES, a model to support greenhouse gas reduction policies' of the SPSD II program. It has also benefited from the development of TIMES and the associated software VEDA within the EU research project 'NEEDS'.

In the first section of this report, the different scenarios developed for this analysis are described, then in a second section the results are analysed and the final section concludes. These results are still preliminary and must be complemented by sensitivity studies around the most crucial assumptions. In annex a brief description of the model is given.

II. CONSTRUCTION OF THE SCENARIOS

A. *General Approach*

The general objective of this analysis is to evaluate for Belgium possible paths for its contribution to the EU 20% reduction target for GHG emissions. The starting point is the construction of the reference scenario. It is important to stress the role of this scenario for policy analysis with the TIMES model. The reference scenario has not as objective to give a forecast of the energy system. It gives a consistent path for the energy system, given the cost optimisation approach and the simplified representation of the energy users and suppliers behaviour in TIMES. It is the comparison basis for the policy scenarios to evaluate the cost of policies and their impact on the technological choices in the energy system. The reference scenario can therefore deviate from the evolution of the energy system in recent years which reflects the behaviour of the economic agents in real life, their expectations and the dynamic adjustment of the energy system. It allows however a consistent treatment of the technologies in the policy evaluation.

The construction of the reference scenario is based on assumptions regarding the macroeconomic evolution for Belgium and the World energy prices evolution till 2050 complemented with energy policy assumptions. They are briefly described in the next section. These assumptions are kept constant in the scenarios except for those explicitly changed.

Another important input for MARKAL/TIMES is the technology database with all the characteristics of the technologies considered:

1) technical parameters: efficiency of the process, links between inputs and outputs, joint output ratios etc.
2) capacity parameters: earliest investment date (for new technologies), lifetime of the technology, maximum growth ratio or maximum capacity addition per period, residual installed capacity, bounds
3) cost parameters: investment cost per unit of capacity, fixed maintenance cost, variable costs, delivery costs
4) availability parameters: forced outage, maintenance etc.
5) environmental characteristics: emission ratios per type of process

B. *Macroeconomic and Policy Assumptions*

1. *Macroeconomic assumptions*

The construction of the reference scenario and the policy scenarios start with assumptions on the macroeconomic background and on the evolution of the energy prices. The macroeconomic background for Belgium was derived with GEM-E3, a general equilibrium model for the EU countries. It gives the general growth assumption used for deriving the energy service demands in the reference scenario. The demands are obtained based on assumptions on the elasticity of the sectoral demand with respect to the macroeconomic and sectoral evolution. The international energy prices are those derived in July 2007 with the POLES World energy model by IPTS, a research centre of the European Commission. After the sharp increase in 2005, the oil prices are returning to lower prices before gradually increasing after 2010, gas prices are evolving in parallel. The growth assumption for Belgium remains around 2% a year till 2020, slowing down thereafter to an average of 1.5% mainly driven by the population evolution. The share of the energy intensive sectors is gradually decreasing in favour of the service sectors.

Table 1: Macroeconomic Assumptions for Belgium and international energy prices

	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Demographic/Economic Development												
Population	%/y		0.4%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.0%	-0.1%	-0.1%
GDP	%/y		1.4%	2.2%	2.1%	1.9%	1.8%	1.7%	1.6%	1.5%	1.4%	1.3%
Private Consumption	%/y		1.4%	1.9%	1.7%	1.6%	1.6%	1.6%	1.6%	1.5%	1.5%	1.5%
Industrial activity (energy intensive)	%/y		0.9%	2.4%	2.1%	2.0%	1.7%	1.6%	1.4%	1.1%	0.9%	0.6%
Other industrial activity	%/y		1.3%	2.2%	1.9%	1.8%	1.6%	1.4%	1.3%	1.2%	1.0%	0.9%
Transport activity	%/y		0.9%	2.2%	2.1%	2.0%	1.7%	1.5%	1.3%	1.1%	0.9%	0.7%
Service sector activity	%/y		1.5%	2.0%	2.0%	2.0%	1.9%	1.9%	1.9%	1.9%	1.8%	1.8%
World Energy prices												
Import price crude oil	EUR_{2000}/GJ	4.48	7.23	7.06	7.84	8.25	8.72	9.54	10.25	10.68	11.50	12.35
Import price natural gas	EUR_{2000}/GJ	2.36	3.41	3.77	4.41	5.58	6.82	6.88	7.41	8.25	8.77	9.87
Import price coal	EUR_{2000}/GJ	1.20	1.55	1.78	1.93	2.09	2.23	2.39	2.58	2.77	2.92	3.07

2. *Assumptions for Resources Potential*

Potentials for renewable resources are an important element in the evaluation of the GHG reduction possibilities. The availabilities of the different renewables used in the model are those proposed by J. De Ruyck (2006) for the 'Commissie Energie 2030' (De Ruyck J., 2006). For biomass, it is assumed that 10% of the arable land in Belgium can be used for the production of biocrops, such as wheat or rapeseed and 30% of the forest for the production of wood. Both types of biomass are also available from imports. A limit is imposed on their imports though Belgium as a small country could benefit from an unlimited supply. Moreover, the supply is assumed to be available at an increasing cost by considering two price steps to reflect the pressure of demand when a climate policy would be applied in the whole EU.

For wind energy a distinction is made between on and off shore. The cost of the grid expansion needed for the implementation of the full potential of offshore is included in the cost of the power plants[1]. The data related to the wind technologies and the potentials were also checked with (Palmers G. et al., 2004), (Palmers G. et al., 2004) and (Devriendt N. et al., 2005).

The table hereafter summarizes the potentials assumed for the different sources.

Table 2: Potential for energy sources

		Domestic	Import
Biomass (PJ)	Woodresidue	10.8	
	Wood	22.7	25-83
	Biocrops (wheat & rapeseed)	16.5	25-83 for each crop
Wind (GW)	Onshore cat1	0.63	
	Onshore cat2	0.92	
	Onshore cat3	0.47	
	Offshore cat1	0.60	
	Offshore cat2	0.30	
	Offshore cat3	1.80	
Solar (GW, GWth)	PV	10	
	Hot water	3	

Carbon capture and storage could be an important option when a high reduction target is imposed. Geological disposal in deep aquifers and coal sinks is modelled for the storage of the removed CO_2. A maximum cumulative potential of 100 Mt at a distance less than 20km and of 1000 Mt at higher cost is considered. This potential is present in Belgium (Laenen B. et al., 2004). The 100 Mt can be performed with high certainty in Belgium; 1000 Mt is uncertain (although, if not in Belgium, this could represent foreign sinks).

3. *General policy assumptions*

In the reference scenario, no profound changes regarding the Belgian economic, energy and environmental policies are assumed. The nuclear phase-out is implemented. No climate policy and thus no Kyoto policy is assumed.

In all scenarios, the discount rate is fixed to 4%, reflecting the public sector approach in the policy evaluation with TIMES. Policy measures like subsidies for energy efficient investment or similar measures implemented in the different regions are not explicitly accounted for. This is necessary to allow for a consistent comparison of the technologies. It must be mentioned that in the reference scenario, the perfect foresight/optimisation approach in TIMES can already induce the use of some of the policy-promoted options without any carbon constraint, if they are cost-efficient (the ‘no-regret’ options).

[1] As TIMES is not a mixed integer program, the cost is included as a cost per kw installed; therefore the cost computation is only correct if the full potential is installed in one time when this option is used. (rem. this is usually the case).

4. *Assumptions in the CO_2 reduction scenarios*

Two CO_2 reduction targets were evaluated with TIMES, implying for 2030 a reduction of 15% and 30% respectively and for 2050 a reduction of 22.5% and 52.5% each time compared to the 1990 emissions. Though the second scenario imposes a very high reduction target, it is in the range of reduction targets allowing to reach a 450ppm concentration if there is international cooperation and satisfies the -20% target of the European Commission for 2020.

The Belgian Kyoto target and the nuclear phase-out are imposed in both scenarios. Only CO_2 emissions are considered as the other GHG are not yet modelled and the energy system is only responsible for a small part of the other GHG.

Table 3: CO_2 Targets in the scenarios (emission reduction versus 1990 level)

	2010	2020	2030	2050
KYOTO+	-7.5%	-11.3%	-15.0%	-22.5%
KYOTO++	-7.5%	-20.0%	-30.0%	-52.5%

For the most stringent reduction scenario, 3 possible variations are also assessed. The possibility of using some of the flexibility mechanisms foreseen in the Kyoto protocol is considered in a third scenario associated with the most stringent reduction target. It is assumed that a quarter of the reduction target can be achieved by buying permits abroad. The price of the permits was derived from simulations with the GEM-E3 World general equilibrium model for the European Commission[2]. As the nuclear option is under discussion, a fourth scenario as a variant for the more stringent CO_2 reduction is considered where the nuclear option is allowed up to the existing capacity plus an additional 1700GW. The importance of carbon capture is evaluated in a fifth scenario in which this option is not available.

Climate policy measures such as EU permit system or the promotion of less carbon intensive technologies already in place are not considered explicitly in these scenarios. They might be reflected in the shift in technologies appearing in the policy simulations in time periods before an explicit climate constraint is imposed induced by the expected carbon constraint because of the perfect foresight characteristic of the model.

The scenarios considered in this report are thus:

1. CO2step1-BE-2050: -15% in 2030 and -22.5% in 2050
2. CO2step2-BE-2050: -20% in 2020, -30% in 2030 and -52.5% in 2050
3. CO2step2perbuy-BE-2050: -20% in 2020, -30% in 2030 and -52.5% in 2050 with buying permits abroad for 1/4th of the reduction target
4. CO2step2withnuclear-BE-2050: -20% in 2020, -30% in 2030, -52.5% in 2050, with nuclear
5. CO2step2nostorage-BE-2050: -20% in 2020, -30% in 2030, -52.5% in 2050, without carbon storage

[2] European Commission's Communication of January 2007 "Limiting Global Climate Change to 2 degrees Celsius – The way ahead for 2020 and beyond"

III. THE REFERENCE SCENARIO

A. *Energy services demand*

The macroeconomic evolution as given in the previous section is used to derive a consistent trend in the demands for energy services (tons of steel, km driven, etc..) from the different consumption sectors. The sectoral activity levels and the growth in housing stock and private income (reflected in private consumption evolution) are the main determinants or drivers for the evolution in the demand for energy services in our reference scenario. The heat demand of the base year is corrected for temperature (2000 was a warm year) to compute the demand projections. The heat demand corresponds therefore to an average temperature. The drivers' evolutions are combined with assumptions on the elasticities relating the energy service demand or the product demand to the activity of the sector or the disposable income. The trend obtained determines the shift of the demand curves for these services in MARKAL/TIMES over the horizon considered. The demands are exogenous in the reference scenario but can change in the policy scenarios in function of price changes. Table **4** summarises the growth rates for most energy-demand activities.

Table 4: Energy service demand (annual growth rate)

	2010/2005	2020/2010	2030/2020	2040/2030	2050/2040
Iron&Steel	0.5%	0.4%	0.1%	-0.3%	-0.6%
Ammonia	1.9%	1.5%	1.3%	1.0%	0.6%
Chlorine	1.9%	1.5%	1.3%	1.0%	0.6%
Other Chemical	2.0%	1.5%	1.1%	0.8%	0.2%
Cement	1.5%	1.6%	1.6%	1.4%	1.1%
Glass	1.7%	1.8%	1.7%	1.5%	1.2%
Lime	1.5%	1.6%	1.6%	1.4%	1.1%
Paper	0.6%	0.8%	0.7%	0.5%	0.2%
Other Industry	1.2%	0.9%	0.6%	0.3%	0.0%
Commercial heating/hotwater	0.9%	0.6%	0.5%	0.5%	0.5%
Commercial other	1.2%	1.1%	1.1%	1.1%	1.1%
Residential heating/hot water	0.2%	-0.1%	-0.1%	-0.1%	-0.1%
Residential other	0.7%	0.4%	0.3%	0.3%	0.3%
Agriculture	1.2%	0.7%	0.5%	0.5%	0.4%
Train freight transport	2.1%	1.9%	1.6%	1.3%	0.9%
Road freight transport	1.8%	1.7%	1.4%	1.2%	0.8%
Passenger transport by Bus	0.1%	0.2%	0.2%	0.5%	0.4%
Passenger transport by Car	1.2%	0.9%	0.9%	0.9%	0.9%
Passenger transport by Train	0.2%	0.2%	0.2%	0.0%	-0.1%
Aviation & Navigation	2.7%	2.3%	1.7%	1.4%	1.0%

The economic sectors demands follow the evolution of the economic activity though at a lower pace. The residential sector demand and more specifically the heating and hot water demand grows less because of the small population growth and because of the gradual disappearance of the oldest and less energy efficient dwellings.

B. *Energy use and energy production in the reference scenario in Belgium*

Given the demand for energy services computed with the trends above and the base year (2000) demand, MARKAL/TIMES optimizes the choice of energy processes, the energy efficiency, the choice of fuel by the energy users as well as the choice of energy production processes by the energy sector. The choice is based on the information on the present and future availability of energy technologies, their costs and performance at the level of the energy user and at the level of the energy producer. It is clear therefore that the energy path as derived from this optimisation process, takes into account all the no-regret options and may therefore slightly underestimate the growth of the energy demand. Other criteria besides cost minimisation are driving consumer behaviour and are not reflected in this reference. Expectations on the implementation of a carbon policy that may induce investment in less CO_2 intensive technologies are also not taken into account[3].

The final energy demand increases around 0.2% over the time horizon. The growth is highest in the industry and the transport sector. A gradual improvement in the insulation of buildings contributes to a decrease in the demand of energy for heating. The electricity demand increases more than the fuel demand except for oil products where demand is driven by the increase in transport. The coal consumption remains rather high in the absence of any carbon constraint. The continuous increase of the energy prices after 2020 limits also the increase in energy demand.

Table 5: Final Energy Consumption in the reference scenario (PJ)

	2005	2010	2020	2030	2040	2050	2050/ 2005	share in 2005	share in 2050
by Energy Carrier									
Coal	335	348	383	424	438	431	0.6%	21.1%	24.7%
Petroleum products	572	510	463	500	539	564	0.0%	36.1%	32.4%
Gas	377	432	440	404	338	292	-0.6%	23.8%	16.8%
Electricity	277	287	306	329	361	382	0.7%	17.5%	22.0%
Bio	17	16	27	26	40	56	2.7%	1.1%	3.2%
Waste	7	7	8	9	9	10	0.9%	0.4%	0.6%
Others (Hydrogen)	0	0	0	4	5	5			0.3%
Total	1584	1600	1627	1696	1730	1740	0.2%	100.0%	100.0%
by Sector									
Industry	627	655	717	784	820	822	0.6%	39.6%	47.2%
Commercial	171	172	166	145	124	120	-0.8%	10.8%	6.9%
Households	400	375	336	322	306	293	-0.7%	25.2%	16.9%
Transport	358	367	375	410	445	467	0.6%	22.6%	26.9%
Agriculture	28	30	32	34	36	37	0.6%	1.8%	2.1%
Total	1584	1600	1627	1696	1730	1740	0.2%	100.0%	100.0%

In terms of primary energy, the average growth follows the final energy demand growth. There is a shift to solids when coal power plants replace the nuclear power plants. Oil products keep a relatively high share because they remain the dominant fuel in the transport sector. Renewable energy does not really penetrate given the energy price assumptions (except some wood for heating in the residential sector).

Table 6: Primary Energy Consumption in the reference scenario (abs. in PJ and % share)

	2005	2010	2020	2030	2040	2050
Coal	485	461	773	1124	1198	1228
Oil	1156	1131	1154	1256	1352	1415
Natural gas	483	583	473	435	368	321
Nuclear	505	505	350	0	0	0
Hydro, wind, photovoltaic	3	3	8	8	8	8
Other renewables	18	17	28	28	42	57
Waste	14	24	25	21	23	24
Total	2663	2724	2812	2873	2991	3053
Coal	18%	17%	27%	39%	40%	40%
Oil	43%	42%	41%	44%	45%	46%
Natural gas	18%	21%	17%	15%	12%	10%

[3] When implementing a Kyoto constraint, CO2 savings options in the industrial sector are already appearing in the first period (2000-2005) reflecting the expectations in that sector.

Nuclear	19%	19%	12%	0%	0%	0%
Hydro, wind, photovoltaic	0%	0%	0%	0%	0.3%	0.3%
Other renewables	1%	1%	1%	1%	1.4%	1.9%
Waste	1%	1%	1%	1%	0.8%	0.8%
Total	100%	100%	100%	100%	100%	100%

After the nuclear phase-out, coal becomes the dominant fuel for electricity generation, in the absence of any carbon constraint. There is no further penetration of cogeneration in this scenario.

Table 7: Net electricity generation in the reference scenario (abs. in TWh and % share)

	2005	2010	2020	2030	2040	2050
Coal	17.5	13.6	48.9	92.6	97.3	103.3
Oil	0.0	0.0	0.0	0.0	0.0	0.0
Gas	10.4	16.8	0.1	0.0	0.0	0.0
Nuclear	46.9	46.9	32.4	0.0	0.0	0.0
Hydro	0.7	0.7	0.7	0.7	0.7	0.7
Wind	0.0	0.0	1.5	1.5	1.5	1.5
Solar photovoltaic	0.0	0.0	0.0	0.0	0.0	0.0
Others	1.2	1.9	2.1	2.3	2.3	2.4
Total	76.7	80.0	85.7	97.1	101.8	107.9
of which CHP	4.0	4.4	4.9	6.0	6.1	6.3
Coal	23%	17%	57%	95%	96%	96%
Oil	0%	0%	0%	0%	0%	0%
Gas	14%	21%	0%	0%	0%	0%
Nuclear	61%	59%	38%	0%	0%	0%
Hydro	1%	1%	1%	1%	1%	1%
Wind	0%	0%	2%	2%	1%	1%
Solar photovoltaic	0%	0%	0%	0%	0%	0%
Others	2%	2%	2%	2%	2%	2%
Total	100%	100%	100%	100%	100%	100%
of which CHP	5%	5%	6%	6%	6%	6%

The evolution in the primary energy consumption induces an increase in the CO_2 emissions linked to energy. They are in 2010 15% above the level of 1990 and continue to increase thereafter, especially after 2025 when coal power plants should replace the nuclear power plants. Belgium would therefore have to reduce its CO_2 emissions with 17% in 2010 compared to the reference to reach its Kyoto target. Industry and transport remain the biggest emitters in the first periods but the electricity sector becomes an important polluter when new coal power plants are installed.

Table 8: CO_2 emissions in the reference scenario (Mio.ton)

	2005	2010	2020	2030	2050	share 2005	share 2010	share 2030	share 2050
Industry	41	48	47	50	57	38%	40%	35%	35%
Hous, Com & Agr	28	31	29	26	22	23%	21%	11%	8%
Transport	25	26	25	26	26	20%	20%	16%	16%
Electricity	17	19	19	18	37	15%	14%	36%	38%
Other supply	4	4	4	5	5	4%	4%	3%	3%
Total emissions	117	128	125	125	147	100%	100%	100%	100%

IV. THE CO_2 REDUCTION SCENARIOS

A. General

The impact of imposing the CO_2 reduction targets is threefold:

- a decrease in the demand for energy services because of the price increase induced by the carbon constraint
- a shift towards less carbon intensive fuels, initially from coal to gas[4] and afterwards towards more renewables
- a shift towards more energy efficient technologies.

The total welfare cost in the table hereunder is the additional cost of the CO_2 reduction scenarios in comparison with the reference scenario. This overall welfare cost increases with the stringency of the target, reaching in annual terms approx. 1.3% of GDP for the -30% target. Allowing the nuclear option reduces the cost of the -30% target to the level of the cost of the -15% target without nuclear. The possibility of buying permits abroad reduces also the cost. The availability of carbon storage plays also an important role as the cost almost doubles without this possibility.

Table 9: Total discounted welfare cost (incl. consumer/producer surplus loss)

	%DIF	%GDP2000	annualised%GDP2000
CO2step1-BE-2050	2.8%	15.5%	0.69%
CO2step2-BE-2050	4.9%	28.1%	1.26%
CO2step2perbuy-BE-2050	4.1%	24.9%	1.11%
CO2step2withnuclear-BE-2050	2.9%	17.1%	0.76%
CO2step2nostorage-BE-2050	8.5%	50.0%	2.24%

This cost is the cost on the market of energy services. It does not take into account possible side benefits through the reduction of other external costs linked to energy use. Neither does it include the derived effects on other markets which depend on the policy instrument used[5].

The cost increase is also reflected in the marginal abatement cost of CO_2, i.e. the shadow price of the CO_2 constraint. The marginal cost gives the level of CO_2 tax that would have to be imposed to arrive at this result, i.e. the adoption of the technological options which can satisfy the energy needs in the most cost efficient way given the carbon constraint. The non availability of carbon storage induces a sharp increase in the marginal abatement cost at the end of the horizon because very expensive technologies have to be adopted at the margin. Allowing nuclear, though reducing the total cost, has only a small effect on the marginal abatement cost because the technologies adopted at the margin do not change much. The price of electricity is determined by the marginal technology in the electricity sector and this does not change.

Table 10: Marginal abatement cost of CO_2
(€/ton)

	2010	2020	2030	2040	2050
CO2step1-BE-2050	32	49	76	103	111
CO2step2-BE-2050	31	68	122	257	531
CO2step2perbuy-BE-2050	31	51	104	139	235

[4] At this stage we did not consider the possibility of an increase in the gas price if all countries would shift to gas because of climate constraint.

[5] Cf. double dividend literature.

CO2step2withnuclear-BE-2050	31	60	116	231	499
CO2step2nostorage-BE-2050	34	101	296	771	2471

B. CO_2 emissions

The main contributors to the CO_2 emission reduction are first the power sector and the industry and then the other sectors. The contribution of transport to the emission reduction remains limited and becomes only significant at the end of the horizon with the -52.5% constraint. Storage of carbon penetrates after 2020 and uses its full potential in the -52.5% scenario.

Table 11: CO_2 emissions
(abs. in Mio.t and % difference compared to reference)

	CO2step1-BE-2050			CO2step2-BE-2050			CO2step2perbuy-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Absdif									
Industry	-10	-24	-37	-11	-36	-51	-10	-30	-40
Hous, Com & Agr	-2	-3	-2	-2	-6	-8	-2	-4	-11
Transport	0	-1	-7	0	-5	-16	0	-3	-6
Electricity	-10	-63	-68	-9	-63	-76	-10	-64	-66
Other supply	0	1	4	0	2	3	0	2	2
Total emissions	-22	-89	-110	-22	-109	-149	-22	-98	-122
Storage	0	21	67	0	28	39	0	25	33
% dif									
Industry	-21%	-38%	-54%	-21%	-56%	-75%	-21%	-47%	-59%
Hous, Com & Agr	-6%	-14%	-12%	-7%	-32%	-61%	-7%	-18%	-88%
Transport	-1%	-2%	-22%	-1%	-17%	-48%	-1%	-9%	-17%
Electricity	-57%	-95%	-90%	-53%	-96%	-100%	-56%	-96%	-87%
Other supply	0%	21%	86%	-5%	37%	54%	0%	31%	41%
Total emissions	-18%	-49%	-56%	-18%	-59%	-76%	-18%	-54%	-62%

When nuclear is available, it replaces mostly carbon storage but the reduction pattern remains approximately the same. Without carbon storage the reduction effort becomes relatively more important in the transport and the residential sector.

Table 12: CO_2 emissions
(abs. in Mio.t and % difference compared to reference)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
absdif									
Industry	-11	-36	-51	-10	-35	-51	-10	-38	-45
Hous, Com & Agr	-2	-6	-8	-2	-6	-8	-2	-10	-10
Transport	0	-5	-16	0	-3	-15	0	-9	-23
Electricity	-9	-63	-76	-10	-66	-76	-10	-53	-71
Other supply	0	2	3	0	1	2	0	0	1
Total emissions	-22	-109	-149	-22	-109	-149	-22	-109	-149
Storage	0	28	39	0	10	18	0	0	0
% dif									
Industry	-21%	-56%	-75%	-21%	-55%	-75%	-20%	-59%	-66%
Hous, Com & Agr	-7%	-32%	-61%	-6%	-30%	-59%	-9%	-49%	-74%
Transport	-1%	-17%	-48%	-1%	-9%	-46%	-1%	-32%	-70%
Electricity	-53%	-96%	-100%	-54%	-99%	-100%	-53%	-79%	-94%
Other supply	-5%	37%	54%	-5%	10%	33%	-5%	2%	24%
Total emissions	-18%	-59%	-76%	-18%	-59%	-76%	-18%	-59%	-76%

C. *Energy service demand*

The demand function for energy services, linking the demand to the price of the demand is a short cut to represent all substitution and behavioural reactions outside the energy use and production sectors. Every policy scenario that affects the energy sector will alter the marginal cost or price of energy services and this will affect the level of demand for energy services.

The impact on the demand increases with the stringency of the carbon constraint, especially when carbon storage is excluded. The reductions are more limited where the abatement possibilities through change in technologies or fuel substitution are large. Reduction in demand remains however an important contribution to CO_2 reductions. It can cover various options such as the substitution of energy by another good, a better overall organisation in the industry and the service sector or a loss in comfort, a change in life style, construction norms or urban planning. The high increase in the energy cost can make the tracking of energy savings a high priority.

Table 13: Energy service demand in 2030 and 2050
(% difference compared to reference)

	2030			2050		
	CO2step1-BE-2050	CO2step2-BE-2050	CO2step2perbuy-BE-2050	CO2step1-BE-2050	CO2step2-BE-2050	CO2step2perbuy-BE-2050
Iron&Steel	-13%	-13%	-13%	-10%	-20%	-13%
Ammonia	-10%	-12%	-12%	-12%	-20%	-15%
Chlorine	-5%	-5%	-5%	-5%	-5%	-5%
Other Chemical	-17%	-20%	-20%	-18%	-33%	-25%
Cement	-25%	-25%	-25%	-25%	-30%	-28%
Glass	-5%	-8%	-7%	-8%	-20%	-12%
Lime	-25%	-33%	-30%	-30%	-50%	-40%
Paper	-8%	-8%	-8%	-7%	-15%	-10%
Other Industry	-20%	-22%	-22%	-20%	-35%	-28%
Commercial heating/hotwater	-6%	-7%	-6%	-8%	-11%	-8%
Commercial other	-1%	-1%	-1%	-2%	-2%	-2%
Residential heating/hot water	-7%	-9%	-9%	-8%	-17%	-11%
Residential other	-4%	-6%	-5%	-6%	-9%	-6%
Agriculture	-12%	-15%	-15%	-13%	-28%	-20%
Road freight transport	-2%	-5%	-5%	-5%	-15%	-10%
Train freight transport	0%	-2%	-2%	-3%	-2%	-2%
Passenger transport by Bus	-2%	-3%	-2%	-3%	-6%	-3%
Passenger transport by Car	0%	0%	0%	-2%	-7%	-5%
Passenger transport by Train	-2%	-2%	-2%	-2%	-2%	-2%
Aviation & Navigation	-2%	-3%	-3%	-3%	-7%	-4%

The availability of nuclear does not induce a smaller shift in the demand. Though it reduces the total cost of the climate policy, it has only a small impact on the marginal cost of electricity and hence on the energy service demand[6]. No carbon storage induces however a further shift in demand.

Table 14: Energy service demand in 2030 and 2050
(% difference compared to reference)

	2030			2050		
	CO2step2-BE-2050	CO2step2withnuclear-BE-	CO2step2nostorage-BE-	CO2step2-BE-2050	CO2step2withnuclear-	CO2step2nostorage-BE-2050

[6] The marginal technology remains the same whether nuclear is available or not.

		2050	2050		BE-2050	
Iron&Steel	-13%	-13%	-23%	-20%	-20%	-45%
Ammonia	-12%	-12%	-28%	-20%	-20%	-50%
Chlorine	-5%	-5%	-10%	-5%	-5%	-32%
Other Chemical	-20%	-20%	-32%	-33%	-33%	-50%
Cement	-25%	-25%	-43%	-30%	-30%	-50%
Glass	-8%	-8%	-15%	-20%	-19%	-42%
Lime	-33%	-30%	-42%	-50%	-50%	-50%
Paper	-8%	-8%	-12%	-15%	-15%	-38%
Other Industry	-22%	-22%	-33%	-35%	-35%	-50%
Commercial heating/hotwater	-7%	-7%	-15%	-11%	-10%	-39%
Commercial other	-1%	-1%	-5%	-2%	-2%	-15%
Residential heating/hot water	-9%	-9%	-18%	-17%	-16%	-40%
Residential other	-6%	-6%	-11%	-9%	-9%	-32%
Agriculture	-15%	-15%	-25%	-28%	-28%	-48%
Road freight transport	-5%	-5%	-12%	-15%	-15%	-37%
Train freight transport	-2%	-2%	-2%	-2%	-2%	-17%
Passenger transport by Bus	-3%	-3%	-5%	-6%	-6%	-26%
Passenger transport by Car	0%	0%	0%	-7%	-7%	-17%
Passenger transport by Train	-2%	-2%	-5%	-2%	-2%	-19%
Aviation & Navigation	-3%	-3%	-6%	-7%	-7%	-13%

D. *Final energy consumption*

There is a shift away from coal, which is replaced by gas and to a smaller extent by electricity and renewables. At the beginning of the period the main reductions are in the industry but at the end of the horizon higher reductions are observed in the residential sector and also in the transport sector. The reduction in final energy demand attains -27% compared to the reference in 2050 in the most stringent case.

Table 15: Final energy consumption (abs difference compared to reference in PJ)

	CO2step1-BE-2050			CO2step2-BE-2050			CO2step2perbuy-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
by fuel									
Coal	-86	-182	-217	-87	-270	-394	-85	-206	-347
Petroleum products	-26	-24	-120	-18	-89	-382	-29	-55	-230
Gas	-11	-45	-14	-23	-42	175	-10	-54	114
Electricity	-13	-29	-30	-12	-17	-7	-12	-29	-30
Renewables (wind, hydro, sol)	0	0	0	0	0	3	0	0	0
Bio	53	53	99	51	99	146	52	72	83
Waste	2	3	4	1	0	-10	1	3	1
Others (Hydrogen)	0	0	0	0	0	0	0	0	0
Total	-81	-224	-278	-88	-320	-470	-83	-269	-408
by sector									
Industry	-53	-160	-172	-54	-188	-250	-52	-179	-227
Commercial	-8	-19	-8	-13	-42	-11	-9	-26	-8
Residential	-14	-34	-53	-16	-67	-126	-16	-45	-108
Transport	-4	-7	-40	-4	-18	-72	-4	-15	-57
Agriculture	-2	-4	-5	-2	-5	-11	-2	-5	-7
Total	-81	-224	-278	-88	-320	-470	-83	-269	-408
Total (% diff comp. to reference)	-4%	-12%	-14%	-4%	-17%	-27%	-4%	-14%	-22%

With nuclear there are no major shifts in the final demand compared to the case without as the price of electricity is not very different. Without carbon storage the reduction in demand is higher and other options are becoming cost efficient because of the higher price of electricity. In the transport sector there is a shift towards bio-fuels. The reduction in total final demand compared to the reference is nearly doubled attaining -46% in 2050.

Table 16: Final energy consumption
(abs difference compared to reference in PJ)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
by fuel									
Coal	-87	-270	-394	-84	-253	-384	-85	-337	-371
Petroleum products	-18	-89	-382	-18	-57	-377	-18	-304	-492
Gas	-23	-42	175	-25	-48	163	-29	91	21
Electricity	-12	-17	-7	-12	-19	-10	-12	-43	-141
Renewables (wind, hydro, sol)	0	0	3	0	0	3	0	0	7
Bio	51	99	146	51	70	136	52	110	157
Waste	1	0	-10	1	0	-10	2	-2	-10
Others (Hydrogen)	0	0	0	0	0	0	0	0	-2
Total	-88	-320	-470	-88	-307	-480	-90	-486	-831
by sector									
Industry	-54	-188	-250	-54	-186	-274	-57	-278	-420
Commercial	-13	-42	-11	-13	-38	-10	-15	-55	-35
Residential	-16	-67	-126	-15	-64	-125	-12	-106	-194
Transport	-4	-18	-72	-4	-15	-61	-4	-40	-172
Agriculture	-2	-5	-11	-2	-5	-11	-2	-8	-11
Total	-88	-320	-470	-88	-307	-480	-90	-487	-831
Total (% diff comp. to reference)	-4%	-17%	-27%	-4%	-17%	-26%	-4%	-27%	-46%

E. Technological options in the final demand sectors

1. Residential sector

Oil still remains the dominant fuel for heating till the middle of the horizon, after that gas boiler and heat pump on electricity and gas (delivering heat and hot water), are penetrating. The shift occurs faster when the carbon constraint increases. However, when the electricity price increases more, as in the scenario without carbon storage, the penetration is slower. As an illustration, the table hereafter gives the increase in the total system cost if investing one unit of the technology in relation to the investment cost of the technology for technologies in the residential sector (in new and existing four walls houses). It gives the % change of the investment cost of a technology needed to allow its penetration in an optimised system given the fuel price assumptions. It shows clearly the comparative advantage of heat pump especially in new houses when high carbon constraints are imposed. They are competing with wood pellets in existing houses.

Table 17: Change needed in investment cost for the penetration of the technologies
(space heating for existing and new houses in %)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
[RSD.Space Heat.Single.Rural.BIOpellet.Ex01.Boiler]	0%	17%	0%	4%	15%	0%	9%	3%	0%
[RSD.Space Heat.Rural.ELC.Ex01.Ground Heat Pump.]	7%	3%	12%	14%	2%	11%	2%	16%	15%
[RSD.Space Heat.Rural.OILELC.Ex01.Boiler Heat Pump.]	6%	1%	10%	12%	0%	10%	0%	10%	20%
[RSD.Space Heat.Rural.GASELC.Ex01.Boiler Heat Pump.]	10%	0%	0%	15%	0%	0%	1%	0%	3%
[RSD.Space Heat.Rural.GAS.Ex01.CondensedBoiler]	0%	21%	15%	7%	12%	10%	0%	13%	65%
[RSD.Space Heat.Rural.OIL.Ex01.Boiler]	25%	90%	132%	34%	84%	132%	42%	132%	132%
[RSD.Space Heat.Single.Rural.BIOpellet.NE01.Boiler]	35%	78%	100%	30%	76%	100%	51%	84%	100%
[RSD.Space Heat.Rural.ELC.NE01.Ground Heat Pump.]	0%	6%	20%	0%	5%	19%	2%	8%	0%
[RSD.Space Heat.Rural.OILELC.NE01.Boiler Heat Pump.]	0%	0%	0%	0%	0%	0%	0%	0%	3%

[RSD.Space Heat.Rural.GASELC.NE01.Boiler Heat Pump.]	0%	0%	0%	0%	0%	0%	0%	0%	0%
[RSD.Space Heat.Rural.GAS.NE01.CondensedBoiler]	39%	94%	123%	34%	88%	123%	58%	114%	123%
[RSD.Space Heat.Rural.OIL.NE01.Boiler]	88%	132%	132%	82%	132%	132%	109%	132%	132%

For hot water, gas is the dominant fuel, but solar hot water combined with gas takes a small share of the market with the high carbon constraint and no carbon storage.

The additional contribution of insulation is very limited as nearly the whole potential was cost efficient in the reference. Energy-efficient lamps were also cost-efficient in the reference scenario.

2. *Service sector*

Heat pumps of different types (ground heat pump on electricity and on gas with absorption technology) are penetrating fast for heating. For the rest the evolution is rather similar as the one in the residential sector.

3. *Industry*

There is a gradual shift to the more energy efficient technologies and towards less CO_2 intensive fuels when the substitution is possible as for steam and heat production. CHP technologies are not really penetrating except for the CHP on wood; this is the most cost efficient application of wood taking into account the carbon constraint.

Looking more specifically at two subsectors in the industry, one can see the importance of carbon capture availability for the relative advantage of technologies making use of it. Improved efficiency is the determining factor for the chlorine technology choice.

Table 18: Change needed in investment cost for the penetration of ammoniac and chlorine technologies (in %)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050LOBO		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
IAMADVCAP01 [IAM.Advanced Production.CO2 Capture]	0%	0%	0%	0%	0%	0%	128%	142%	142%
IAMADVPRO01 [IAM.Advanced Production.]	126%	152%	152%	121%	152%	152%	3%	0%	0%
IAMSTDPRO01 [IAM.Standard Production.]	113%	148%	148%	109%	148%	148%	0%	57%	118%
ICLADVPRO01 [ICL.Advanced Membrane Production]	12%	15%	18%	12%	15%	18%	42%	89%	140%
ICLADVPRO05 [ICL.Improved Membrane Production]	0%	0%	0%	0%	0%	0%	0%	0%	0%
ICLSTDPRO01 [ICL.Standard Production]	294%	307%	307%	292%	307%	307%	304%	307%	307%

4. *Transport*

There are no major shifts in the transport sector as long as the highest carbon constraint is not imposed and as long one considers the period to 2020. Compressed natural gas, ethanol and biodiesel are penetrating from 2030 onwards as alternative fuels till the full potential of import and domestic production of biocrops is used[7]. The table hereafter gives as an illustration the relative position of car technologies.

Table 19: Change needed in investment cost for the penetration of the car technologies (in %)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
[Car.Biodiesel]	21%	13%	0%	22%	14%	1%	19%	5%	26%
[Car.Hydrogen.Combustion]	56%	59%	45%	55%	58%	43%	61%	89%	104%
[Car.DST.EURO4]	1%	1%	7%	1%	1%	6%	1%	10%	51%

[7] Mixing biofuels with oilfuels can be seen as a first step to a more generalised use, cars on biofuels being more efficient.

[Car.Electric.Battery]	41%	146%	163%	41%	150%	163%	39%	91%	146%
[Car.Hydrogen.FuelCell]	58%	29%	20%	58%	29%	20%	60%	33%	24%
[Car.Hydrogen.Hybrid.FuelCell]	59%	34%	25%	59%	34%	26%	60%	36%	27%
[Car.GAS.CNG]	3%	0%	0%	4%	1%	0%	2%	0%	11%
[Car.GSL.EURO4]	0%	0%	7%	0%	0%	6%	0%	10%	53%
[Car.DST.EURO4.parallelhybrid]	18%	17%	20%	18%	17%	19%	18%	23%	51%
[Car.GAS.CNG.parallelhybrid]	13%	8%	4%	13%	9%	5%	12%	4%	0%
[Car.GSL.EURO4.parallelhybrid]	6%	3%	1%	6%	3%	1%	5%	4%	17%
[Car.Hydrogen.Hybrid.Combustion]	57%	63%	49%	56%	63%	48%	60%	85%	95%

The results show that bio fuels and compressed natural gas are important options when high carbon constraints are imposed. Hydrogen remains more expensive with the data in the model. The options remain rather close in terms of costs and may be very sensitive to the cost of the fuel. For instance the gas price may increase sharply if there is a general shift towards gas in the EU. It is therefore important to make sensitivity studies around the relative fuel prices, the technology cost and the potential of biocrops to be able to identify the more promising technological options.

F. Electricity generation and technological options

The impact of the carbon constraint is twofold: the electricity demand decreases and gas replaces coal. The electricity demand decreases less in the most stringent case because options using electricity in the demand sectors are cheaper to reduce the CO_2 emissions (e.g. heat pumps for heating). The carbon sequestration is linked to gas power plants. The cost of sequestration per ton of CO_2 is lower when linked to a coal power plant, but the final cost per kWh (including the penalization of CO_2 and the sequestration cost) is lower with gas power plants and this is the relevant variable for the choice of the sequestration option. This result depends however on the relative cost of gas. If the increased demand of gas due to climate policy in many countries leads to an increase of the international gas price, this relative advantage of carbon sequestration associated with gas may be reduced.

The contribution of CHP is increasing slightly when the carbon constraint is not too stringent but not anymore with the more stringent case. Wind energy is penetrating in all scenarios. The share of renewables in electricity generation reaches 17% in 2020 and 23% in 2050 in the most stringent scenario.

Table 20: Net Electricity generation
(abs. differences compared to reference in TWh)

	CO2step1-BE-2050			CO2step2-BE-2050			CO2step2perbuy-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Coal	-9.4	-87.1	-30.4	-8.8	-87.8	-103.3	-9.1	-87.8	-103.3
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas	-2.2	66.0	0.0	-2.2	70.6	82.8	-2.2	66.6	71.1
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind	1.5	4.4	13.7	1.5	4.4	14.1	1.5	4.4	14.1
Solar photovoltaic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	5.9	8.7	10.0	5.7	8.6	5.8	5.9	9.1	10.5
Total	-4.1	-8.0	-6.7	-3.8	-4.2	-0.5	-3.9	-7.7	-7.5
of which CHP	5.9	5.8	6.1	5.4	5.0	-1.4	5.9	5.6	3.7

When nuclear is allowed, it becomes the dominant fuel for electricity generation but it has no impact on the total demand for electricity (cf. Table 15 and Table 16) as the marginal cost of electricity production does not change.

The non availability of carbon storage increases the marginal cost of electricity dramatically and therefore induces a sharp decrease in electricity demand.

Table 21: Net Electricity generation
(abs. differences compared to reference in TWh)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Coal	-8.8	-87.8	-103.3	-8.9	-87.8	-103.3	-9.6	-87.8	-103.3
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas	-2.2	70.6	82.8	-2.1	11.5	21.0	0.1	44.0	33.1
Nuclear	0.0	0.0	0.0	0.0	57.9	57.9	0.0	0.0	0.0
Hydro	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind	1.5	4.4	14.1	1.5	4.4	14.1	1.5	14.1	14.1
Solar photovoltaic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	9.5
Others	5.7	8.6	5.8	5.7	8.6	8.0	4.4	8.0	5.7
Total	-3.8	-4.2	-0.5	-3.8	-5.4	-2.2	-3.6	-12.6	-40.9
of which CHP	5.4	5.0	-1.4	5.6	5.0	3.2	4.5	4.5	11.4

The relative position of the different electricity generation technologies are reflected in the table hereafter, where the increase in total system cost relative to the technology investment cost is given.

Table 22: Change needed in investment cost for the penetration of the technology (in %)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
[EPLT: Comb Cyc.GAS.New]	22%	27%	26%	21%	27%	27%	0%	0%	75%
[EPLT: Comb Cyc CO2Seq.GAS.New]	0%	0%	0%	0%	0%	7%	75%	61%	106%
[EPLT: Fuel Cell.GAS.New]	137%	124%	95%	138%	123%	96%	124%	0%	0%
[EPLT: Fuel Cell.HH2.New]	163%	114%	86%	163%	114%	86%	171%	81%	134%
[EPLT: IGCC.COH.New]	115%	100%	99%	114%	100%	99%	116%	100%	134%
[EPLT: IGCC.CO2Seq.COH.New]	65%	74%	80%	58%	71%	82%	115%	106%	125%
[EPLT: IGCC.WOO.New]	109%	129%	126%	105%	128%	126%	140%	103%	74%
[EPLT: IGCC CO2Seq.WOO.New]	45%	20%	41%	46%	24%	13%	128%	122%	136%
[EPLT: PV Plant Size.SOL.New]	78%	48%	29%	79%	49%	31%	0%	0%	36%
[EPLT: PV Roof panel.SOL.New]	92%	73%	59%	93%	74%	60%	36%	5%	16%
[EPLT: SC.Steam.Turb.COH.New]	103%	89%	88%	103%	89%	88%	109%	89%	130%
[EPLT: SC.Steam.Turb.CO2seq.COH.New]	93%	92%	93%	86%	91%	93%	111%	99%	123%
[EPLT: Steam.Turb.WOO.HT.New]	133%	120%	117%	133%	120%	117%	139%	120%	157%
[EPLT: Wind Offshore 1.Close]	0%	0%	0%	0%	0%	0%	0%	0%	0%
[EPLT: Wind Offshore 2.Medium]	1%	0%	0%	3%	0%	0%	0%	0%	0%
[EPLT: Wind Offshore 3.Far]	23%	4%	0%	25%	5%	0%	0%	4%	17%
[EPLT: Wind Onshore 1.High]	29%	0%	0%	29%	0%	0%	0%	0%	0%
[EPLT: Wind Onshore 2.Medium]	15%	0%	0%	15%	0%	0%	13%	0%	0%
[EPLT: Wind Onshore 3.Low]	27%	12%	2%	29%	12%	2%	8%	0%	0%

Wind energy and power plants with carbon sequestration, when allowed, are the more interesting technologies. Fuel cell technologies on gas and solar roof technologies are considered when no carbon storage is available. CHPs on wood are also becoming more interesting with high carbon constraint.

G. *Primary energy*

The different options chosen in the energy system are reflected in the impact on the primary energy consumption. The carbon constraints reduce the primary energy consumption of coal; it is replaced by natural gas or nuclear when it is allowed. Renewables are penetrating further but only to their full potential when the high carbon constraint is imposed.

Table 23: Primary Energy
(abs. differences compared to reference in PJ)

	CO2step1-BE-2050			CO2step2-BE-2050			CO2step2perbuy-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Coal	-177	-871	-342	-171	-948	-1189	-173	-898	-1113
Oil	-26	-24	-117	-18	-86	-377	-29	-54	-226
Natural gas	-25	378	57	-38	427	719	-25	382	579
Nuclear	0	0	0	0	0	0	0	0	0
Hydro, wind, photovoltaic	5	16	49	5	16	54	5	16	51
Other renewables	82	92	214	82	200	322	82	138	231
Waste	-9	0	0	-13	-8	-8	-11	0	-8
Total	-150	-408	-139	-152	-399	-478	-150	-416	-486
Total (% diff comp. to reference)	-6%	-14%	-5%	-6%	-14%	-16%	-6%	-14%	-26%

Table 24: Primary Energy
(abs. differences compared to reference in PJ)

	CO2step2-BE-2050			CO2step2withnuclear-BE-2050			CO2step2nostorage-BE-2050		
	2010	2030	2050	2010	2030	2050	2010	2030	2050
Coal	-171	-948	-1189	-170	-943	-1180	-177	-994	-1145
Oil	-18	-86	-377	-18	-56	-372	-18	-301	-487
Natural gas	-38	427	719	-39	35	321	-29	349	170
Nuclear	0	0	0	0	590	590	0	0	0
Hydro, wind, photovoltaic	5	16	54	5	16	54	5	83	92
Other renewables	82	200	322	82	138	322	78	223	322
Waste	-13	-8	-8	-13	-8	-8	-11	-8	-8
Total	-152	-399	-478	-153	-227	-273	-153	-648	-1056
Total (% diff comp. to reference)	-6%	-14%	-16%	-6%	-8%	-9%	-6%	-23%	-35%

Oil remains the dominant fuel mainly because of transport. Gas becomes important when carbon capture is available. The share of renewables reaches 5% in 2020 and rises to 17% in 2050 in the most stringent CO2 reduction scenario. Without carbon storage, their share can reach 24%. These results have to be put in line with the EU 20% renewable target for 2020. They indicate that, at least for Belgium and taking into account only climate change, the target seems to be too high.

Table 25: Shares in primary energy (%)

	CO2step2-BE-2050		CO2step2withnuclear-BE-2050		CO2step2nostorage-BE-2050	
	2020	2050	2020	2050	2020	2050
Coal	11%	2%	11%	2%	7%	4%
Oil	45%	40%	43%	38%	46%	46%
Natural gas	24%	40%	17%	23%	26%	25%
Nuclear	14%	0%	24%	21%	15%	0%
Renewables	5%	17%	5%	16%	6%	24%
Waste	0%	1%	0%	1%	0%	1%

V. CONCLUSION

The scenarios analysed above show that it is possible to attain very stringent CO_2 reductions in Belgium. The welfare cost remains limited in the case of a -22.5% reduction in 2050 compared to 1990. The cost is 0.7% of GDP on an annual base but it can become more expensive when further reductions are imposed, up to 1.3% of GDP on an annual base. These costs are the costs within the energy system without considering any potential side benefits (reduction of other air pollutants and energy security) and assuming a CO_2 tax or a permit system as policy instrument for achieving the CO_2 reduction target, i.e. an efficient instrument.

The CO_2 constraints do not impose major shifts in the energy system in the medium term. The use of more energy efficient technologies and a switch to gas are predominant. It should be mentioned that building insulation and saving lamps are already cost efficient in the reference scenario and because of the many barriers to their use in real life, it is important to address this issue by specific policies. Renewables such as wood and wind on shore are also penetrating rapidly. While their share in the electricity production is between 15% and 20%, it attains only 5% in total primary energy. Therefore, the cost efficient contribution of Belgium to the EU 20% renewable target for 2020, at least regarding the climate change objective, is far below 20%.

In the long term, after 2030, alternative fuels such as compressed natural gas, ethanol, biodiesel are penetrating in the transport sector, offering further reduction possibilities. The relative cost of these technological options seems to be rather close and the same is true for hydrogen (which does not penetrate in the scenarios here). Therefore the choice between these different options is very sensitive to the various assumptions underlying the scenarios.

A major contribution to the reduction of the CO_2 emissions is also obtained from a reduction in the energy service demand. This reduction can cover a great number of changes outside the energy system: new production organisations, change in life style, in urban planning, ….

These different conclusions are clearly dependent on the cost and assumptions implemented in the model database and in the scenarios. If all countries were shifting to natural gas for the reduction of their CO_2 emissions this could have a large impact on the price of gas on the international market. This possible impact has not been taken into account in these first results and must be further examined. Moreover some technologies are relatively close in terms of overall cost and changes in the cost of one component could induce shifts in the choice of technologies. There is not one technology or one energy stream dominating the future picture. Therefore this analysis should be complemented by sensitivity studies around the main parameters. Also, though the cost of implementing a complete infrastructure for the penetration of some option is taken into account, large resources will have to be mobilised over a rather short period for these infrastructures.

The possibility of buying CO_2 permits abroad through the European trading system or through JI or CDM projects can reduce the cost of CO_2 reduction for Belgium. The potential for cost reduction is however only large when the number of countries with reduction targets and the level of the targets are not too high.

The analysis of the different CO_2 reduction scenarios has shown the interactions between the choice of technologies in the different sectors in function of their relative cost and the availability of technologies such as nuclear or carbon storage. This stresses the importance of evaluating reduction potentials with a model such as TIMES, which integrates the whole energy system and takes into account the different trade-off in the system in a consistent way.

One should however keep in mind the characteristics and limitations inherent to a model as MARKAL/TIMES. The strongest point of the model is its consistency in treating technology related problems in the energy-environment domain. It gives good first insights for energy policy formulation and guidelines for technology policy but should be supplemented by complementary studies in both fields. A major difficulty in the direct use of the TIMES model results for specific policy formulation comes from the naive representation of energy users and suppliers in the model. It is assumed that all market participants use the same objective function (cost minimisation with imputed shadow costs for the active environmental constraints), that they have the same information and the same subjective beliefs (perfect foresight solution) and finally that the market prices equal the discounted marginal costs corrected for imputed shadow prices. The model has also limitations due to its structure: no explicit uncertainty, convex cost functions (no increasing returns to scale) and linear technologies, limited geographical scope (internal energy market), and aggregation of activities.

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Annex: The MARKAL/TIMES model

I. INTRODUCTION

The Markal/Times model is a long term multi-period energy technology optimisation model developed within an IEA Implementing agreement, ETSAP, in which Belgium participate with the financing of Belgian Science Policy Office through SPSD Programs. It is therefore the result of an international cooperative effort. The Belgian version of the model was developed by CES-KULeuven and VITO with the financing of the Belgian Science Policy Office.

Markal/Times has been used in the past for a wide variety of problem ranging in geographical scope from the energy problems of a city to the energy problems of a large country like the US. It has been used for the estimation of the overall costs for the economy of certain energy policy options (like nuclear moratorium), for feasibility studies of certain energy-environmental policy goals (acid rain reduction, CO2 emissions limits), for the estimation of the potential market of certain new technologies (renewables, substitute fuels).

II. THE MODEL APPROACH

The basic idea of energy flow models is to represent explicitly the trade-offs in the energy systems going from the mining, import or production of energy, over the transformation and distribution up to the level of the energy users delivering useful energy. The different phases involved are represented in figure 1.

Figure 1

The trade-offs are total economic cost versus environmental effects or versus other energy objectives like energy security. Environmental effect can be CO2, SO2 or NOx emissions or other external effects like land use.

Not all trade-offs in the energy-environment-economy field are present in the model. In the actual version are excluded :

1. *The economic costs in the model are based on input prices which do in principle not depend on the activities of the energy sector itself.* There is no feedback via balance of payments constraints, via intermediate deliveries to the energy sector etc... The input prices can however be an increasing function of the quantity used by the energy sector.
2. The availability and other *characteristics of technologies are given, certain and exogenous to the model*.
3. There is no detailed modelling of the behaviour of the different actors. Their behaviour is simulated in a coherent but naive way.

III. MODEL STRUCTURE

The basic structure is represented in figure 2.

Figure 2

A. Basic Components

The model contains four types of information: sources of supply which are linked to useful demands via energy activities and finally a cost function and environmental objectives.

1. Sources of supply

The sources of supply of energy cover all means by which energy can enter or leave the system (other than to meet energy demands). The sources of supply are distinguished by type of energy, cost, origin and environmental characteristics (e.g. sulphur content of coal). The national production possibilities can be limited absolutely or can be available at rising marginal costs.

2. *Energy activities/Technologies*

The energy activities are described through technologies. Three types of technologies are generally distinguished:

1. conversion technologies: load dependent plants generating electricity or district heat
2. process technologies: all other transformation activities, load-independent
3. demand technologies: all devices consuming energy to meet energy demands

3. *Useful energy demands*

Exogenous useful energy demands have to be specified for the reference scenario in function of the delivery characteristics (small or large consumers), in function of their existing energy-using capital (e.g. number of installations with central heating by gasoil) and for the load dependent types of energy (electricity and heat) in function of the season and the period within the day (day/night). These demands are flexible in function of the price evolution in the scenarios.

4. *Objective function*

The minimisation of the cost function selects one of the feasible solutions. The cost function includes in a planning framework all cost elements relevant for the society as a whole. Consequently excludes in principle the amortisation and financial costs of existing equipments and excludes taxes except when they represent genuine social costs like e.g. the motorfuel taxes which represent congestion costs.

One could include in principle also other environmental costs but the most important are handled through an absolute constraint. When absolute upper bounds are put on the total emissions of a pollutant (like CO2) and when these bounds are active, all activities generating CO2 are internally penalised at the level of the marginal cost of CO2 reduction - this is equivalent to the inclusion of a social cost element in the cost function.

5. *A multi-period model*

The model is a long term model: the period 1990-2030 is covered through successive 5 year periods, and the different periods are linked through residual capacities. The costs in the different periods are weighted using a discount factor of 5 %. This 5 % is often justified as "public" investment discount rate.

6. *Technology characterisation*

The most important input to the model are the characteristics of present and future technologies. It is among these technologies that the model will have to choose in order to satisfy exogenous demand. The technologies are characterised by the following information:

1. technical parameters: efficiency of the process, links between inputs and outputs, joint output ratios etc.
2. capacity parameters: earliest investment date (for new technologies), lifetime of the technology, maximum growth ratio or maximum capacity addition per period, residual installed capacity
3. cost parameters: investment cost per unit of capacity, fixed maintenance cost, variable costs, delivery costs
4. availability parameters: forced outage, maintenance etc.
5. environmental characteristics: emission ratios per type of process used
6. bounds: on annual process activity, on investment per period

B. *Mathematical Formulation and Model Implementation*

The problem is formulated as a linear program. The different elements are

- the objective function,
- the "static" constraints which have to do with the feasibility of the energy flow activities during each sub-period of 5 years and
- the "dynamic" constraints which define the available capacities in each period as a function of present and past investments.

The software consists of:

- the GAMS software
- an interactive users support system designed for Markal/Times (VEDA-FE and VEDA-BE) facilitating the data entry and management as well as the interpretation and comparison of results.

IV. MODEL USES AND LIMITATIONS

1. The strongest points of the model are its consistency in treating technology related problems in the energy-environment domain. The model has been used already extensively for the computation of the economic costs of CO2 emission constraints and its relation with other environmental problems like the use of nuclear energy, SO2, NOx etc.

The model gives good first insights for energy policy formulation and guidelines for technology policy but should be supplemented by complementary studies in both fields.

2. The major difficulties in the use of Markal/Times model results for policy formulation come from the *naive representation of energy users and suppliers in the model*. It is assumed that all market participants use the same objective function (cost minimisation with imputed shadow costs for the active environmental constraints), that they have the same information and the same subjective beliefs (perfect foresight solution) and finally that the market prices equal the discounted marginal costs corrected for imputed shadow prices.

3. The model has also important limitations due to its structure: no explicit uncertainty, convex cost functions (no increasing returns to scale) and linear technologies, limited geographical scope (internal energy market), and aggregation of activities.

The Center for Economic Studies (CES) is the research division of the Department of Economics of the Katholieke Universiteit Leuven. The CES research department employs some 100 people. The division Energy, Transport & Environment (ETE) currently consists of about 15 full time researchers. The general aim of ETE is to apply state of the art economic theory to current policy issues at the Flemish, Belgian and European level. An important asset of ETE is its extensive portfolio of numerical partial and general equilibrium models for the assessment of transport, energy and environmental policies.

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