FINAL REPORT

Commission of the European Communities:
Directorate General XVII

DILEMMA STUDY: Study of the Contribution of Nuclear Power to the Reduction of Carbon Dioxide Emissions from Electricity Generation

July 1999

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EXECUTIVE SUMMARY

The *DILEMMA* Study was carried out on behalf of DG XVII to investigate the *Contribution of Nuclear Power to the Reduction of Carbon Dioxide Emissions from Electricity Generation*.

Nuclear power is not generally perceived to have fulfilled the great expectations of its early days. It is marginally economic at best at present in most countries in Europe, and there is great uncertainty over its future.

On the other hand, there is increasing international concern with climate change, and the targets agreed by the European Union under the Kyoto Protocol to reduce emissions of greenhouse gases in 2010 by 8% compared to 1990 levels represent a real challenge. Clearly nuclear power can make a significant contribution to reducing emissions of carbon dioxide (CO_2), but the technology engenders its own environmental impacts, notably waste products of various levels of radioactivity, spent fuel and plutonium.

Therefore the European Union and its Member States face a dilemma in assessing whether or not the climate change benefits of the nuclear option outweigh the economic costs and the environmental impacts of nuclear itself. There are two main issues concerned with sustaining the European nuclear park as the existing plants come to the end of their design life. They are:

- the extension of the lifetime of existing plant;
- the timing and extent of new build (if any).

Using a specifically designed power system model (*DILEMMA*, written in MS EXCEL and handed over to DG XVII), this study has produced:-

- a quantitative assessment of the implications for emissions of CO_2 of various nuclear strategies;
- comparison with the consequences of adopting various strategies for electricity generation;
- a quantitative assessment of the consequential nuclear wastes arising.

Seven scenarios are examined, comprising a Base case and high and low variants for nuclear, renewables and gas respectively. In each case the remaining fuels are adjusted to adapt to the higher or lower availability of the fuel that is principally varied.

The study is based on making projections of future values of carbon dioxide emissions and nuclear wastes arising. All projections are subject to uncertainty, whatever projection method is employed. These uncertainties are relatively high when assessing projections of *absolute values* of emissions and wastes arising. However the main objective of the study is to compare the *differences* in emissions and wastes arising between scenarios of power sector development (e.g. ‘High Nuclear’ and ‘Low Renewables’). Since the scenarios are based on common assumptions of energy demand, energy prices, the political and regulatory framework, etc., the projections of the *differences* in carbon dioxide emissions and wastes arising between scenarios are relatively low, and are much lower than the uncertainties resulting from the projections of the *absolute values* of emissions and wastes arising.

Conclusions

The major conclusions from the study are as follows:-

1. In 1995, the 125 GWe of nuclear capacity accounted for 23% of the EU's capacity of 554 GWe.

2. In 2025, the three scenarios project that this share will be:-

- High Nuclear : 164 GWe (23%)
- Base Scenario : 66 GWe (9%)
- Low Nuclear : 7 GWe (1%)

3. This is clearly a very wide range of options that are technically available. Retaining nuclear's share of capacity would require the building of an extra 100 GWe of capacity by 2025. This may be difficult in the current climate of public opinion.

4. The Base scenario assumes that nuclear plant is retired after a life-time of 40 years. By 2025, half of the EU's existing capacity will have been retired. The majority of nuclear plant was completed in the period 1970-1990. Thus it can be expected that nuclear's share of capacity will decline strongly from its 2025 value of 9% in the period 2025-2035; it will be no more than 1% by 2035.

5. EU CO_2 emission in 1990 were 3164 Mtonne. The most important emitters were Germany (30%), UK (18%) and Italy (12%).

6. CO_2 emissions from the power generation sector were 964 Mtonne and represented 30% of the total EU emissions.

7. In the main Kyoto target year of 2010, the Base scenario emissions are projected to be 1000 Mtonnes, 4% above the 1990 value. The Kyoto target for all sectors is a reduction of 8%. Emissions from the High Nuclear scenario are projected to be 952 Mtonne (roughly equal to the 1990 level). Under the Low Nuclear scenario, emissions are projected to be 1078 Mtonne (12% above the 1990 level).

8. After 2010, emissions in the Base scenario continue to decline to 2015 but then increase as electricity demand increases and nuclear plant is retired. By 2025, emissions are projected to be 1175 Mtonne, 22% above the 1990 level.

9. Nuclear policy has a significant impact on 2025 emissions. Supporting Nuclear power by retaining its share of capacity in those countries with nuclear generation leads to CO_2 emissions in 2025 of 926 Mtonnes (4% below the 1990 value). Retiring nuclear plant early gives emissions of 1349 Mtonnes, 15% above the Base scenario and 40% above the 1990 level. This is a major conclusion: the major problems of limiting carbon dioxide emissions in the EU and its Member States are not in 2010, but in later years and it is in this later period that any decline of the nuclear industry will have its greatest impact.

10. Meeting the Kyoto target for all sectors will require emissions reduction of 546 Mtonne in 2010 (16%) [based on EE2020 projections from the Conventional Wisdom scenario]. There are no targets for years post-2010 at present. Assuming, for indicative purposes, that targets post-2010 are set equal to those in 2010, required reductions increase to 600 Mtonne in 2015 (17%), 700 Mtonne in 2020 (19%) and 800 Mtonne in 2025 (22%).

11. There are no targets for carbon dioxide emissions from the power generation sector in the EU or in its Member States. Again assuming, for indicative purposes, that all sectors must contribute equally to emissions reductions and that targets for all sectors post-2010 equal those for 2010, the EU will exceed its notional targets for the power sector by over 100 Mtonne in 2010 (13%), and by almost 300 Mtonne in 2025 (33%). Supporting Nuclear generators reduces excess CO_2 emissions to 70 Mtonne in 2010 (8%), then targets are very nearly met in 2015, 2020, and 2025. Supporting nuclear plant is projected to lead to emissions being 250 Mtonne less than Base scenario in 2025. Excess emissions from retiring nuclear plant early are almost 200 Mtonne in 2010 (22%) and rise to over 450 Mtonne by 2025 (52%). In 2025, Low Nuclear scenario emissions are 170 Mtonne more than the base scenario and 420 Mtonne more than the High Nuclear scenario.

12. Spent fuel arising in 1995 was 3500 tHM. Spent fuel declines in the Base Scenario to 2600 tHM in 2010 and 1250 tHM in 2025 (65% below 1995 level). In the High Nuclear scenario spent fuel arising stabilises at 2800 tHM, 20% below 1995 levels.

13. LLW discharges in 2025 in the high, base and low scenarios are approximately 105%, 43% and 5% of the values in 1995 (74,000 m^3).

14. The increase in the inventory of plutonium, both that contained within spent fuel elements and that separated after reprocessing, raises concerns of proliferation. Over the period 1995-2025 (31 years), total plutonium production is as follows:-

- Low Nuclear 555 tonne
- Base Scenario 764 tonne
- High Nuclear 901 tonne

15. Relative differences between the three scenarios are shown in *Table 1*. Reducing CO_2 emissions by 1 Mtonne will lead to an increase of 6.2 tHM of spent fuel.

Table 1 ***Relative Differences between Scenarios, 2025***

Scenario	Emission / Waste Type	Low Nuclear	Base Scenario	High Nuclear
Low Nuclear	CO_2 (Mtonne/yr)	-	+174	+423
	Spent Fuel (tHM/yr)	-	-1108	-2655
	LLW/ILW (k. $m^{3/yr}$)	-	-27	-74
	Plutonium (tonne/yr)	-	-13.2	-33.6
Base Scenario	CO_2 (Mtonne/yr)	-174	-	+249
	Spent Fuel (tHM/yr)	+1108	-	-1548
	LLW/ILW (k. $m^{3/yr}$)	+27	-	-47
	Plutonium (tonne/yr)	+13.2	-	-20.4
High Nuclear	CO_2 (Mtonne/yr)	-423	-249	-
	Spent Fuel (tHM/yr)	+2655	+1548	-
	LLW/ILW (k. $m^{3/yr}$)	+74	+47	-
	Plutonium (tonne/yr)	+33.6	+20.4	-

16. Reprocessing has a significant effect on the accumulated volumes of spent fuel, and reduces the total in 2025 from between 60,000-95,000 tHM to under 30,000 tHM even in the High scenario. In the Low Nuclear scenario the back-log of accumulated spent fuel is fully reprocessed by 2020.

17. The cumulative total of plutonium arising if MOx fuel is not used, ranges from 550 to 900 tonne in 2025 depending on the scenario. If MOX is used as a fuel source, starting at 5% of the total fuel requirement and moving progressively to 30% by 2025, then the inventory of free plutonium is drastically reduced to less than 100 tonnes in the low case and effectively to zero in the base and high cases. The proportional impact is greater in the latter cases because the utilisation of plutonium in MOx is growing faster than the output from reprocessing. This ignores the very large stocks of plutonium that will arise from the decommissioning of nuclear weapons.

1 *INTRODUCTION*

Nuclear power is a technology that is not generally perceived to have fulfilled its earlier expectations. It is marginally economic at best at present in most countries, and there is great uncertainty over its future.

The European Union and its Member States face several options for replacing nuclear plant as they come to the end of their life. Within the nuclear power sector, the main issues are:-

- the extension of the lifetime of existing plant;
- the timing and extent of new build (if any).

There is increasing concern with climate change, and the targets agreed by the European Union under the Kyoto Protocol to reduce emissions of greenhouse gases in 2010 by 8% compared to 1990 levels represent a real challenge. Clearly nuclear power can make a significant contribution to carbon dioxide (CO_2) emission reduction.

If the external costs of CO_2 were quantified, the economic performance of nuclear would improve. At the same time, nuclear has its own environmental impacts and these need to be set off against the benefits.

Section 2 states the Objectives of the Study. The Approach used to fulfil these objectives is described in *Section 3*, with sub-sections on the data used, the scenarios developed and the Power System Planning Model specifically designed and developed for this study.

Section 4 details the main references used. *Section 5* presents the assumptions adopted for carbon dioxide emissions factors used and then includes a fully referenced analysis of all the factors affecting nuclear waste arising both now and in the future.

Full country reports for each of the eight countries with nuclear generation are given in *Sections 6-14*. Following analysis of Reprocessing in *Section 15*, a synthesis of the results for the EU as a whole is presented in *Section 16*. Finally, Conclusions are drawn in *Section 17*.

A *Glossary* of terms used in the Study is attached following *Section 17*. The *Modelling Methodology and Environmental Attributes* are presented in *Annex 1*, with detailed results for each country presented in *Annexes A-H* in a separate volume.

2 *OBJECTIVES OF THIS STUDY*

The objective of the DILEMMA Study, as given in the *Terms of Reference*, is:-

"The quantitative assessment of the effects of a broad range of possible policies on nuclear electricity generation on the overall CO_2 emissions from electricity generation in Europe for a time-frame of 25 years and the parallel quantitative estimation of the amounts of radioactive wastes and used fuels which will be generated".

This objective can be summarised as three major outputs:-

- a quantitative assessment of the implications for emissions of CO_2 of various nuclear strategies;
- comparison with the consequences of adopting various strategies for electricity generation;
- a quantitative assessment of the consequential nuclear wastes arising.

A further objective has been the production of an MS Excel model capable of being used by DGXVII to develop and run extra scenarios. This will allow further analysis of a wide range of options relating to the development of the EU power systems, the role of nuclear power and the effects on carbon dioxide and nuclear wastes arising. The "DILEMMA" model has been developed and handed over to DGXVII.

3 THE APPROACH

The approach to the problem has been to develop a specific power system planning model with associated data and scenarios. This is summarised in *Figure 3.1*, and is based on the following steps:-

1. A series of eight *Country Data Spreadsheets*, one for each EU country with nuclear generation, have been produced. Each of these country data spreadsheets includes:-
- a Nuclear Database, consisting of Nuclear Plant characteristics and Nuclear Waste Arising factors;
- a non-Nuclear Database, consisting of Plant characteristics and Carbon Dioxide Emissions factors.

2. Seven *Scenarios* have been developed for each country to cover the range of options for development of the power system to 2025.

3. A *Power System Planning Model* has been specifically developed for the Study. This model takes in the data contained in the *Country Data Spreadsheets* and the options contained in the *Scenarios*. The model uses this information to produce the *Results* to fulfil the objectives of the study.

Further detail on each element of the approach are presented following a discussion of the limitations involved when making projections.

3.1 LIMITATIONS OF THE APPROACH: MAKING PROJECTIONS

The study relies on making projections of carbon dioxide emissions and nuclear wastes arising to the year 2025. These projections are themselves dependent on a series of projections including energy demand, plant capacities available, the political and regulatory environment and technological development.

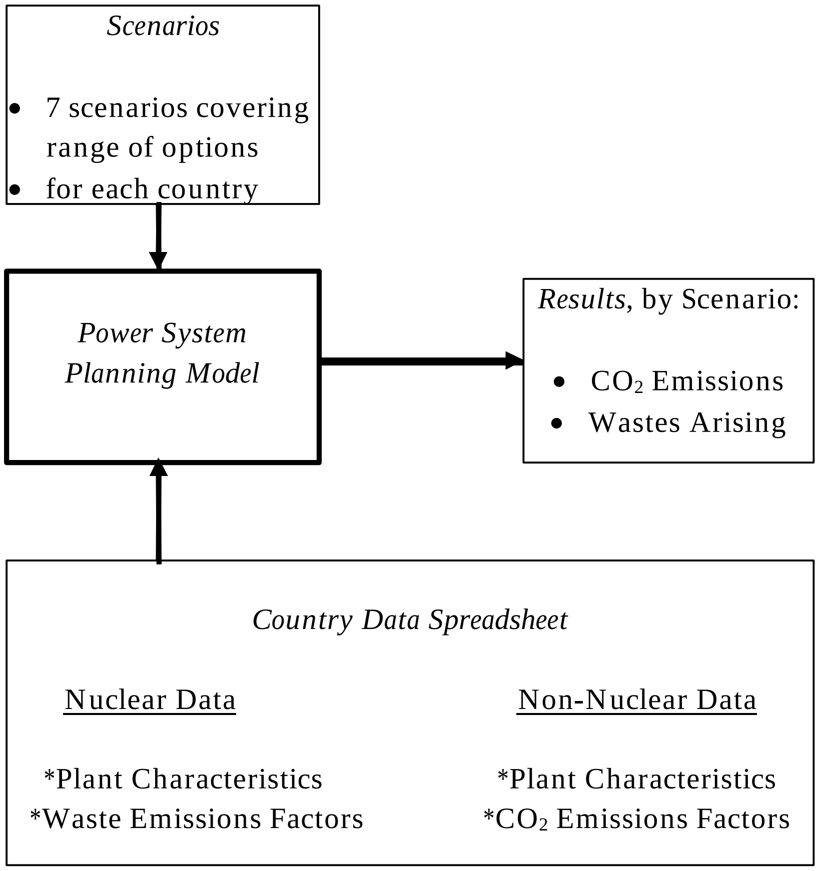
Projections for any factor in the future are clearly subject to a degree of uncertainty, which increases with time. It is impossible to state that carbon dioxide emissions will be a certain value in 2025 or in any other year. Although it is impossible to project that a factor will take a certain value in a given year, it is possible to use scenarios to describe a range of possibilities within which the factor will lie. For example, it is known that energy demand is linked to economic output (GDP) by a relationship (which can be derived from an analysis of past data). Thus if we make a projection of GDP, we can obtain a projection of energy demand by applying this relationship to the GDP projection. However if we make projections of ‘optimistic GDP growth’ and ‘pessimistic GDP growth’ and then apply the relationship linking energy demand to output, we obtain ‘optimistic’ and ‘pessimistic’ projections of energy demand. We can then say that future energy demand is likely to lie somewhere between these two values - we do not know exactly where, but by describing a range we are able to gain a measure of the uncertainty surrounding our future projections. This is a powerful technique: for example, if our analysis of a given energy investment in the future shows that it will give a good rate of return whether the energy demand projection is ‘optimistic, or ‘pessimistic’, we are able to conclude that the energy investment represents a good option whatever happens to energy demand in the future.

The discussion above concluded that projections of the *absolute values* of carbon dioxide emissions and nuclear wastes arising are subject to relatively high levels of uncertainty. These uncertainties arise whatever projection methodology is used.

Thus projections made in this study of *absolute values* of overall emissions and wastes arising are subject to a degree of uncertainty. However, the main objective of the study is to compare the carbon dioxide emissions and nuclear wastes arising from different scenarios of power sector development in the EU and its Member States. The study compares the *differences* in emissions and wastes arising from three scenarios of nuclear power generation (‘High’, ‘Base’, ’Low’). Since all three of these scenarios are based on the same projections of energy demand, energy prices, political and regulatory framework, etc., the *differences* in emissions and wastes arising are dependent only on the assumptions made regarding power sector development. These differences are thus subject to relatively low levels of uncertainty when compared to the projections of the *absolute values* of emissions and wastes arising.

In conclusion, the study projects the *differences* in emissions and wastes arising between power generation scenarios to a good level of certainty. The projections of *absolute values* of emissions and wastes arising are less certain. These conclusions should be borne in mind when assessing the results of the study.

Figure 3.1 ***The Approach***



3.2 COUNTRY DATA SPREADSHEETS

The Nuclear Data Base

The core of the approach is a detailed data base of nuclear plant, maintained on an annual basis to 2025.

Data has been taken from the IAEA's MicroPRIS and PRIS-PC databases for existing plant (see *Section 4* for reference). Data was complete to 31st December 1997. This data includes capacities and the start of commercial operation for each unit of each plant in the EU. In the Base scenario, it has been assumed that the lifetime of each unit will be 40 years. It is not considered that altering the lifetime of existing plant on an individual basis would lead to any significant improvements to the results. Only lifetime is a common characteristic for nuclear plant - all other characteristics vary on a unit-by-unit basis.

Depending on scenario, there is a need to build new nuclear plant. There are very few specific plans for new capacity in the EU at present, and thus it has been assumed that all new plant will be PWR. Specific geographical locations have not been suggested for this new nuclear plant.

Box 3.1 shows the nuclear database for Belgium. Note that new plant x1-x9 will only be built under certain scenarios. Sizes are indicative and have been selected such that nuclear's share of generating capacity will remain constant with time. The model does not recommend whether specific sizes of plant (e.g. 500 MWe, 1000 MWe) will be the best options in the future.

Box 3.1 ***Nuclear Database, Belgium***

Name	Type	Start Date	Capacity (MW)	Lifetime (Base)	Lifetime	End Date	Load Fac (Base)	Load Fac. (target)
DOEL-1	21	1975	412	40	40	2015	83%	82%
DOEL-2	21	1975	412	40	40	2015	77%	82%
DOEL-3	21	1982	1056	40	40	2022	83%	82%
DOEL-4	21	1985	1041	40	40	2025	78%	82%
TIHANGE-	21	1975	1009	40	40	2015	80%	82%
TIHANGE-	21	1983	1000	40	40	2023	86%	82%
TIHANGE-	21	1985	1065	40	40	2025	86%	82%
x1	21	2009	1000	40	40	2049	0%	82%
x2	21	2016	1000	40	40	2056	0%	82%
x3	21	2016	1000	40	40	2056	0%	82%
x4	21	2017	500	40	40	2057	0%	82%
x5	21	2018	500	40	41	2059	0%	82%
x6	21	2019	500	40	40	2059	0%	82%
x7	21	2023	1000	40	40	2063	0%	82%
x8	21	2024	1000	40	40	2064	0%	82%
x9	21	2020	500	40	40	2060	0%	82%

Nuclear Environmental Attributes

Discharges of spent fuel and nuclear wastes are calculated according to the annual generation from the plant. The following types of waste are included:-

- Spent fuel (including Plutonium);
- free Plutonium (i.e. separated from spent fuel and not recycled as MOx);
- Low Level Waste (including Intermediate Level Waste)
- High Level Waste.

Waste arising has been calculated from both operation and decommissioning activities. Decommissioning wastes have been attributed equally across the lifetime of a nuclear unit. Thus if a unit has a 40 year lifetime, it is assumed that 2.5% of the wastes arising from decommissioning arise in each year of the unit's operation. Waste categories are defined in the Glossary.

Waste discharge factors are both country and technology specific. Full details are given in *Annex 1*.

Non-Nuclear Database

The Non-Nuclear database includes all data relating to non-nuclear plant types and their characteristics. The database has been designed to allow sufficient flexibility for all different plant types to compete with each other without giving excessive detail. Thus there is a category "NG CCGT" but no individual plant details - all natural gas CCGT plant are contained in this one category.

Box 3.2 shows the Non-Nuclear Database for Belgium in 2015. Tables with the same format have been produced for each country for each 5 year period. The first table *Box 3.2* shows "Others", i.e. those plant which are not competitively despatched. This category contains Renewables (including Large Hydro) and CHP plant. It is assumed that these plant types are despatched first and that the remainder of the electricity demand is then made up from the competitive despatch of the plant categories shown in the second table in *Box 3.2*.

Non-despatchable plant is split into 2 types - base load plant, and mid-merit plant where a certain capacity of plant generates a certain amount of electricity. Minor fuel plant includes electricity generated from Hydrogen, Derived Gases, Other Solids, Other Liquids and Diesel. Polyvalent plant contains capacity that can be run on a combination of natural gas and / or coal and / or oil. Emissions factors for both types of plant are calculated on a weighted average basis.

Box 3.2 ***Plant Database, 2015, Belgium***

Plant Database - Others (not competitively despatched)

Plant Type	Capacity (GWe)	Gross O/P (TWh)	Efficiency	Load Factor	Fuel Type	CO_2 (g/kWh)
Hydro Base Load	-	-	100.0%	0.000	1	-
Hydro Mid Merit	0.10	0.36	100.0%	0.405	1	-
Waste Base Load	-	-	30.0%	0.000	2	104
Waste Mid Merit	0.15	0.65	30.0%	0.500	2	104
Biomass Base Load	-	-	33.6%	0.000	3	-
Biomass Mid Merit	0.61	3.80	33.6%	0.715	3	-
Biofuels Base Load	-	-	30.0%	0.000	4	-
Biofuels Mid Merit	-	-	30.0%	0.000	4	-
Other Ren. Base Load	-	-	100.0%	0.000	5	-
Other Ren. Mid Merit	0.15	0.24	100.0%	0.185	5	-
New Gas CHP Base Load	-	-	39.0%	0.000	8	182
New Gas CHP Mid Merit	0.54	1.83	39.0%	0.383	8	182
New Coal CHP Base Load	-	-	38.3%	0.000	13	334
New Coal CHP Mid Merit	0.81	2.70	38.3%	0.383	13	334

Plant Database - Competitively despatched plant

Plant Type	Capacity (GWe)	Gross O/P (TWh)	Efficiency	Load Factor	Fuel Type	CO_2 (g/kWh)
NG CCGT	2.72	20.34	52.9%	0.855	8	182
NG Peak Plant	0.78	0.01	30.0%	0.002	8	182
NG Fuel Cells	0.11	0.19	54.9%	0.210	8	182
Diesel Oil Peak Plant	0.78	0.00	34.4%	0.001	9	251
Oil CCGT	0.00	0.00	0.0%	0.000	11	248
Hard Coal - New	0.00	0.00	43.0%	0.000	13	334
Lignite	0.00	0.00	0.0%	0.000	14	339
Minor Fuel Plant	0.42	1.83	45.1%	0.500	17	200
Polyvalents & Autoproducers	4.52	17.25	37.7%	0.436	18	196

Carbon Dioxide Emissions

Emissions factors for each fuel type have been used based on the gross calorific value of each fuel. These emissions factors thus apply to fuel input, not to electricity output. Further details are given in *Section 5.1*.

3.3 SCENARIOS

A set of scenarios has been defined which capture what appear to be the practical technical limits of the development of various generating technologies. The scenarios allow a full sensitivity analysis to be performed by assessing the various emissions from each scenario.

Requirements and Constraints

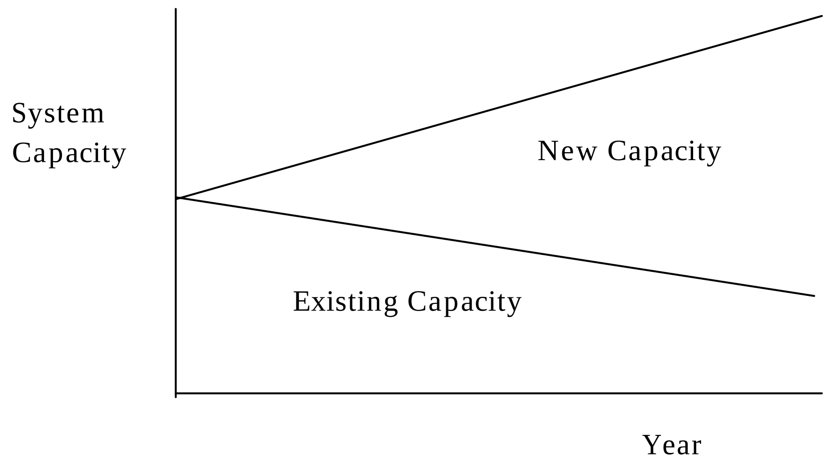
The main aim is to examine the trade-offs between nuclear and climate change environmental attributes as a function of different developments of the nuclear option. The sensitivity of the findings to the assumptions regarding renewable penetration and the composition of the fossil fuel burn should be examined.

There are therefore three main axes: nuclear, renewable and fossil-fuel. If N independent scenarios are adopted for each then there are N^3 possible combinations. Even with three scenarios for each axis, there are then 27 combinations. Producing results for 27 scenarios would be inefficient both in terms of running the model and in terms of explaining the effects of the different scenarios. Thus seven scenarios have been developed, as described below.

Scenarios Developed

Figure 3.2 shows the basic principle used for scenarios. A certain capacity of electricity generation is needed to meet the needs of a given country in a given year. A proportion of this capacity is already supplied by existing plant, which is progressively retired. The shortfall in capacity is then made up by new plant. The scenarios specify which types of new plant should be built and when. Retirement of existing plant is taken directly from EE2020 figures.

Figure 3.2 Capacity Additions and Retirements



A base case has been defined that will represent a central estimate for all three main aspects. The scenarios will then allow the separate examination of the sensitivity of the findings along each main axis. This option enables us to retain the key elements of the analysis while not generating vast quantities of confusing output.

The individual scenarios in broad terms are:-

Individual Nuclear scenarios N-,N0, N+

- N0 is the base case where nuclear plant is retired after a 40 year lifetime and no new nuclear plant is built;
- N- features early plant retirement (30 years) and again, no new nuclear capacity;
- N+ is the optimistic scenario, where the nuclear fraction of capacity is maintained.

Individual Renewables scenarios R-,R0,R+

- R0 is the base case, considered to be a 'Business as Usual' condition;
- R- represents a pessimistic view of future renewables penetration;
- R+ represents an optimistic view of future renewables penetration.

Individual Fossil Fuel scenarios G-,G0,G+

- G0, the Base case, assumes that 67% of new fossil fuel plant will be natural gas fired and 33% by hard coal;
- G+, the High Gas/Low Coal scenario, sees 100% of new fossil fuel capacity being natural gas;
- G-, the Low Gas/High Coal scenario, sees Coal favoured with 33% of new fossil fuel capacity being natural gas and 67% being hard coal.

The **combined scenarios** will then be as shown on *Figure 3.3* and *Table 3.1*.

Figure 3.3 ***Combined Scenarios***

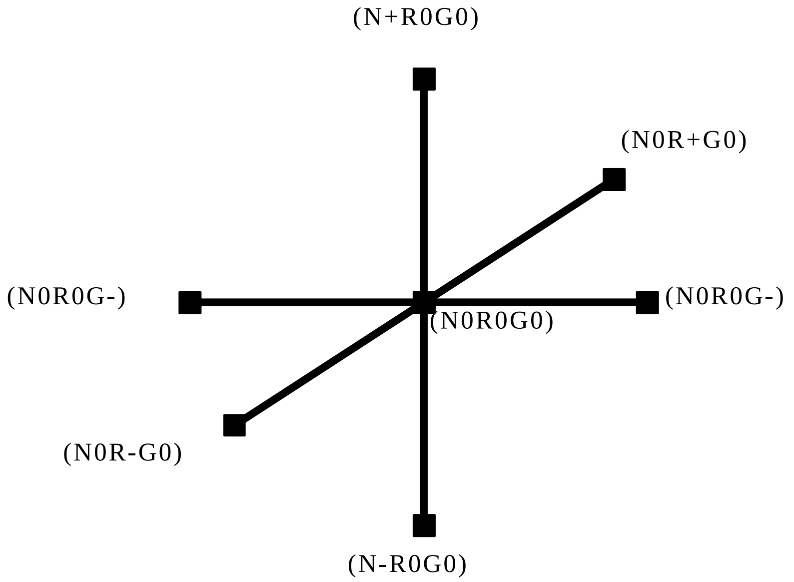


Table 3.1 ***Combined Scenarios***

Scenario	Nuclear	Renewables	Gas/Coal
Base	N_o	R_o	G_o
High Nuclear	**N+**	R_o	G_o
Low Nuclear	**N-**	R_o	G_o
High Renewables	N_o	**R+**	G_o
Low Renewables	N_o	**R-**	G_o
High Gas/Low Coal	N_o	R_o	**G+**
Low Gas/High Coal	N_o	R_o	**G-**

Renewables Scenarios

The prospects for electricity generation from renewables in the EU are uncertain. On the positive side, the need for countries to reduce carbon dioxide emissions means that many countries are introducing support schemes for renewables. Furthermore, valuable operating experience has been built up from wind, biomass, waste and landfill gas schemes and the costs of such schemes continues to decrease. On the negative side, the introduction of competitive and liberalised electricity markets means that countries are not permitted to introduce schemes which would distort the market or be considered in some way 'unfair'. The EC and its Member States are currently exploring ways to support renewables in this newly liberalised market (for instance compulsory purchase of renewables electricity, fiscal incentives). Similar initiatives are on-going in support of electricity from CHP.

Policies and prospects for renewables are now discussed. This section ends with a description of the High Renewables and Low Renewables scenarios and the reasons for their derivation.

The EC White Paper

The EC's White Paper for a Community Strategy and Action Plan *"Energy for the Future: Renewable Sources of Energy"*, COM(97)599 final (26/11/97) presents renewables targets for the EU and its Member States. The target is "to double the share of renewables to 12% of energy requirement by 2010". No specific targets are given for electricity production from renewables: the target applies to gross inland consumption. Many commentators believe that this target will be difficult to meet.

The White Paper includes a summary of current policies by Member States to support the take up of renewables. *Table 3.2* details these targets/policies for the eight EU countries with nuclear capacity.

Table 3.2 Renewables Targets and Policies

Country	Targets/Policies
Belgium	Promotion of renewables without specific targets
Finland	+25% bioenergy by 2005; 100 MW installed of wind energy by 2005
France	1996-2000 targets of 225 MW wood combustion, 20,000 solar thermal panels, 250-500 MW of wind capacity
Germany	DM 100M national support 1995-98, many Lander have programmes. Much support for Research & Development.
Netherlands	Action Programme for 1997-2000 plus targets for 2007 and 2020. 2000 MW of wind capacity by 2007, 119 MW PV capacity by 2007, biomass, energy crops, solar thermal, heat pumps targets.
Spain	National Energy Plan for 1991-2000 sets targets for SMP, biomass, wind, PV, solar, geothermal.
Sweden	Sustainable Energy Supply Bill of 1996/97 sets 5 year targets for biofuel-based CHP of +0.75 TWh electricity/year, +0.5 TWh/year from land - based wind, +0.25 TWh/year from small hydro.
UK	Target of 10% of electricity generation from renewables by 2010
EU	Doubling of renewables energy production to 12% by 2010

DGXVII's Study "The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"

This study has been used to estimate the renewable energy potential in the EU. *Table 3.3* shows the major conclusions for renewables used to develop scenarios. Wind and Waste (including landfill) are the sectors with the highest potential growth rates; however biomass is the largest present contributor in many countries and offers the greatest potential in absolute terms. The study considers that no new large hydro schemes will be built, both for economic reasons (the best sites having already been taken) and for environmental impacts. This view is supported in the EC White Paper().

Table 3.3 Potential for Increases/Decreases in Renewables Contribution

Country	Technologies with potential for increases in favourable conditions	Technologies which could decrease in unfavourable conditions
Belgium	Biomass, Waste	Biomass
Finland	Biomass, Wind, Biofuels	Biomass, Others
France	Wind, Biomass	Biomass
Germany	Wind, Biomass, Others	Biomass
Netherlands	Waste, Wind	Biomass
Spain	Biomass, Wind, Others	Biomass
Sweden	Wind, Biomass, Biofuels	Biomass
UK	Waste, Wind	Biomass

Scenarios by Country

The Base scenario for each country has been taken to be the Conventional Wisdom scenario of EE2020. Other than being a good choice in terms of consistency with the rest of the Study, it was found to represent a middle ground when compared to the 2 renewables scenarios developed (N0R+G0, N0R-G0).

Technologies with short-medium term potential are considered to be:-

- small hydro (less than 10 MWe);
- energy from waste (either combustion or landfill gas);
- wind (particularly onshore);
- biomass (the dominant renewable technology now; considered to remain so in the period of this study).

The prospects from other technologies (PVs, energy crops, etc.) are considered too uncertain to be included in the analysis. It is also considered that no new large hydro schemes will be built, due to a combination of the least cost opportunities having already been exploited and to increasing opposition to the schemes on environmental grounds.

Final scenarios as a percentage of electricity generation are presented in *Table 3.4*. Note that these figures include contributions from large hydro schemes.

Table 3.4 Renewables contribution to Electricity generation by Scenario

Country	1995 Share (%)	2025 Low Renewables (%)	2025 Base Scenario (%)	2025 High Renewables (%)
Belgium	1.8	5.4	8.9	10.4
Finland	28.5	25.0	30.7	35.0
France	15.8	13.5	17.2	22.0
Germany	5.6	7.0	9.3	12.0
Netherlands	3.5	3.6	5.3	12.1
Spain	14.3	15.5	15.5	26.5
Sweden	47.5	53.4	55.6	64.8

Country	1995 Share (%)	2025 Low Renewables (%)	2025 Base Scenario (%)	2025 High Renewables (%)
UK	2.5	7.0	9.6	12.5

Calibration of Model and Choice of Scenarios

The scenarios are designed to be broadly consistent with the 'Conventional Wisdom' scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020').* The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement.

The 'Conventional Wisdom' scenario denotes a 'business as usual' world, representing a traditional economic view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. The 'Conventional Wisdom' scenario is one of four developed for the EE2020 study; other scenarios forecast the EU's energy needs and solutions under challenging views of the future:

- In 'Battlefield', contradictions and instabilities in the global system make economic integration very difficult;
- In 'Forum', the process of global economic integration produces new imperatives for collective public action;
- In 'Hypermarket', global economic integration is self-reinforcing and continues.

The following is a more complete description of the 'Conventional Wisdom' scenario, taken directly from the EE2020 study.

"The Conventional Wisdom Scenario represents the baseline (traditional) projection for the European economy to the year 2020 providing a quantitative reference point for the three other 'Scenarios for Rethinking EC Energy Policy' which were developed by a group of external experts.

The scenario assumes that, in the economy, although some progress is made, many of the world's structural, social and economic problems remain. After a strong rebound from recession, economic growth gradually weakens in the long term.

Inflation stays low. The discount rate is 8% in real terms. There is a reduction of interest rate differentials between EC countries. The contribution of industry to European GDP declines. Production share of energy-intensive industry lessens. Investment grows strongly in the short term slowing thereafter.

Energy Policy within Conventional Wisdom remains fragmented as a combined result of unresolved conflicting objectives and different national targets. Already high tax rates leave little room for further increases to contain public deficits, while no inclusion of external costs is envisaged. In brief, the environmental approach stays limited.

Energy prices increase smoothly. The price of crude oil from 17.6 US$93/bbl in 1995 reaches 31 US$93/bbl in 2020, in real terms. Deregulation and growing networks bring lower prices for gas in relation to oil after 2000, a trend that is reinforced by an increasing gas to oil price competition. Coal prices remain stable and lessen relative to oil and gas prices towards the end of the projection period.

The penetration of new, more efficient demand and supply technologies is limited. These technologies, partly driven by public standards and partly by industrialists, aim at increased industrial competitiveness. Energy Demand proceeds with the continuation of current actions, taking some concern on increasing efficiency. Domestic production for oil and gas remains stable until 2010. Beyond 2010 a significant decline is foreseen for oil and a stabilisation for natural gas. Coal production is however in continuous decline.

In this scenario, economic growth gradually weakens as demographic changes mean slower growth in the labour force, while productivity growth remains quite stable, but below the rates experienced before the mid-1970s.

Unemployment rates decline but remain well above the levels experienced before the 1980s. Inflation stays low but not as low as today. Monetary union is achieved but only for a short period clustered around the D-mark.

Public deficits are stabilised but not eliminated, as ageing populations place an increasing burden on the public purse."

3.4 THE POWER SYSTEM PLANNING MODEL

Power system planning is a well-developed activity. The normal aims of power system planning are to determine least cost investment schedules subject to acceptable standards of reliability.

The main aspects to capture in the modelling approach are:

- options for the life-time of existing nuclear plant;
- the age profile of the existing fossil-fuel capacity;
- the evolution of demand;
- options for a future development of new nuclear capacity;
- the penetration of renewables;
- competition between coal and natural gas.

A simulation model has been specifically developed for the Study to capture these aspects. This "DILEMMA" model runs in MS EXCEL and has been handed over to DG XVII. The model is linked to the *Databases* and *Scenarios* described in *Sections 3.1* and *3.2*. The modelling methodology is described in *Annex 1*.

4 MAIN DATA SOURCES

The main data sources used are listed below. Other sources used for specific parts of the study are listed at the end of each chapter of the report as appropriate.

1. the *IAEA* MicroPRIS and PRIS-PC databases of nuclear plant (kindly made available by the IAEA). **[IAEA MicroPRIS and PRIS-PC databases. Data complete to 31st December 1997. Data received February 1999. Data updated on an annual basis]**;

2. DGXVII's *"Energy in Europe to 2020" ('EE2020')* - for demand growth forecasts, composition of existing plant, retirement of existing plant and structure of the fuel-burn. **[European Commission "European Energy to 2020 - A Scenario Approach", Special Issue - Spring 1996. Luxembourg : Office for Official Publications of the European Communities. 1996. ISBN 92-827-5226-7]**;

3. DGXVII's *"Energy in Europe - 1998 Annual Energy Review"*, for calibration of the model to 1995 data for the power system and carbon emissions. **[European Commission "1998 - Annual Energy Review", Special Issue - December 1998. Luxembourg : Office for Official Publications of the European Communities. 1999. ISBN 92-828-4880-9]**;

4. UNIPEDE's *"EURPROG 1998: Programmes and Prospects for the European Electricity Sector"*, for the view of EU Electricity Utilities on capacity expansion. **[EURPROG 1998 "Programmes and Prospects for the European Electricity Sector (1980, 1990-1996, 2000, 2005, 2010)". EURPROG Report - final version 26th Edition. UNIPEDE. June 1998. Ref. 1998-512-0001]**;

5. DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* for estimates of the renewable energy potential in the EU. **[European Communities - Commission "The European Renewable Energy Study - Prospects for Renewable Energy in the European Community and Eastern Europe up to 2010". Luxembourg : Office for Official Publications of the European Communities. 1994. ISBN 92-826-6950-5 (Main Report), ISBN 92-826-6450-3 (Volumes 1 to 4) and ISBN 92-826-6953-X (Annexes)]**;

6. The EC's White Paper for a Community Strategy and Action Plan for renewables targets for the EU and its Member States **[Communication from the Commission "Energy for the Future: Renewable Sources of Energy", COM(97)599 final (26/11/97)];**

7. The EU's targets in response to the Kyoto Protocol, for Percentage Emissions Reductions in 2010 for CO_2, CH_4 and N_20 together (GWP100 weighted) compared to 1990. Targets are stated both for the EU as a whole

and for each Member State. There are no tragets beyond the Kyoto Protocol commitment period of 2008-2012 nor for indiviudal sectors of the economy (e.g. transport, the power sector) within either the EU or in any indivudual Member State. **[Community Strategy on Climate Change - Council Conclusions 3 March 1997].**

5 *EMISSIONS FACTORS*

5.1 *CARBON DIOXIDE EMISSIONS*

These are shown in *Box 5.1*. They are based on gross calorific values of fuels. The same emissions factors have been used for all countries. The major assumptions are as follows:-

- For hard coal, an emissions factor based on a weighted average of coal from the 10 leading world-wide coal producers has been used. These 10 countries produce 85% of the world's hard coal;
- The Waste emissions factor is based on Municipal Solid waste generated in the UK;
- Derived Gases are based on an estimated weighted average of Blast Furnace Gas and Coke Oven Gas;
- All renewables and nuclear plant are assumed to have zero emissions.

Box 5.1 ***Carbon Dioxide Emissions Factors (Gross CV Basis)***

Fuel	Fuel Type	1995	2000	2005	2010	2015	2020	2025
Hydro	1	0	0	0	0	0	0	0
Waste	2	104	104	104	104	104	104	104
Biomass	3	0	0	0	0	0	0	0
Biofuels	4	0	0	0	0	0	0	0
Other Ren.	5	0	0	0	0	0	0	0
Hydrogen	6	0	0	0	0	0	0	0
Derived Gases	7	200	200	200	200	200	200	200
Natural Gas	8	182	182	182	182	182	182	182
Diesel Oil	9	251	251	251	251	251	251	251
Other Liquids	10	248	248	248	248	248	248	248
Light Fuel Oil	11	248	248	248	248	248	248	248
Heavy Fuel Oil	12	262	262	262	262	262	262	262
Hard Coal	13	334	334	334	334	334	334	334
Lignite	14	339	339	339	339	339	339	339
Other Solids	15	339	339	339	339	339	339	339

Life Cycle Analysis Emissions Factors

A true estimate of emissions from power generation would include emissions resulting from the entire life cycle of the various fuel types. Such an analysis would include emissions attributable to mining activities, transport, processing, transmission and distribution, etc. There are two major reasons why such an approach has not been adopted:-

1. The vast majority of other studies do not adopt this method. Thus the results produced would not be directly compatible;
2. Although it is theoretically possible to attribute all extra emissions to generators, in practice it is much more difficult. It would be necessary to source the complete path of all fuels to each separate plant - it is not possible to produce meaningful averages. This is obviously highly problematic and it must be remembered that the vast majority of CO_2 emissions are produced from combustion. The loss of accuracy from not including life cycle emissions is below the loss of accuracy resulting from

other assumptions made within the data collection, scenario building and modelling assumptions.

5.2 NUCLEAR EMISSIONS FACTORS

A full description of the derivation of all nuclear emissions factors and a presentation of their values is given in *Annex 1*.

6 NATIONAL STUDIES

Results are now presented and discussed for each of the 8 countries in the EU with nuclear generation capacity. These sections follow the same format:-

- Calibration of Model and Choice of Scenarios
- Results
- Electricity Generation in 2025 by Origin
- Emissions of Carbon Dioxide
- Carbon Dioxide Emissions and the Kyoto Targets
- Spent Fuel from Nuclear Plants
- Low and Intermediate Level Waste from Nuclear Plant
- Trade-Offs
- Conclusions
- Figures

The 8 countries presented are found in the following sections:-

7 Belgium
8 Finland
9 France
10 Germany
11 Netherlands
12 Spain
13 Sweden
14 UK

Detailed results for each of the 8 countries are attached as Annexes A-H.

Following *Section 15*, Reprocessing, results for the European union as a whole are presented in *Section 16*. Conclusions are drawn in *Section 17*.

7 BELGIUM

7.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the 'Conventional Wisdom' scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020').* The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4.*

The model has been calibrated against the actual performance of the Belgian power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 20 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 23 million tonnes. The discrepancy is due to the model projecting higher electricity generation from nuclear plant. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 7.1.*

Table 7.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 9% with large hydro and 8.5% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 47% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 10% with large hydro and 9.5% excluding large hydro in 2025, other factors as Base Scenario.

Scenario	Description	Composition
N0R-G0	Low RETs	Renewable generation amounts to 5% with large hydro and 4.5% excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

7.2 RESULTS

Electricity Generation in 2025 by Origin

Figure 7.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. Nuclear power accounted for 60% of electricity generation in 1995. In all but the High Nuclear scenario (N+R0G0), nuclear generation falls to no more than 20% in 2025.

Gas is the preferred fuel for power generation in the future, accounting for between 40% and 60% of generation in 2025 in all but the High Nuclear (N+R0G0) and Low Gas/High Coal (N0R0G-) scenarios.

Coal accounted for just over 20% of electricity generation in 1995. This share is maintained except for the High Nuclear and High Gas/Low Coal (N0R0G+) scenarios.

The potential for renewable generation in Belgium is low, and it is projected that renewables will only generate between 5-10% of electricity in 2025.

Emissions of Carbon Dioxide

Figure 7.2 summarises the emissions of carbon dioxide from the Belgian power system up to 2025 as forecast by this model.

The Base scenario (N0R0G0) shows CO_2 emissions declining steadily from 24 Mtonne in 1990 to under 15 Mtonne in 2015. This decrease is due to new plant replacing old and to fuel switching to natural gas. Large step rises in CO_2 emissions are seen in 2016 and 2022-2024: these correspond with the retirement of existing nuclear plant.

Base scenario emissions in 2025 are equal to those in 1990. Favouring Gas (scenario N0R0G+) or Coal (N0R0G-) for new fossil fuel plant does not have a major impact on these results, with the range in 2025 being -3 to +5 Mtonne relative to the Base scenario. The small amount of renewables generation makes very little difference to the results.

With its high share of nuclear generation, Belgium's major decision regarding CO_2 emissions from power generation in the future concerns nuclear power. If plant is retired after 30 years (N-R0G0), CO_2 emissions are higher than those in 1990 from the year 2013 onwards, and are 8 Mtonne higher in 2025.

In contrast, following the High Nuclear scenario results in projected emissions of only 6 Mtonne in 2025, just 25% of the 1990 total.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, Belgium agreed to reduce emissions from 1990 levels by 7.5% in the year 2010. Total emissions in 1990 from all sectors were 111 Mtonne CO_2, of which 24 Mtonne (22%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 7.3* shows the difference between projected values and the Kyoto target. Belgium will need to find reductions of 8 Mtonne in 2010, rising to 33 Mtonne in 2025. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to reduce emissions by 7.5% from the 1990 level to 22 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 7.4 shows how successful Belgium will be in meeting this target under each of the seven scenarios. In 2010 and 2015, Belgium will comfortably meet its target in all cases except for the Low Nuclear scenario (closing nuclear plant after a lifetime of 30 years). 2020 results show that the target will be met in all scenarios but that there are considerable benefits in following the High Nuclear course and considerable disbenefits from following the Low Nuclear course. In 2025, the high benefits from the High Nuclear scenario remain; all other scenarios show modest excesses over the target.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 7.5 shows the discharge of spent fuel from nuclear plant over the period. In the Base scenario (N0R0G0), spent fuel of 130 tHM/year arises until nuclear plant retires in 2016 and 2022-24. By 2025, spent fuel arising is under 50 tHM. Because of nuclear capacity retaining its share of increasing capacity (and generation) in the High Nuclear scenario (N+R0G0), emissions rise to 165 tHM in 2025.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 7.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 34%, 130% and 0% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 7.7*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

Carbon Dioxide emissions and spent fuel arising vary widely depending on whether Belgium remains a nuclear generator. Relative to the Base scenario, High Nuclear leads to savings of 16 Mtonne CO_2 and an increase of 125 tHM in 2025. Renewables policy has very little effect: Belgium's potential generation capacity is low. Favouring gas generation (N0R0G+) means that Belgium can meet its Kyoto target for the power generation sector without building any new nuclear plant.

Figure 7.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

7.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. Nuclear accounted for 60% of generation in 1995 but is projected to fall to no more than 20% in all scenarios other than High Nuclear. The shortfall in generation is made up by Gas.

2. Renewables potential is projected to be low, between 5-10% in 2025.

3. The Base scenario shows CO_2 emissions declining steadily from 24 Mtonne in 1990 to under 15 Mtonne in 2015. Large step rises in CO_2 emissions are seen in 2016 and 2022-2024: these correspond with the retirement of existing nuclear plant.

4. Base scenario CO_2 emissions in 2025 are equal to those in 1990.

5. Favouring Gas or Coal for new fossil fuel plant does not have a major impact on these results, with the range in 2025 being -3 to +5 Mtonne relative to the Base scenario.

6. The small amount of renewables generation makes very little difference to the results.

7. With its high current share of nuclear generation, Belgium's major decision regarding CO_2 emissions from power generation in the future concerns nuclear power. If plant is retired after 30 years, CO_2 emissions are higher than those in 1990 from the year 2013 onwards, and are 8 Mtonne higher in 2025. In contrast, following the High Nuclear scenario results in projected emissions of only 6 Mtonne in 2025, just 25% of the 1990 total.

8. In the Base scenario spent fuel of 130 tHM / year arises until nuclear plant retires in 2016 and 2022-24. By 2025, spent fuel arising is under 50 tHM.

9. Carbon Dioxide emissions and spent fuel arising vary widely depending on whether Belgium remains a nuclear generator. Relative to the Base scenario, High Nuclear leads to savings of 16 Mtonne CO_2 and an increase of 125 tHM in 2025.

10. Favouring gas generation means that Belgium can meet its Kyoto target for the power generation sector without building any new nuclear plant.

Figure 7.1 Electricity Generation in 2025 by Origin

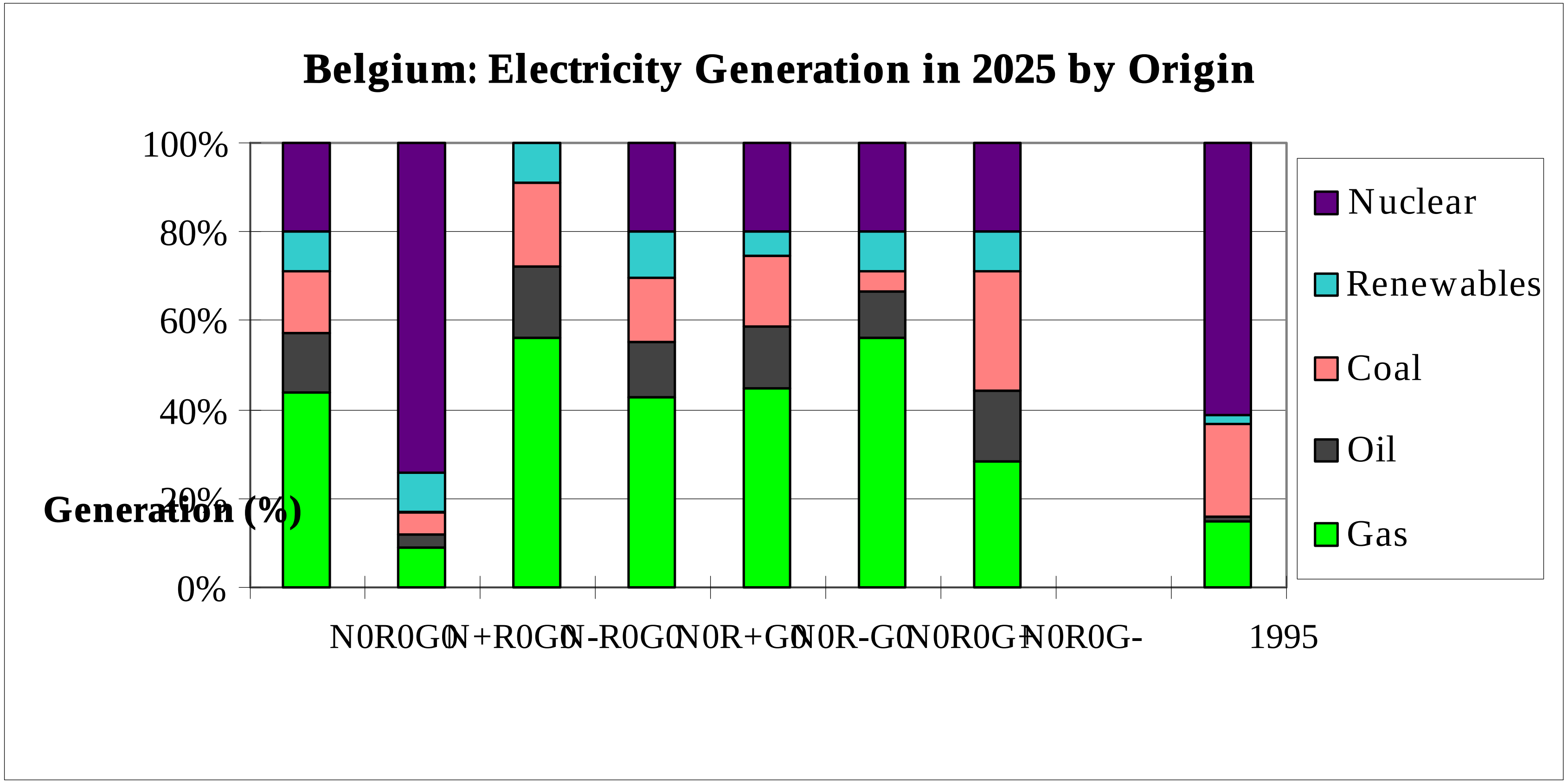


Figure 7.2 Carbon Dioxide Emissions from Power Generation

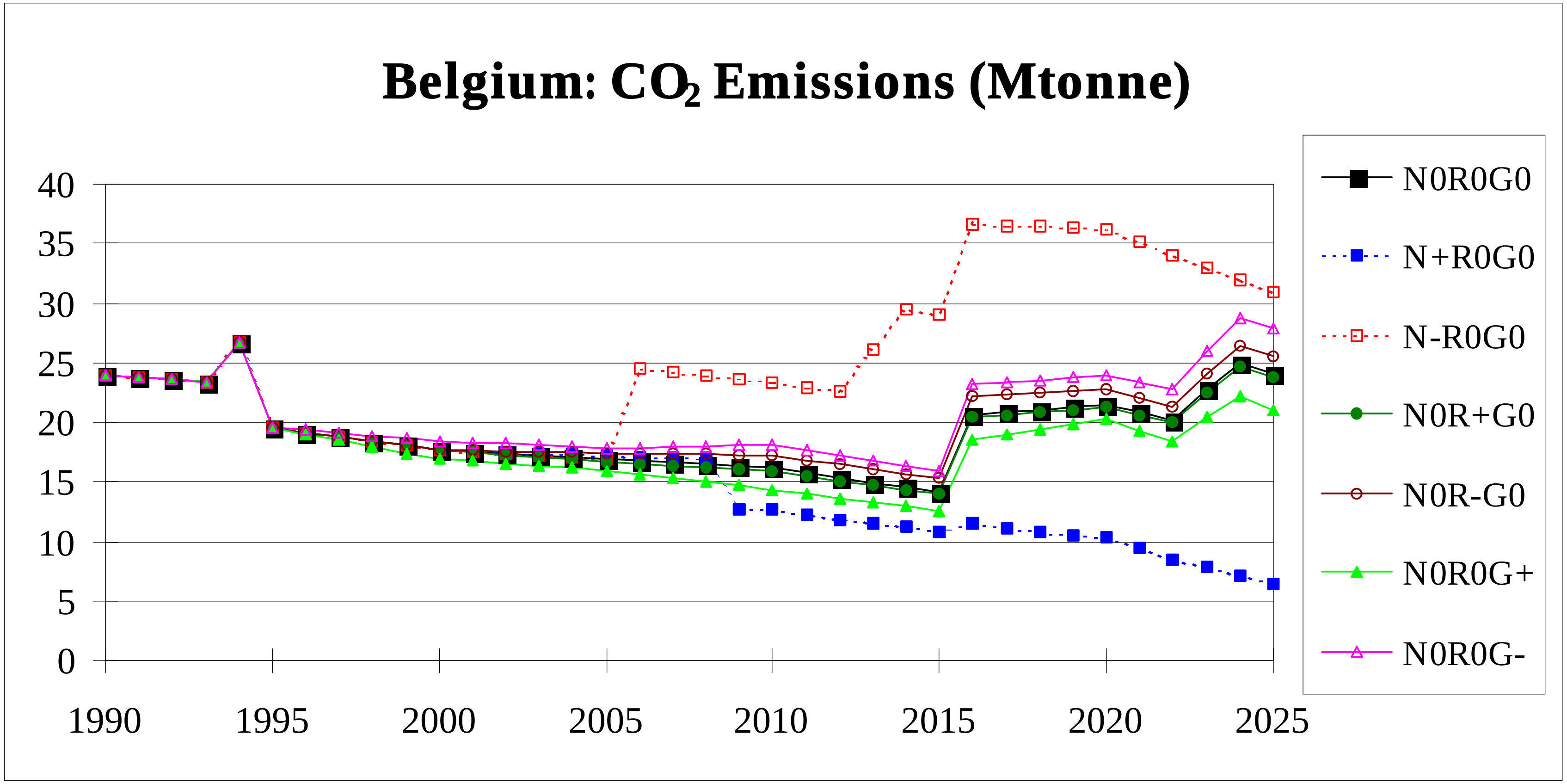


Figure 7.3 Notional Kyoto Target Reductions - All Sectors* (Assuming target in years post-2010 = target in 2010)

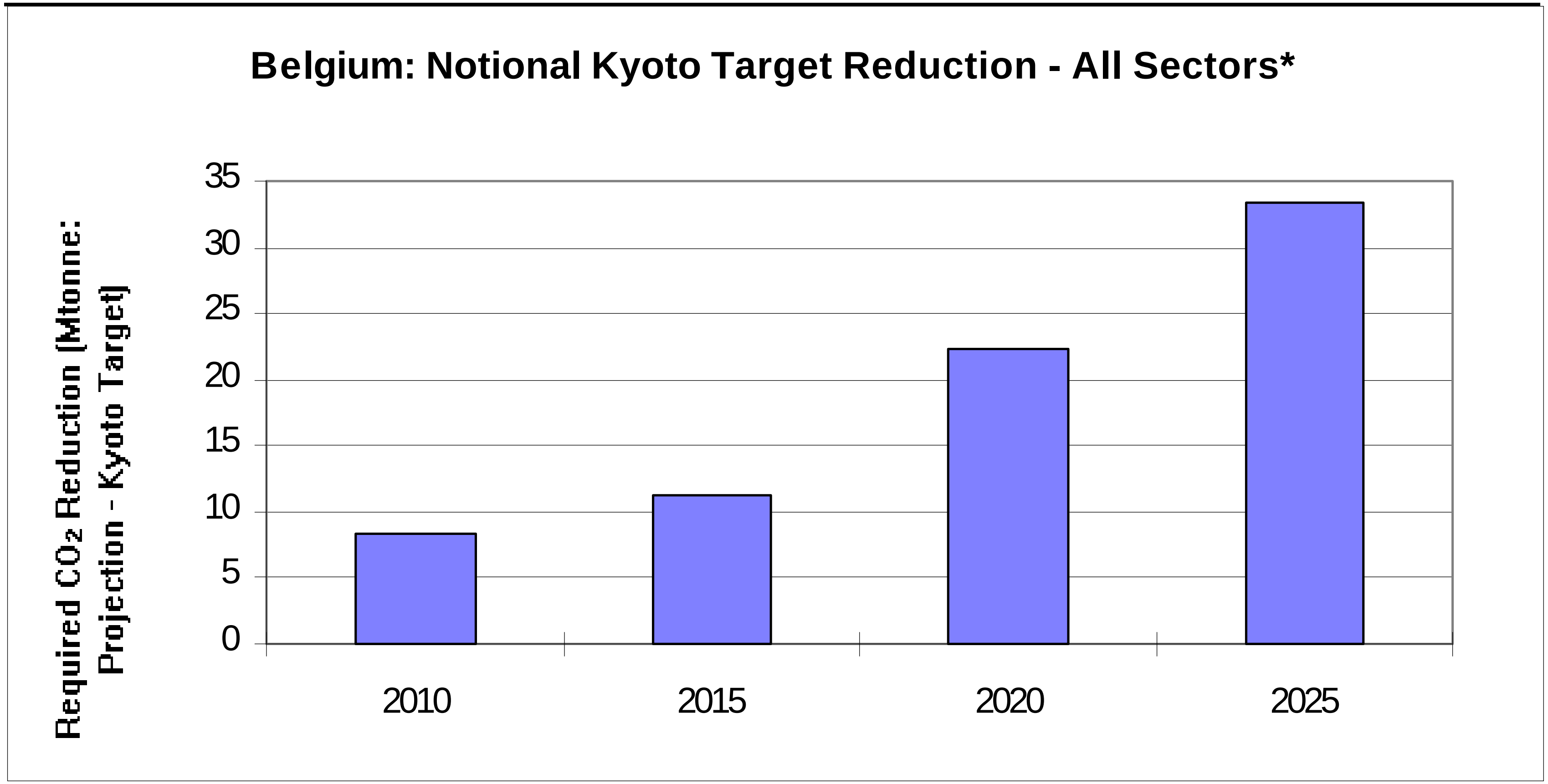


Figure 7.4 ***Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target* (Assuming equal burdens on power generation sector and non-power generation sectors)***

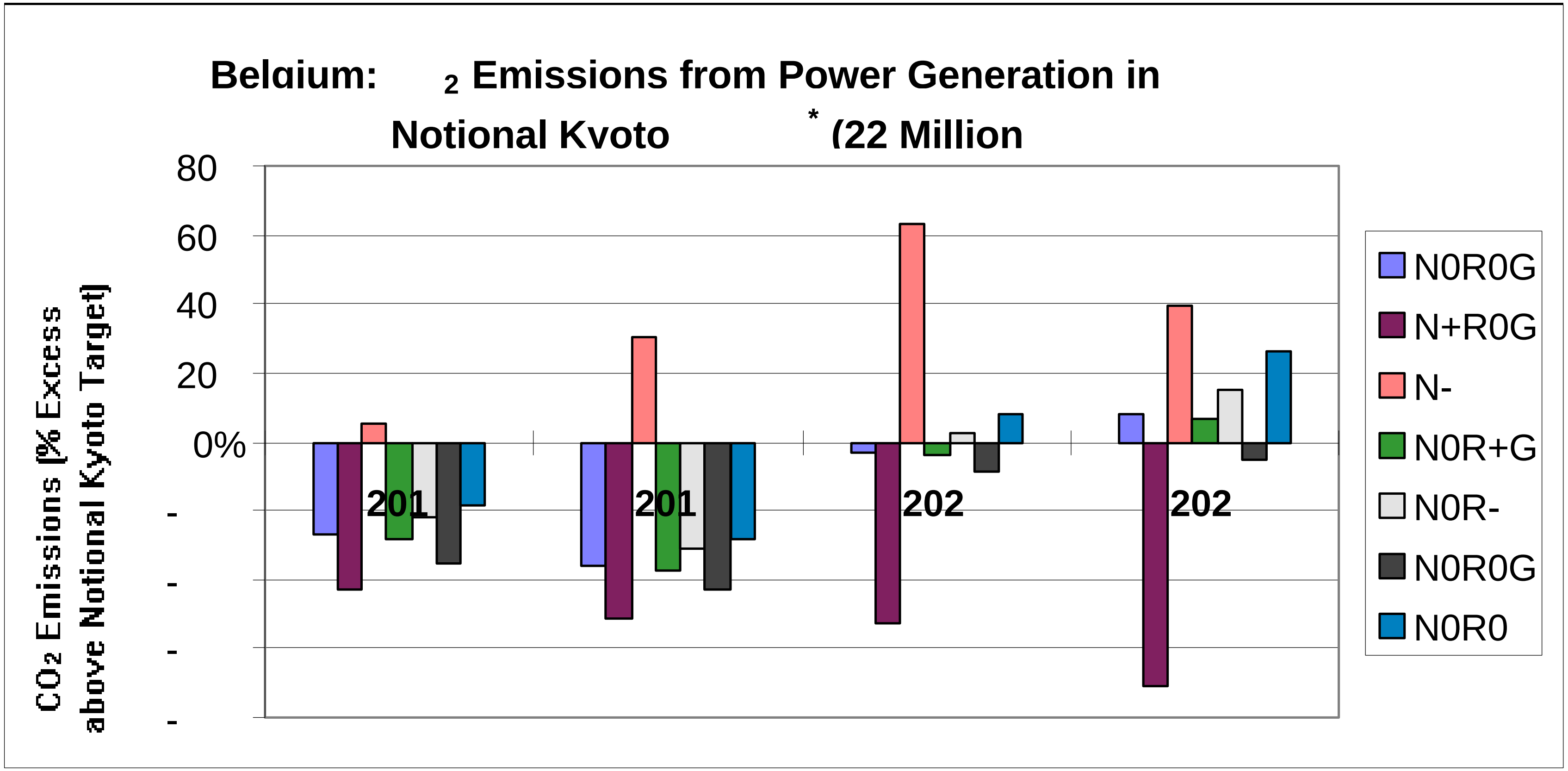


Figure 7.5 Spent Fuel Discharged

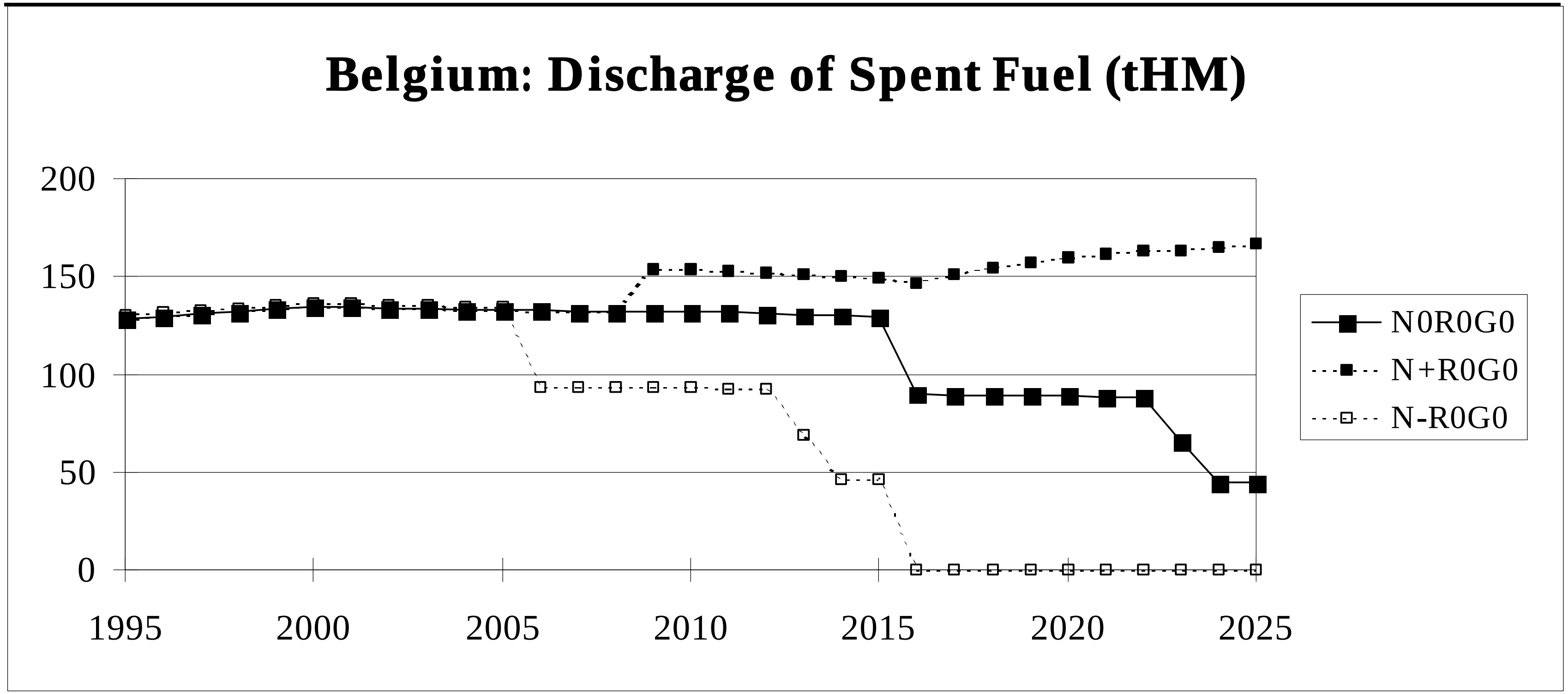


Figure 7.6 Low Level Waste (LLW/ILW)

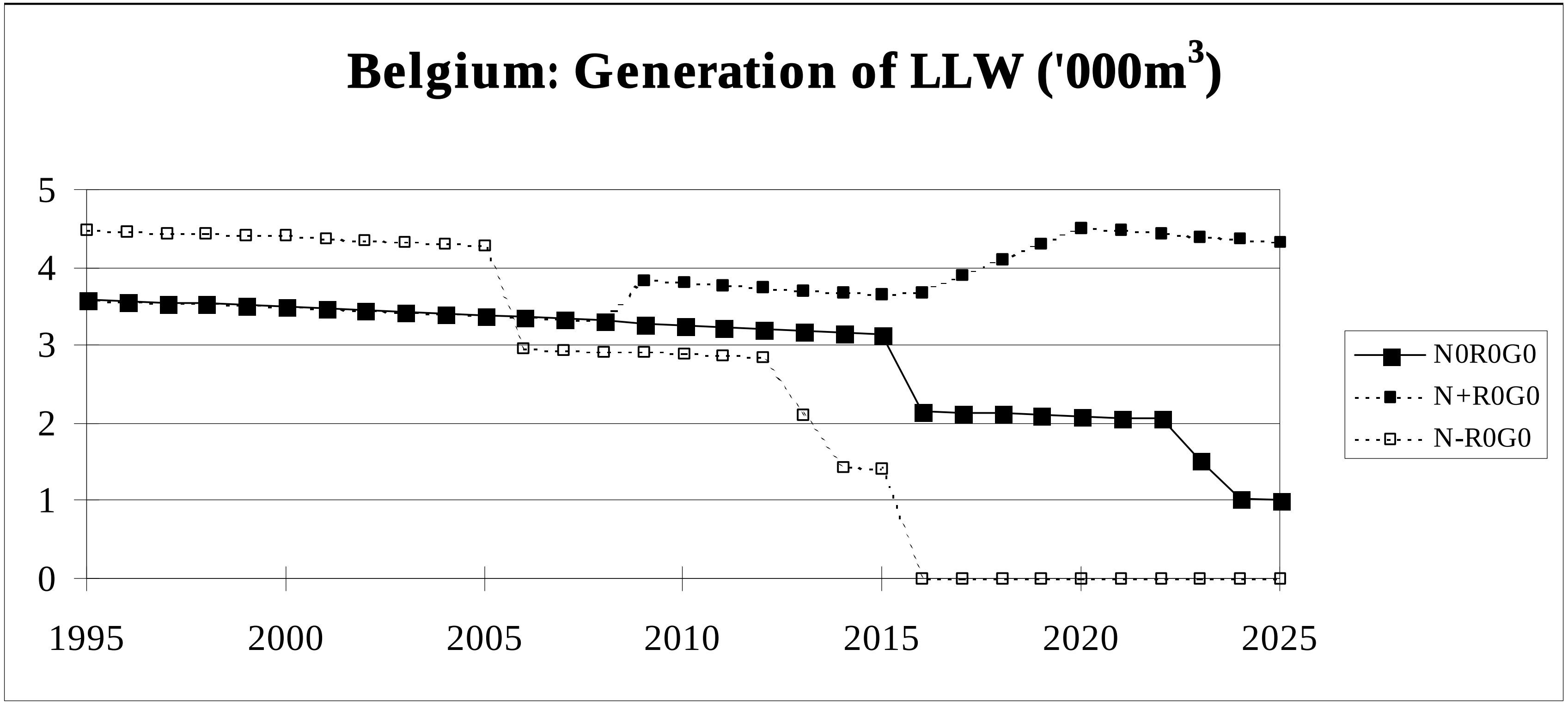


Figure 7.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

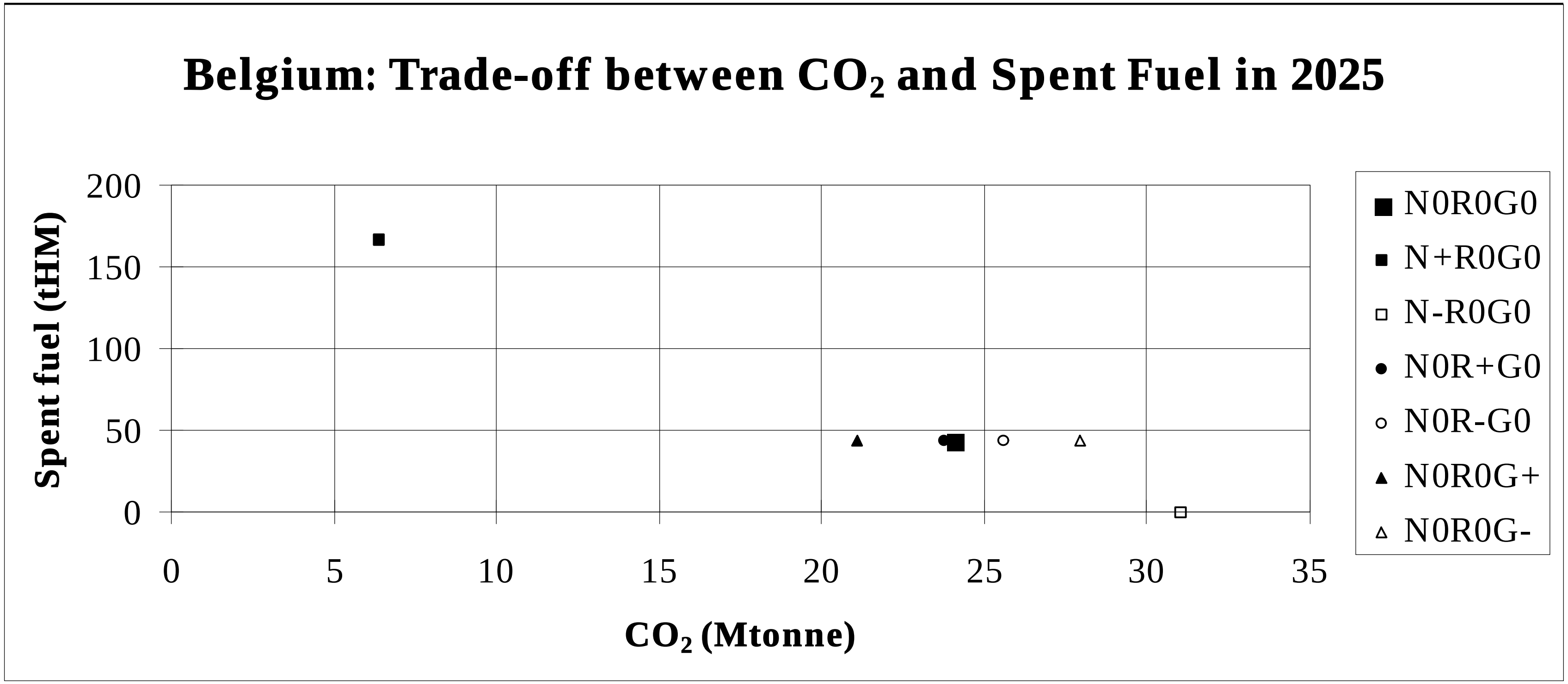
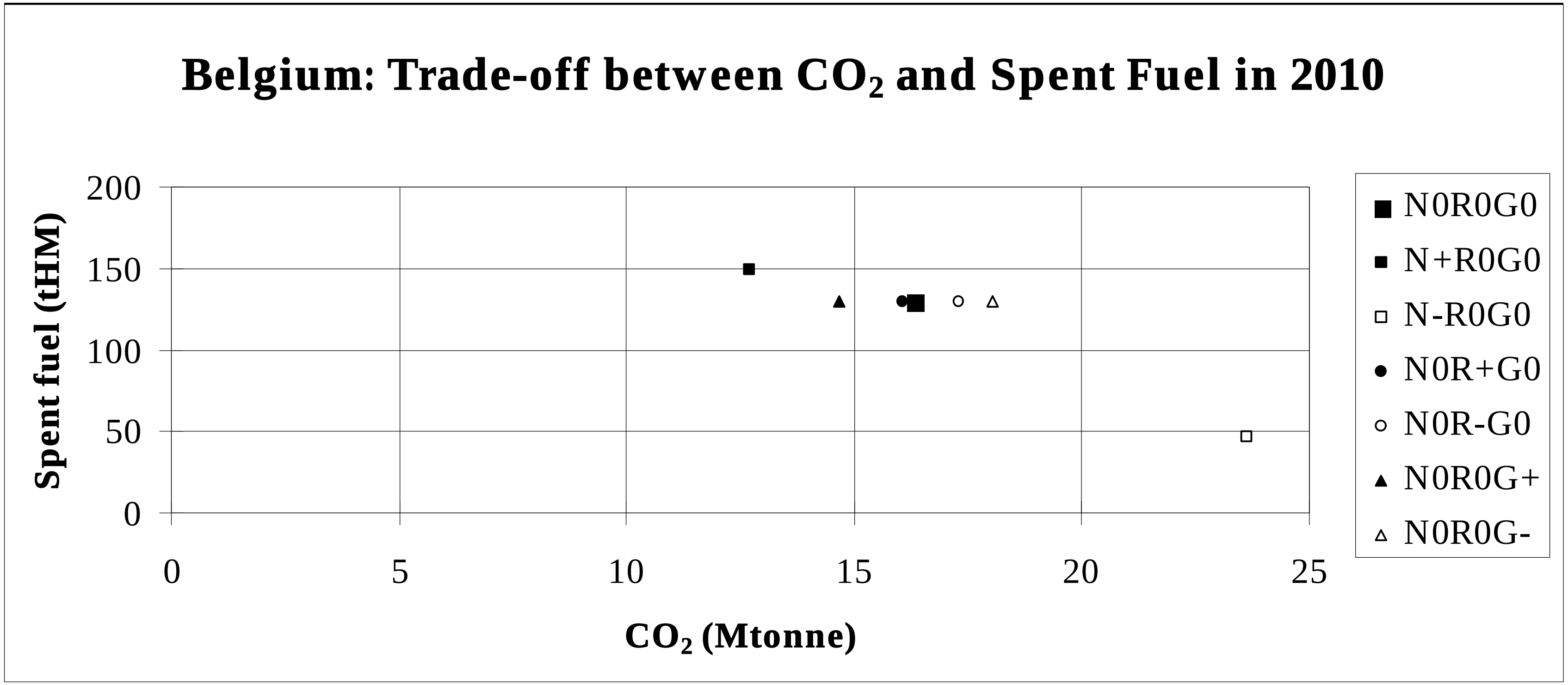


Figure 7.8 *Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010*



8 FINLAND

8.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4*.

The model has been calibrated against the actual performance of the Finnish power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 19.5 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 21 million tonnes. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 8.1*.

Table 8.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 30.5% with large hydro and 15.5% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 18% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 35% with large hydro and 20% excluding large hydro in 2025, other factors as Base Scenario.
N0R-G0	Low RETs	Renewable generation amounts to 25% with large hydro and 10%

Scenario	Description	Composition
		excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

8.2 RESULTS

Electricity Generation in 2025 by Origin

*Figure **8**.1* shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. Nuclear (33%) and Renewables (28%) power accounted for 61% of electricity generation in 1995, with a further 28% from Coal . Finnish nuclear part is relatively old and will be retired between 2017-23 with a 40 year lifetime. Thus nuclear generation is zero in 2025 in all but the High Nuclear scenario (N+R0G0).

Gas replaces the majority of this nuclear generation in 2025, and accounts for between 20-40% of generation in 2025. Coal maintains its share of generation, accounting for 36% of generation in the Base scenario (N0R0G0) and 47% in the Low Gas / High Coal scenario (N0R0G-).

Finland generated 20% of its electricity from large hydro in 1995. This capacity is projected to continue to operate. The potential for renewable generation in Finland is high, and it is projected that renewables (including large hydro) will generate between 25-35% of electricity in 2025.

Emissions of Carbon Dioxide

Figure 8.2 summarises the emissions of carbon dioxide from the Finnish power system up to 2025 as forecast by this model.

Due to its reliance on Nuclear and Renewables generation in 1990, CO_2 emissions were only 16 Mtonne. Emissions rise in all scenarios to approximately 30 Mtonne by 2005. After this, emissions stabilise until nuclear plant retires. By 2025, the Base scenario (N0R0G0) shows CO_2 emissions of 45 Mtonne (an increase of 180% over the 1990 value). Emissions from all scenarios except for High Nuclear (N+R0G0) are closely packed in 2025, ranging from between 40-50 Mtonne. The lower value of this range can be achieved through encouraging Gas (N0R0G+) or High Renewables (N0R+G0); the higher values come about through either Low Gas / High Coal (N0R0G-) or Low Renewables (N0R-G0).

Maintaining a share of nuclear capacity of 18% (N+R0G0) stabilises CO2 emissions at 25 Mtonne (60% higher than the 1990 value).

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, Finland agreed to hold emissions at 1990 levels in the year 2010. Total emissions in 1990 from all sectors were 52 Mtonne CO_2, of which 16 Mtonne (31%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 8.3* shows the difference between projected values and the Kyoto target. Finland will need to find reductions in the range 22-28 Mtonne in 2010-2025. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to hold emissions at the 1990 level of 16 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 8.4 shows that Finland cannot meet this target under any of the seven scenarios. Even the High Nuclear scenario (N+R0G0) shows excesses of the order of 10 Mtonne (+60%). Other scenarios show excesses rising to 23-35 Mtonne by 2025. Because Finnish nuclear plant is relatively old, the Low Nuclear scenario does not have lead to major extra emissions except in 2015.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 8.5 shows the discharge of spent fuel from nuclear plant over the period. In the Base scenario (N0R0G0), spent fuel of 50 tHM/year arises until nuclear plant retires in 2017-23. By 2025, spent fuel arising is zero. The low Nuclear scenario (N-R0G0) follows the same pattern as the Base scenario but advanced by 10 years.

Because of nuclear capacity retaining its share of increasing capacity (and generation) in the High Nuclear scenario (N+R0G0), emissions rise to 76 tHM in 2025.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 8.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the lifetime of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are 0%, 152% and 0% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 8.7,* which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

For all but the High Nuclear scenario (N+R0G0), Carbon Dioxide emissions range from 40-50 Mtonne and the influence of policy choices is not great. The High Nuclear scenario shows reductions in CO2 emissions of 19 Mtonne offset by increases in spent fuel of 76 tHM.

Figure 8.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

8.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. Nuclear (33%) and Renewables (28%) power accounted for 61% of electricity generation in 1995, with a further 28% from Coal .

2. Finnish nuclear part is relatively old and will be retired between 2017-23 with a 40 year lifetime. Thus nuclear generation is zero in 2025 in all but the High Nuclear scenario (N+R0G0).

3. Gas replaces the majority of this nuclear generation in 2025, and accounts for between 20-40% of generation in 2025. Coal maintains its share of generation, accounting for 36% of generation in the Base scenario (N0R0G0) and 47% in the Low Gas / High Coal scenario (N0R0G-).

4. Finland generated 20% of its electricity from large hydro in 1995. This capacity is projected to continue to operate. The potential for renewable generation in Finland is high, and it is projected that renewables (including large hydro) will generate between 25-35% of electricity in 2025.

5. Due to its reliance on Nuclear and Renewables generation in 1990, CO_2 emissions were only 16 Mtonne. Emissions rise in all scenarios to approximately 30 Mtonne by 2005. After this, emissions stabilise until nuclear plant retires.

6. CO_2 Emissions from all scenarios except for High Nuclear (N+R0G0) are closely packed in 2025, ranging from between 40-50 Mtonne.

7. Maintaining a share of nuclear capacity of 18% (N+R0G0) stabilises CO2 emissions at 25 Mtonne (60% higher than the 1990 value).

8. Finland cannot meet its Kyoto target in the power generation sector under any of the seven scenarios. Even the High Nuclear scenario (N+R0G0) shows excesses of the order of 10 Mtonne (+60%). Other scenarios show excesses rising to 23-35 Mtonne by 2025.

9. In the Base scenario (N0R0G0), spent fuel of 50 tHM / year arises until nuclear plant retires in 2017-23. By 2025, spent fuel arising is zero. The low Nuclear scenario (N-R0G0) follows the same pattern as the Base scenario but advanced by 10 years.

10. Because of nuclear capacity retaining its share of increasing capacity (and generation) in the High Nuclear scenario (N+R0G0), emissions of spent rise to 76 tHM in 2025.

11. For all but the High Nuclear scenario (N+R0G0), Carbon Dioxide emissions range from 40-50 Mtonne and the influence of policy choices is not great. The High Nuclear scenario shows reductions in CO2 emissions of 19 Mtonne offset by increases in spent fuel of 76 tHM.

Figure 8.1 *Electricity Generation in 2025 by Origin*

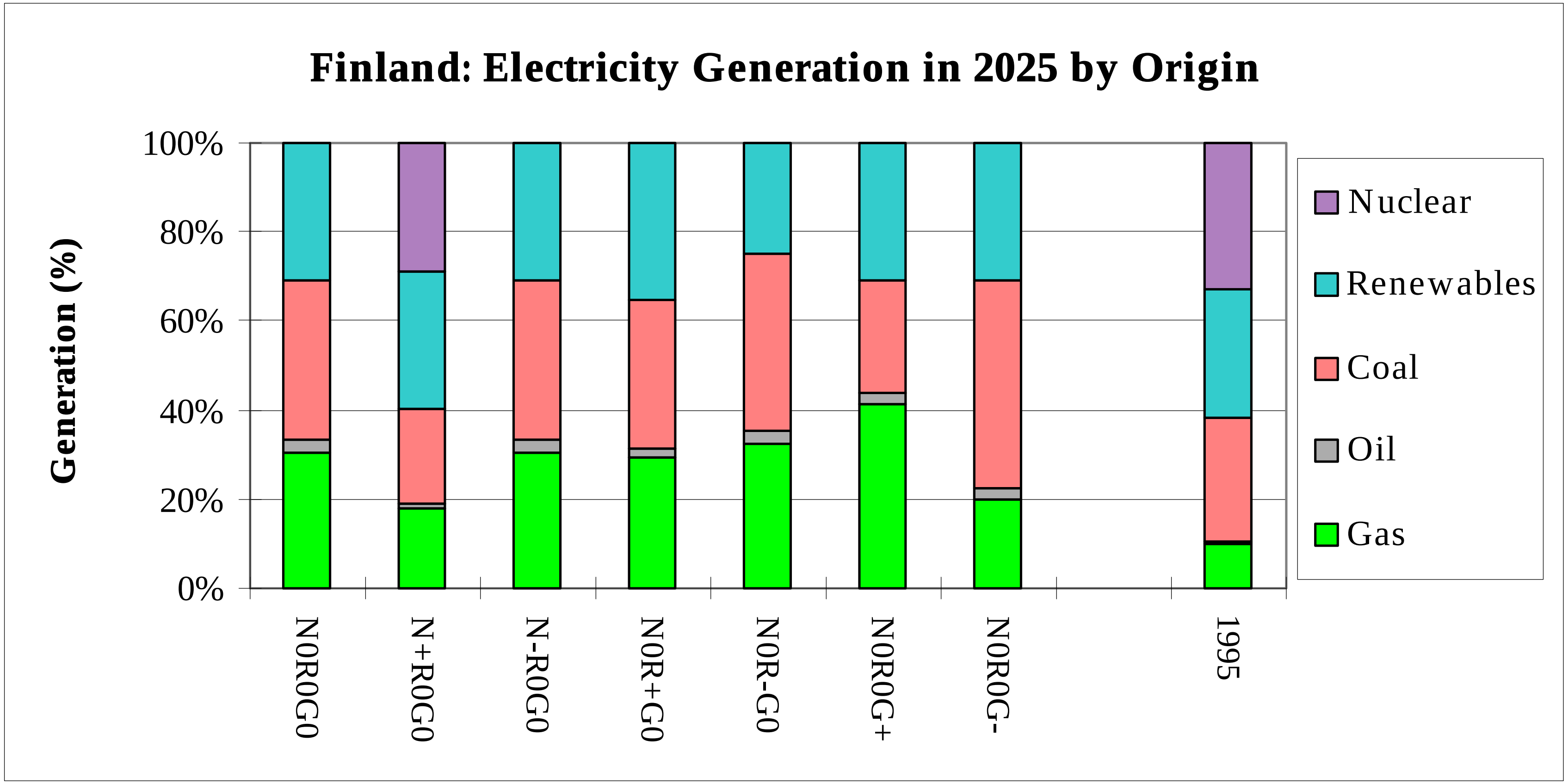


Figure 8.2 Carbon Dioxide Emissions from Power Generation

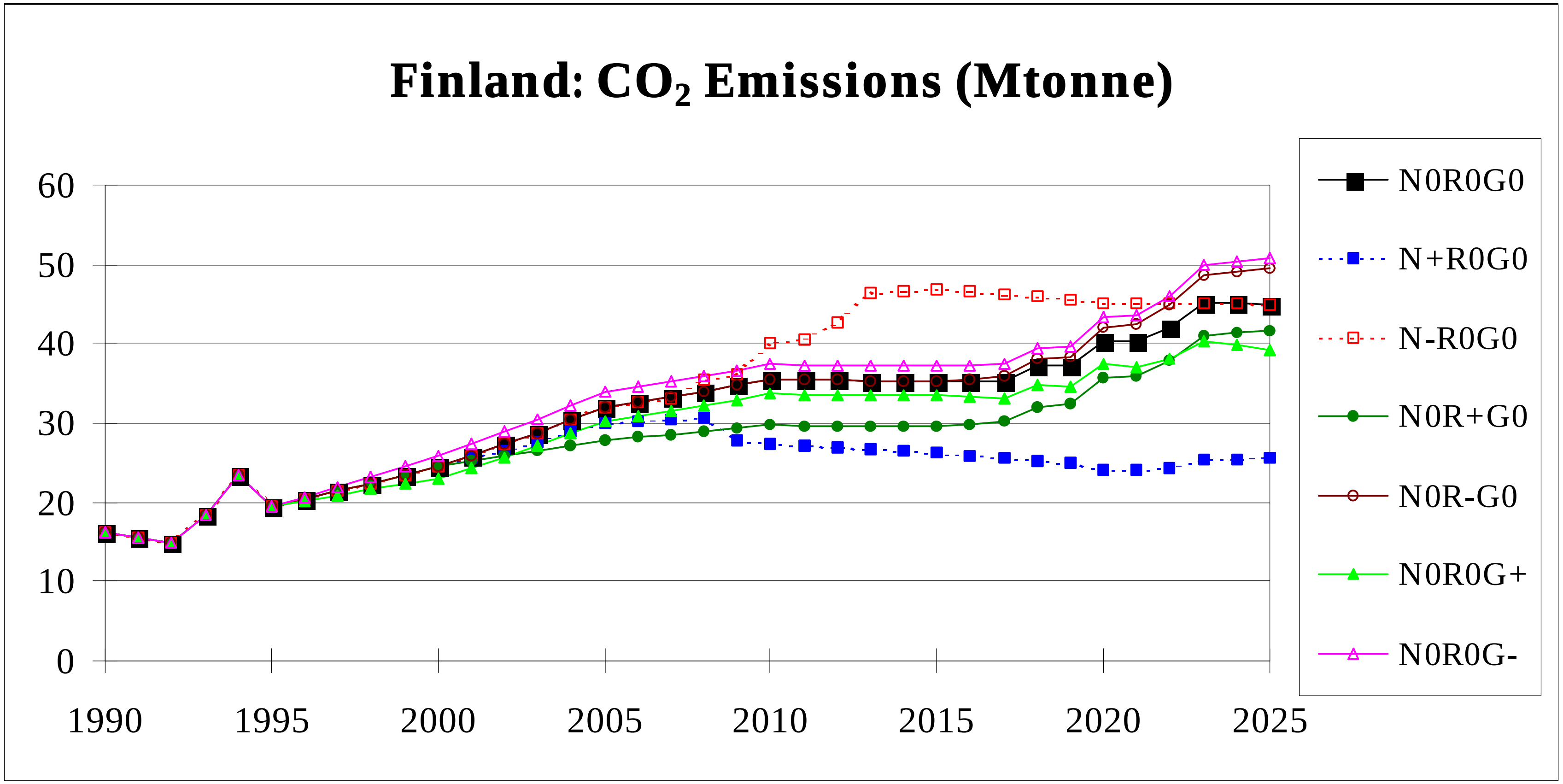


Figure 8.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

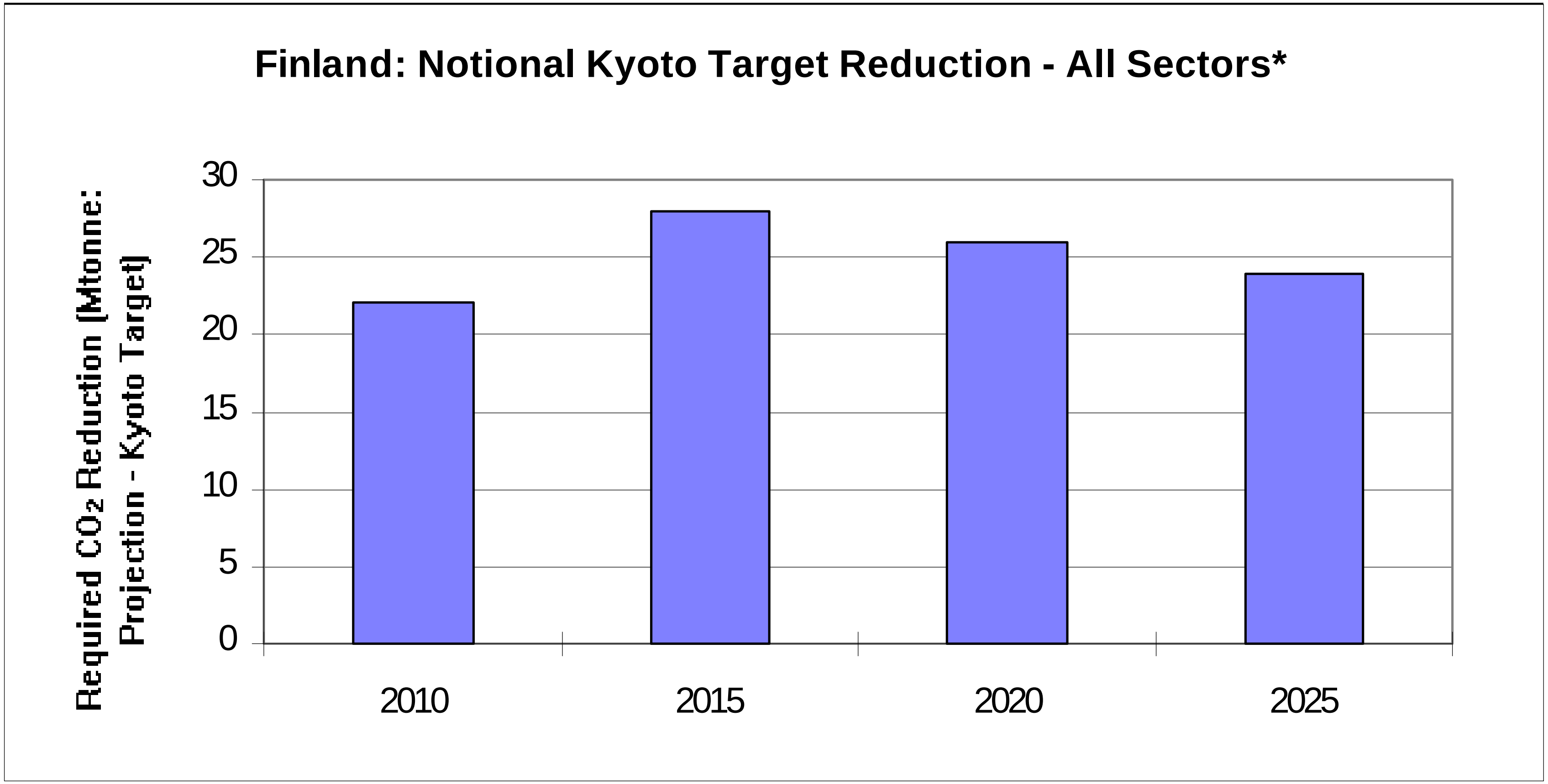


Figure 8.4 Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target (Assuming equal burdens on power generation sector and non-power generation sectors)*

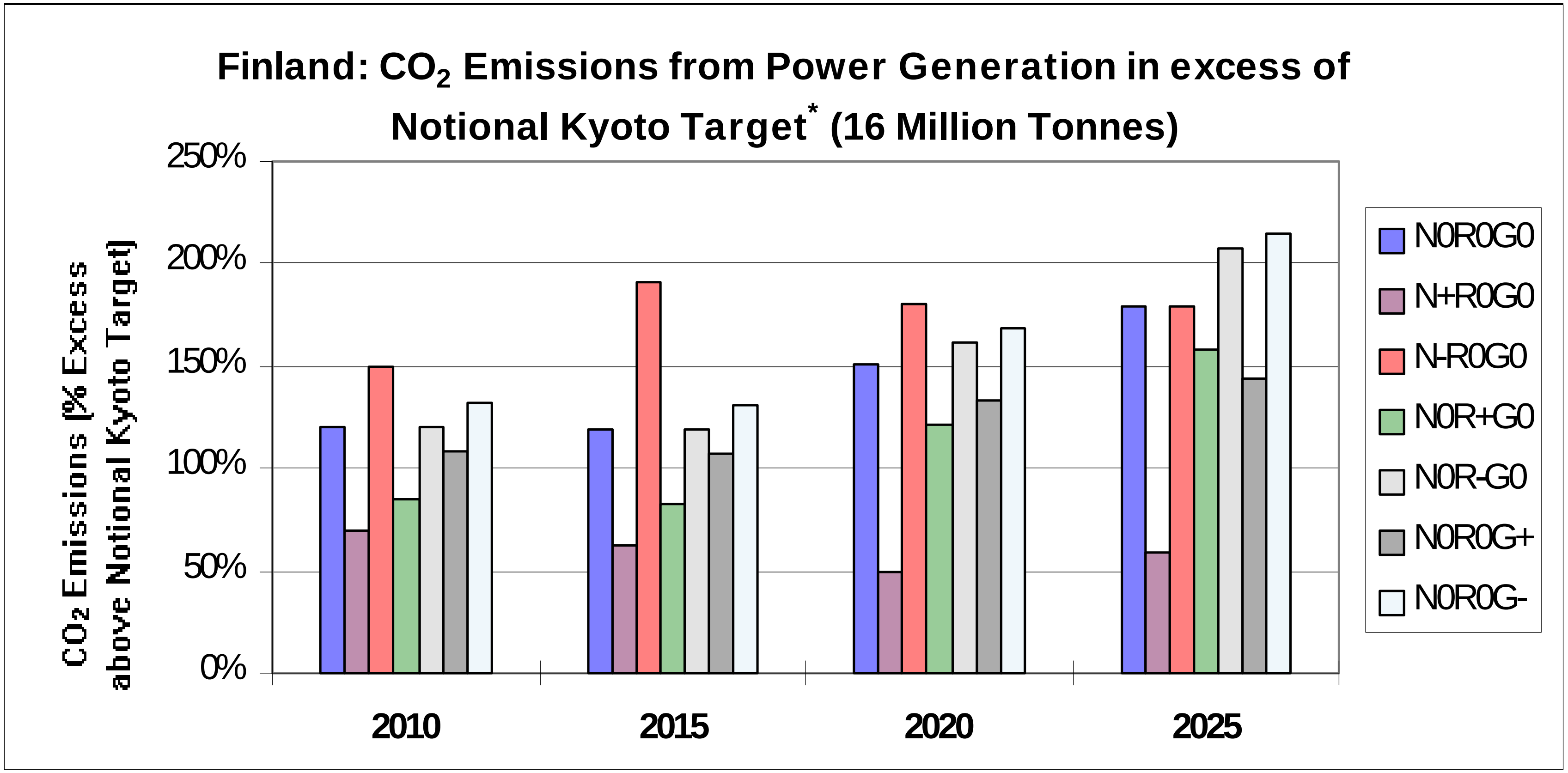


Figure 8.5 Spent Fuel Discharged

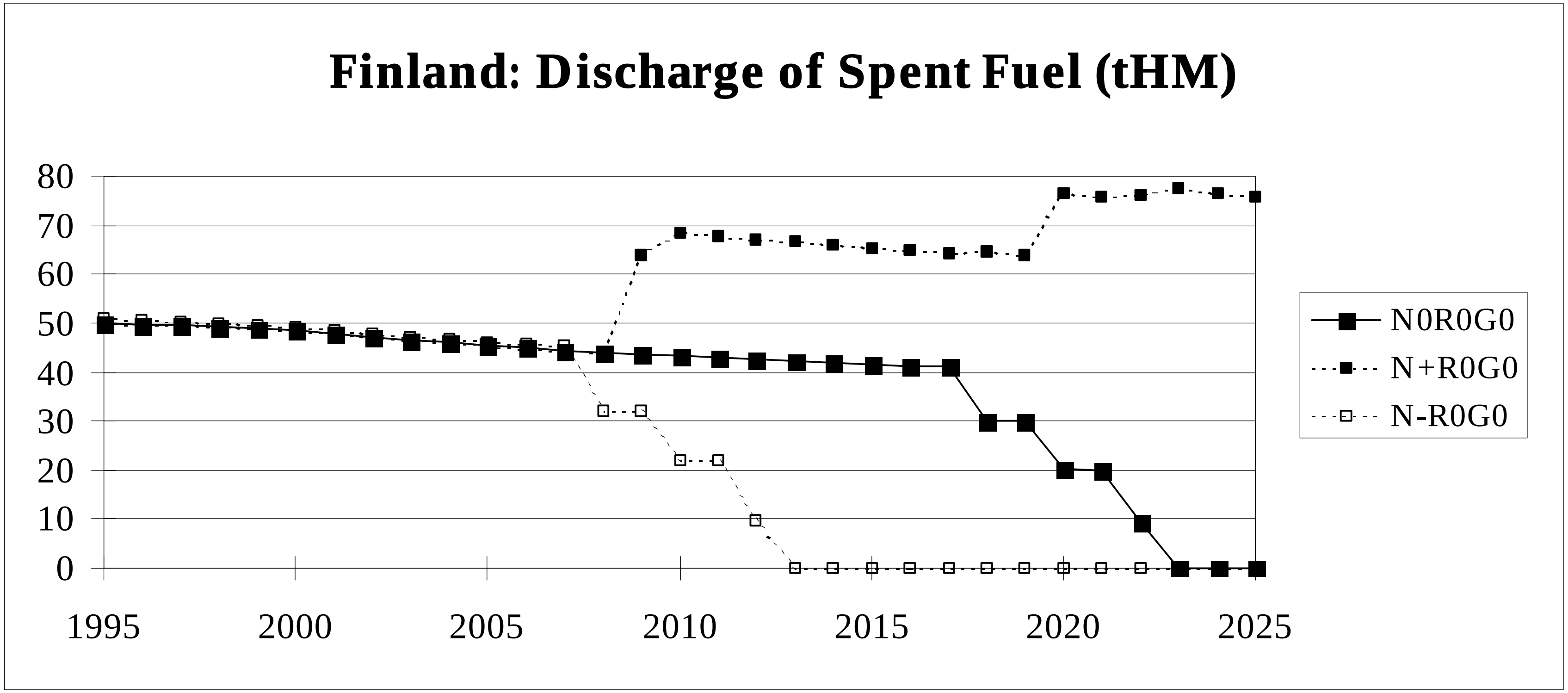


Figure 8.6 Low Level Waste (LLW/ILW)

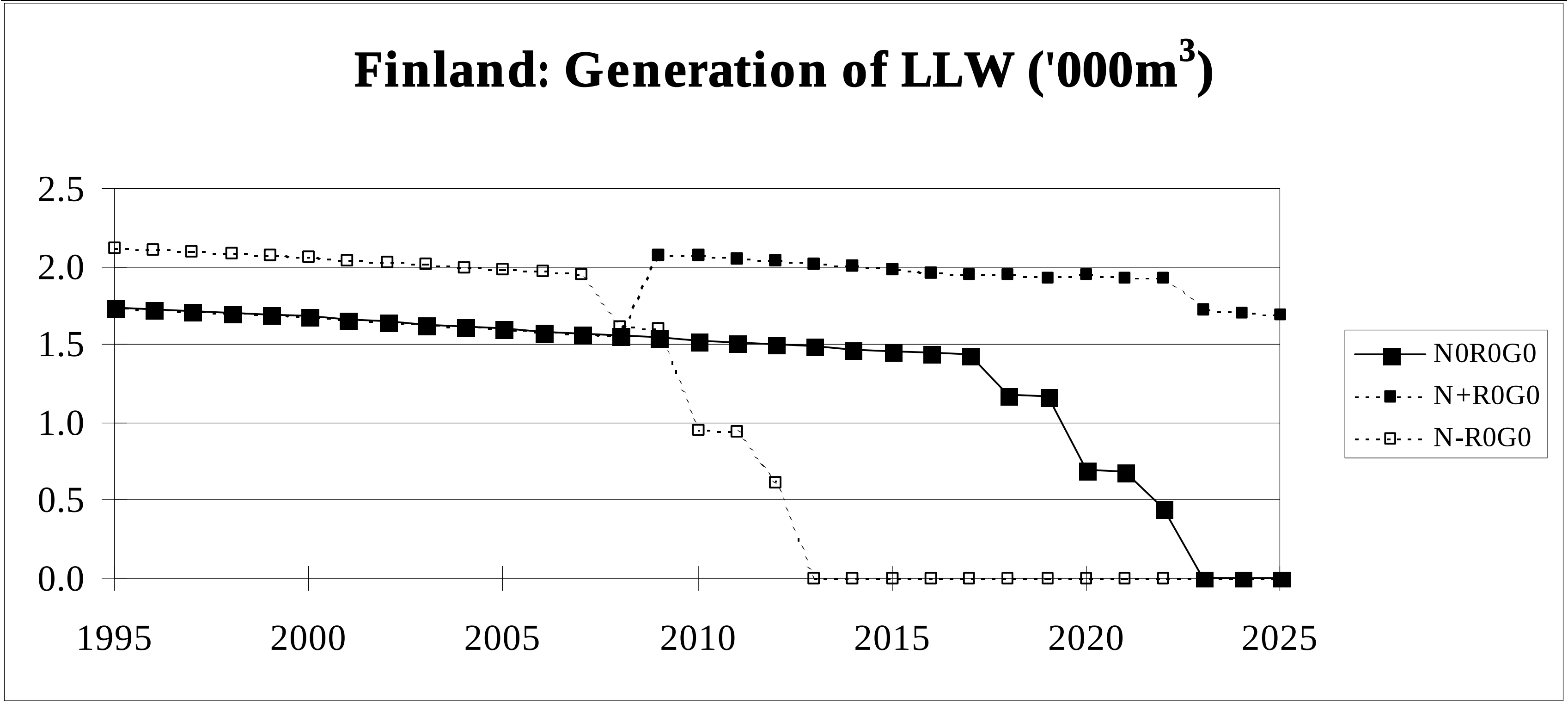


Figure 8.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

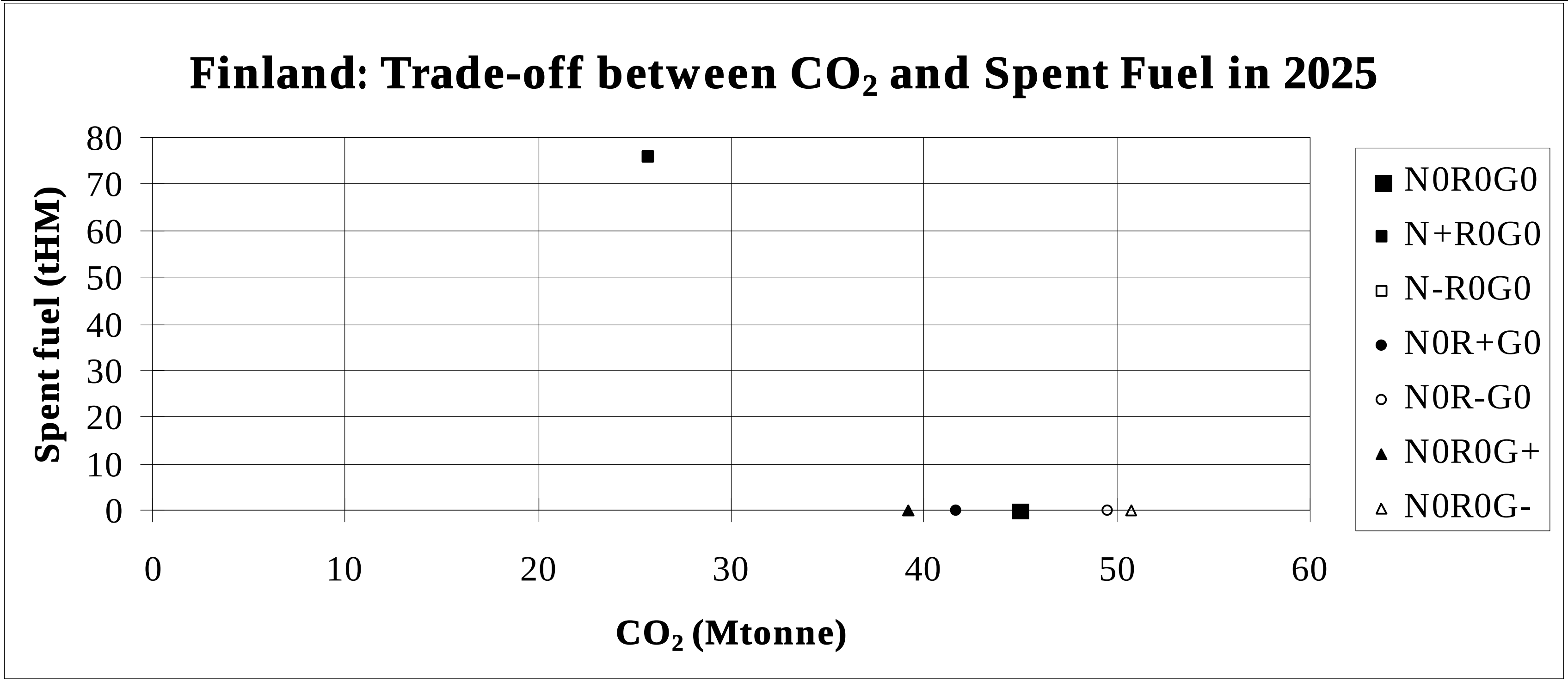
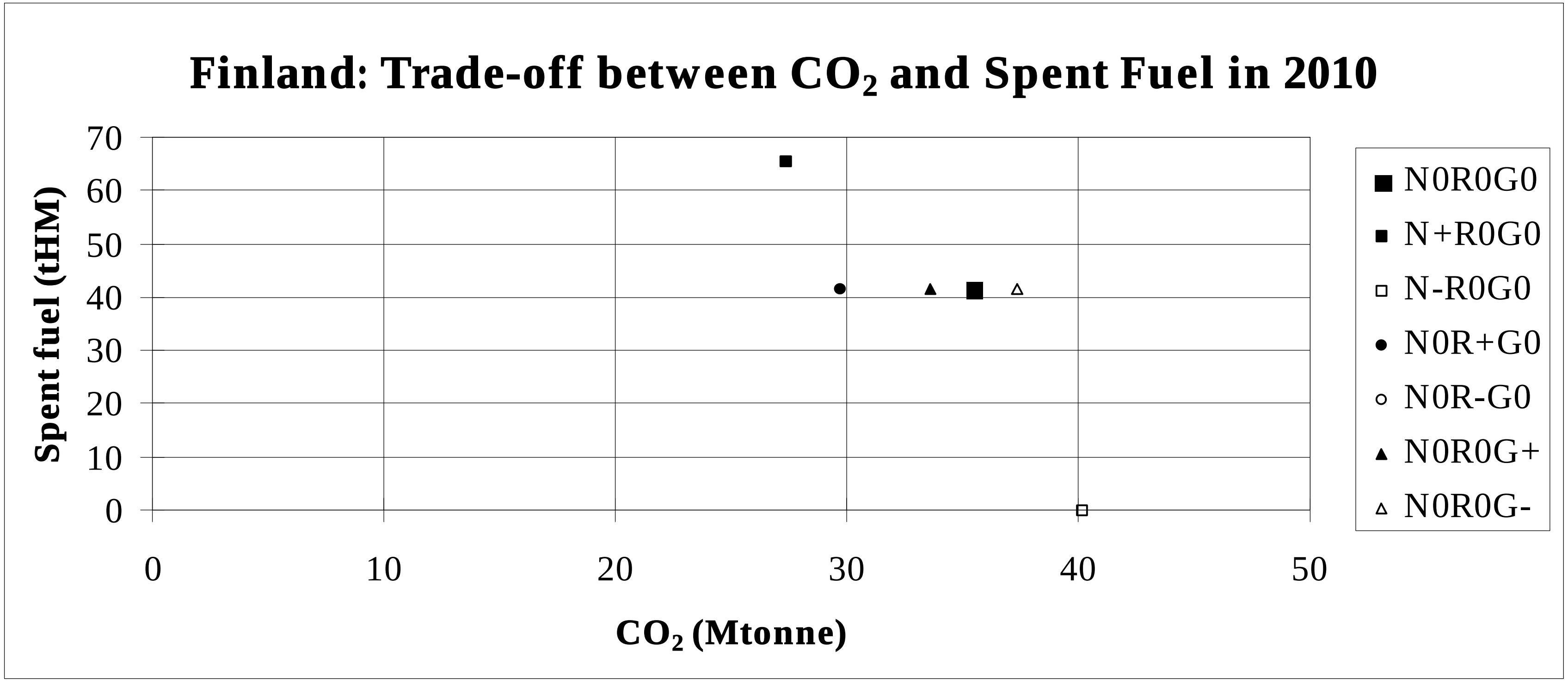


Figure 8.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010



9 FRANCE

9.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4*.

The model has been calibrated against the actual performance of the French power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure and adjustment of the two-part model of hydro generation. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 29.89 million tonnes, which compares well with the estimate in the 1998 Annual Energy Review of 27.52 million tonnes. The discrepancy will be due to minor variations in the share of thermal power that cannot be completed reproduced in a model as they depend on contingent changes in the detailed despatch and operation of plant.

Attention has also been paid to the recent study of the *Commissariat General du Plan, Energie 2010-2020*. The mean renewable scenario is based on the scenario S2 of that study and the high renewable scenario assumes twice the volume of renewables. Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables.

Details of the Scenarios are shown in *Table 9.1*.

Table 9.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation is based on scenario S2 of Energie 2010-2020: amounts to 17% with large hydro and 4% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 60% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation is double that of scenario S2 of Energie 2010-2020: amounts to 22% with large hydro and 9% excluding large hydro in 2025, other factors as Base Scenario.
N0R-G0	Low RETs	Renewable generation is as in European Energy to 2020 (extrapolated): amounts to 14.5% with large hydro and 1.5% excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

9.2 RESULTS

Electricity Generation in 2025 by Origin

Figure 9.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. In the base scenario (N0R0G0), nuclear power is still responsible for 41% of electricity generation by 2025, compared to 76% in 1995; this figure is achieved despite some retirements of nuclear plant. Most of the remainder of the generation in 2025 is provided by gas; the significant share of renewables is mainly from large hydro plant. In the high nuclear scenario (N+R0G0), 68% of the generation is from nuclear plant. The enhanced nuclear generation mainly displaces gas-fired generation, compared to the base scenario.

In the low nuclear scenario (N-R0G0), gas and coal are the predominant replacement fuels. Gas and coal-fired capacity are built in an approximate ratio of two to one, but the gas-fired capacity has a disproportionate share of the generation because it is assumed to run preferentially as a consequence of the take-or-pay structure of the contracts that will underpin gas firing.

In the high renewables scenario (N0R+G0), renewable energy mainly displaces gas in comparison with the base scenario, because the nuclear capacity will be run preferentially. The high renewables scenario makes significant inroads into coal fired generation and displaces some of the new gas-fired capacity. The low renewables scenario (N0R-G0) is associated with a slight increase in the gas burn, largely because it is a postulate of this scenario that no new nuclear capacity is to be built.

The high gas scenario (N0R0G+) displaces coal, but the potential is limited by the fact that coal forms a small part of the base scenario; nuclear and hydro provide a large share of generation in the base scenario. The low gas scenario (N0R0G-) allows a substantial penetration of coal into the share of the generation provided by gas in the base scenario.

In general, the high combined share of nuclear and hydro stabilises the behaviour within the group of scenarios that do not permit a variation in the nuclear share. The high proportion of nuclear obviously means that there is a very large variation within the group of scenarios in which nuclear is allowed to vary.

Emissions of Carbon Dioxide

Figure 9.2 summarises the emissions of carbon dioxide from the French power system up to 2025 as forecast by this model.

The stabilisation of emissions in the beginning of the period is caused by the commissioning of the remaining N4 reactors. The subsequent behaviour is a consequence of the various scenario assumptions. It is clear that the assumptions regarding nuclear have enormous impact. The difference between the high and low nuclear scenarios is more than 150 million tonnes of carbon dioxide by 2025. The ripple towards the end of the period in the low nuclear scenario is caused by shifting proportions of coal and gas as new units are commissioned, a consequence of the “lumpiness” of investment.

The variation within the high and low renewables scenarios is much less, only some 20 million tonnes. The availability of gas is also shown to be a major influence, especially on the downside. The high gas scenario saves only 7 million tonnes of carbon dioxide by 2025 compared to Base, whereas the low gas scenario increases emissions by nearly 50 million tonnes. This is because gas fired plant if built are assumed to be run in preference to coal as they will almost certainly have take-or-pay contracts that induce such behaviour. In the transition from Base to High Gas therefore the extra gas capacity displaces only peaking plant.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, France agreed to hold emissions at 1990 levels in the year 2010. Total emissions in 1990 from all sectors were 369 Mtonne CO_2, of which 44 Mtonne (12%) came from the power generation sector.

EE2020 projections show that France faces a major challenge to hold its emissions levels at 1990 levels. Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 9.3* shows the difference between projected values and the Kyoto target. By 2025, France will need to find reductions of 110 Mtonne. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to hold emissions at the 1990 level of 44 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 9.4 shows how successful France will be in meeting this target under each of the seven scenarios. In 2010 and 2015, France will only have a problem if it follows the Low Nuclear scenario (closing nuclear plant after a lifetime of 30 years). By 2020, the Base Scenario is showing that emissions will be almost 20 Mtonne above the target. The real problem comes in 2025, when a large portion of nuclear plant will have been retired. Only the High Nuclear scenario meets the target; in all other scenarios, excess emissions of 50 - 110 Mtonne are projected, with encouraging renewables (N0R+G0) giving the lowest value and building Coal in preference to Gas (N0R0G-) giving the highest value. It should be remembered that France has to find net reductions of some 110 Mtonne in 2025, and increases from the power generation sector will make this target even harder to match. It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 9.5 shows the discharge of spent fuel from nuclear plant over the period. The spent fuel discharged at decommissioning is averaged over the life of the plant. Consequently the discharges of spent fuel, represented in this fashion, are somewhat higher for the low nuclear scenario, in which plants have a shorter lifetime, than in the other two scenarios.

In the base scenario, spent fuel discharges decline slowly as a consequence of improved burn-up and then begin to decline rapidly in 2020 as the first large nuclear plants are retired. Discharges of spent fuel in 2025 are a little less than half the 1995 value. In the low nuclear scenario the discharges of spent fuel fall off in a similar pattern to the base scenario, but advanced by ten years; they reach in 2025 a little less than 8% of the value in 1995. In the high scenario the discharges decline in the early years in a similar manner, reflecting improved burn-up and then undulate slowly as a consequence of the balance between retirement of old plant and commissioning of new.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 9.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 100%, 50% and 8% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 9.7*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The very wide range of possible outcomes among the nuclear scenarios is evident from this figure. The low scenario has 660% of the emissions of carbon dioxide of the high scenario but only 8% of the discharges of spent fuel.

It is also clear that it is the variation within the nuclear assumptions that has the greatest impact. The range of values of emissions of carbon dioxide for the renewables scenarios is much less than is the range for the nuclear scenarios. The range between the high and low scenarios is only 23 million tonnes or about 20% of the value in the base scenario; the range between the extreme nuclear scenarios is nearly 150% of the value in the base scenario.

It is also interesting, and slightly surprising, that the change in carbon dioxide emissions between the high gas scenarios and base scenarios is modest. As noted earlier, this is because the extra gas displaces peaking plant and has less impact. The downside in the low gas scenario is much more significant. If gas-fired capacity is not built so strongly then the impact on carbon dioxide emissions will be strong, because it affects the mid-merit section of the load duration curve.

Figure 9.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

9.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. In the base scenario (N0R0G0), nuclear power is still responsible for 41% of electricity generation by 2025, compared to 76% in 1995; this figure is achieved despite some retirements of nuclear plant.

2. In the high nuclear scenario (N+R0G0), 68% of the generation is from nuclear plant. The enhanced nuclear generation mainly displaces gas-fired generation, compared to the base scenario.

3. The high proportion of nuclear obviously means that there is a very large variation within the group of scenarios in which nuclear is allowed to vary.

4. The stabilisation of CO_2 emissions in the beginning of the period is caused by the commissioning of the remaining N4 reactors.

5. The difference between the high and low nuclear scenarios is more than 150 million tonnes of carbon dioxide by 2025.

6. The variation within the high and low renewables scenarios is much less, only some 20 million tonnes. The availability of gas is also shown to be a major influence, especially on the downside. The high gas scenario saves only 7 million tonnes of carbon dioxide by 2025 compared to Base, whereas the low gas scenario increases emissions by nearly 50 million tonnes.

7. In 2010 and 2015, France will only have a problem meeting the Kyoto target for the power sector if it follows the Low Nuclear scenario (closing nuclear plant after a lifetime of 30 years). By 2020, the Base Scenario is showing that emissions will be almost 20 Mtonne above the target.

8. The real problem meeting the Kyoto target for the power sector comes in 2025, when a large portion of nuclear plant will have been retired. Only the High Nuclear scenario meets the target; in all other scenarios, excess emissions of 50 - 110 Mtonne are projected, with encouraging renewables (N0R+G0) giving the lowest value and building Coal in preference to Gas (N0R0G-) giving the highest value.

9. In the base scenario, spent fuel discharges decline slowly as a consequence of improved burn-up and then begin to decline rapidly in 2020 as the first large nuclear plants are retired. Discharges of spent fuel in 2025 are a little

less than half the 1995 value. In the low nuclear scenario the discharges of spent fuel fall off in a similar pattern to the base scenario, but advanced by ten years; they reach in 2025 a little less than 8% of the value in 1995.

10. The discharges of LLW/ILW in 2025 in the high, base and low scenarios are approximately 100%, 50% and 8% of the values in 1995.

11. Projections of carbon dioxide in the future show that it is the variation within the nuclear assumptions that has the greatest impact. The range of values of emissions of carbon dioxide for the renewables scenarios is much less than is the range for the nuclear scenarios. The range between the high and low scenarios is only 23 million tonnes or about 20% of the value in the base scenario; the range between the extreme nuclear scenarios is nearly 150% of the value in the base scenario.

Figure 9.1 *Electricity Generation in 2025 by Origin*

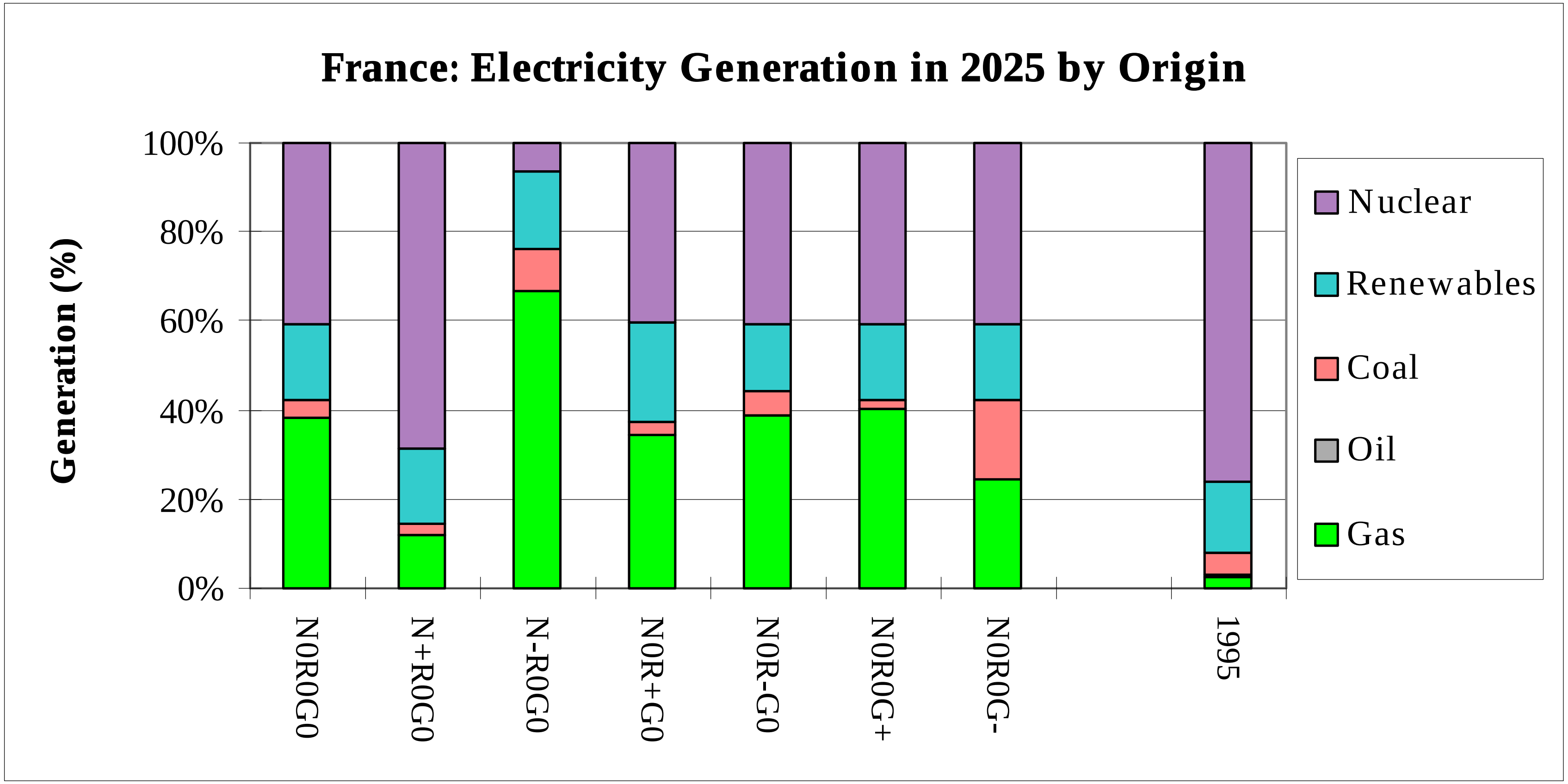


Figure 9.2 Carbon Dioxide Emissions from Power Generation

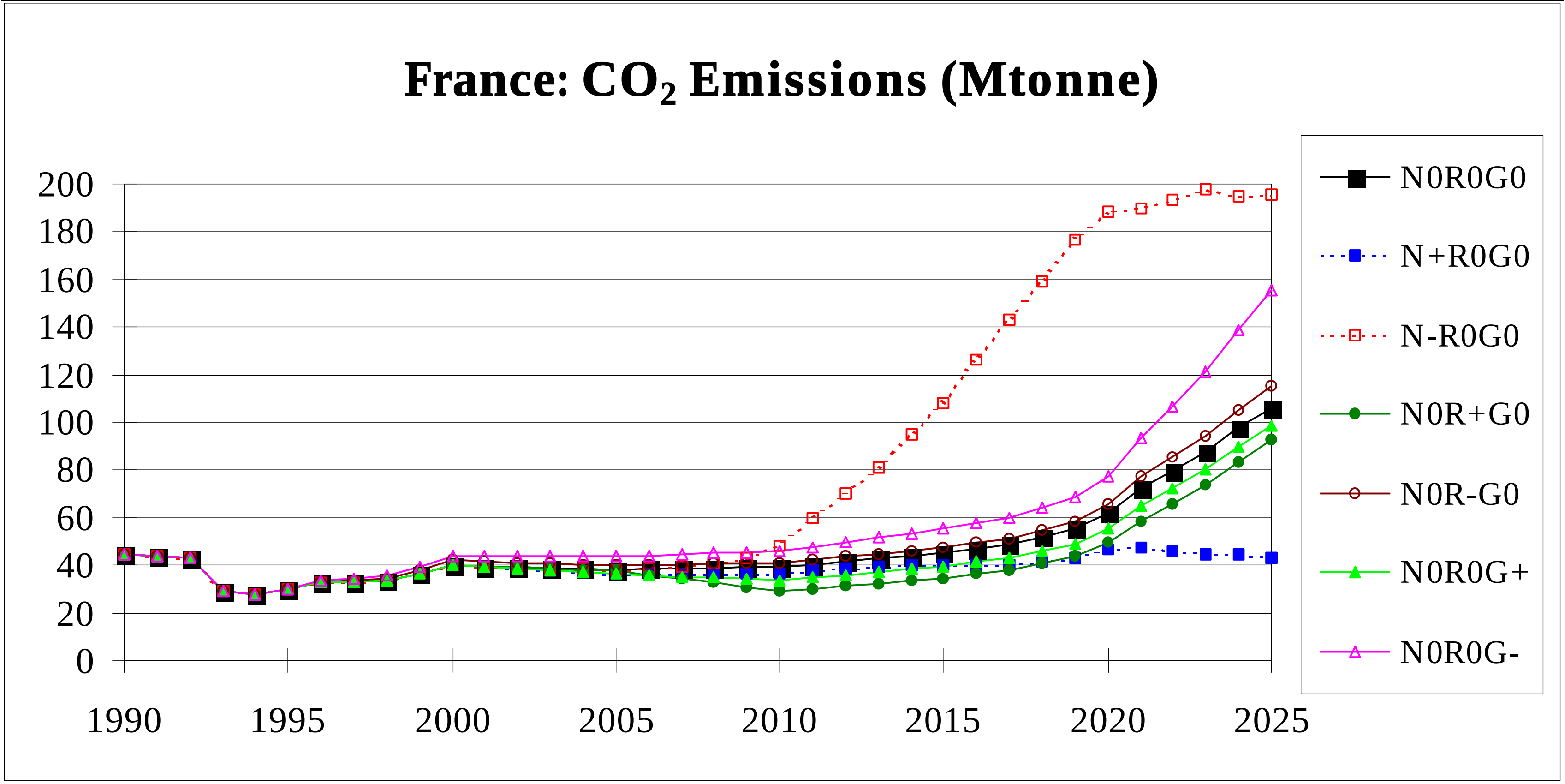


Figure 9.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

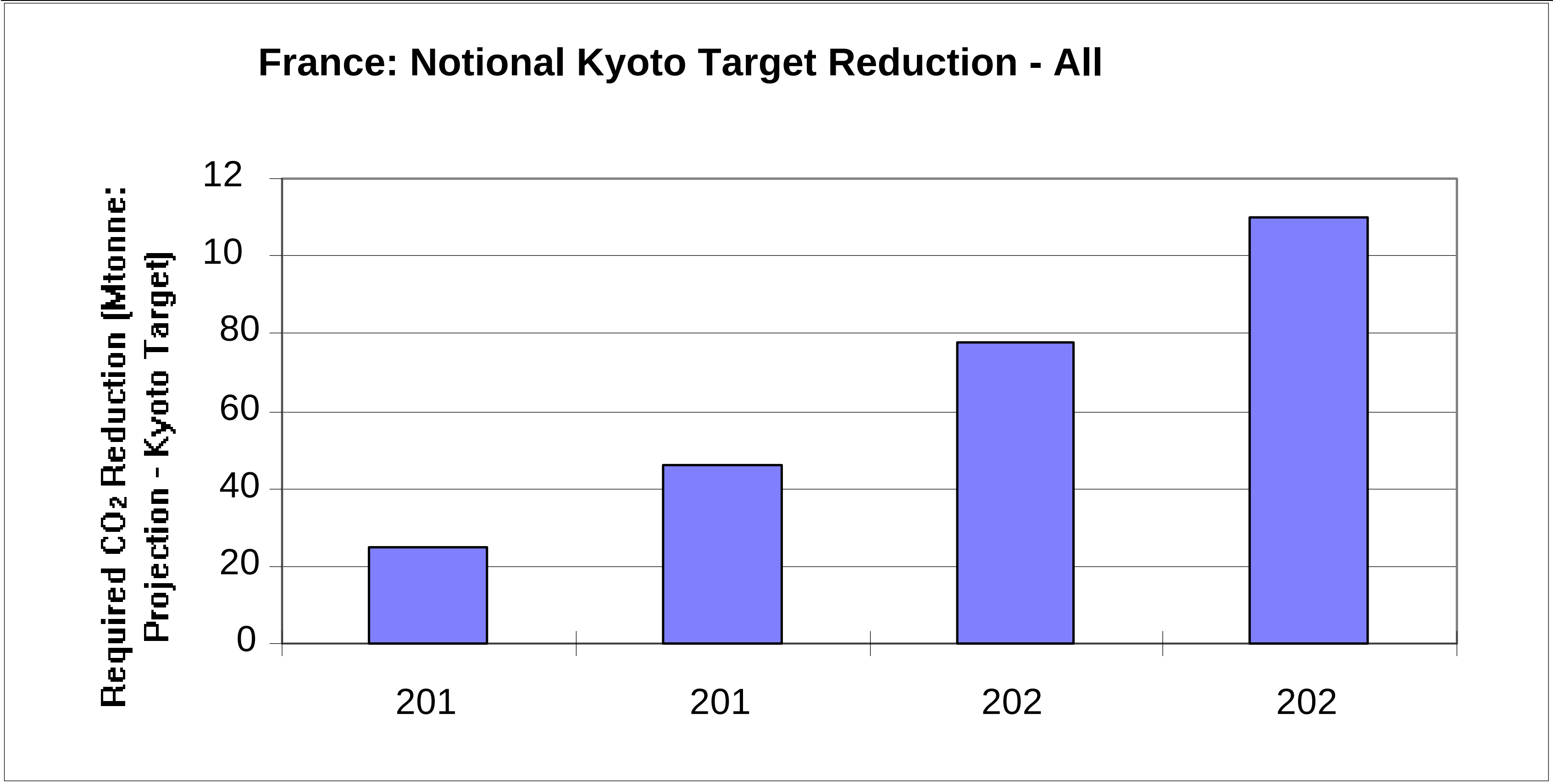


Figure 9.4 ***Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target* (Assuming equal burdens on power generation sector and non-power generation sectors)***

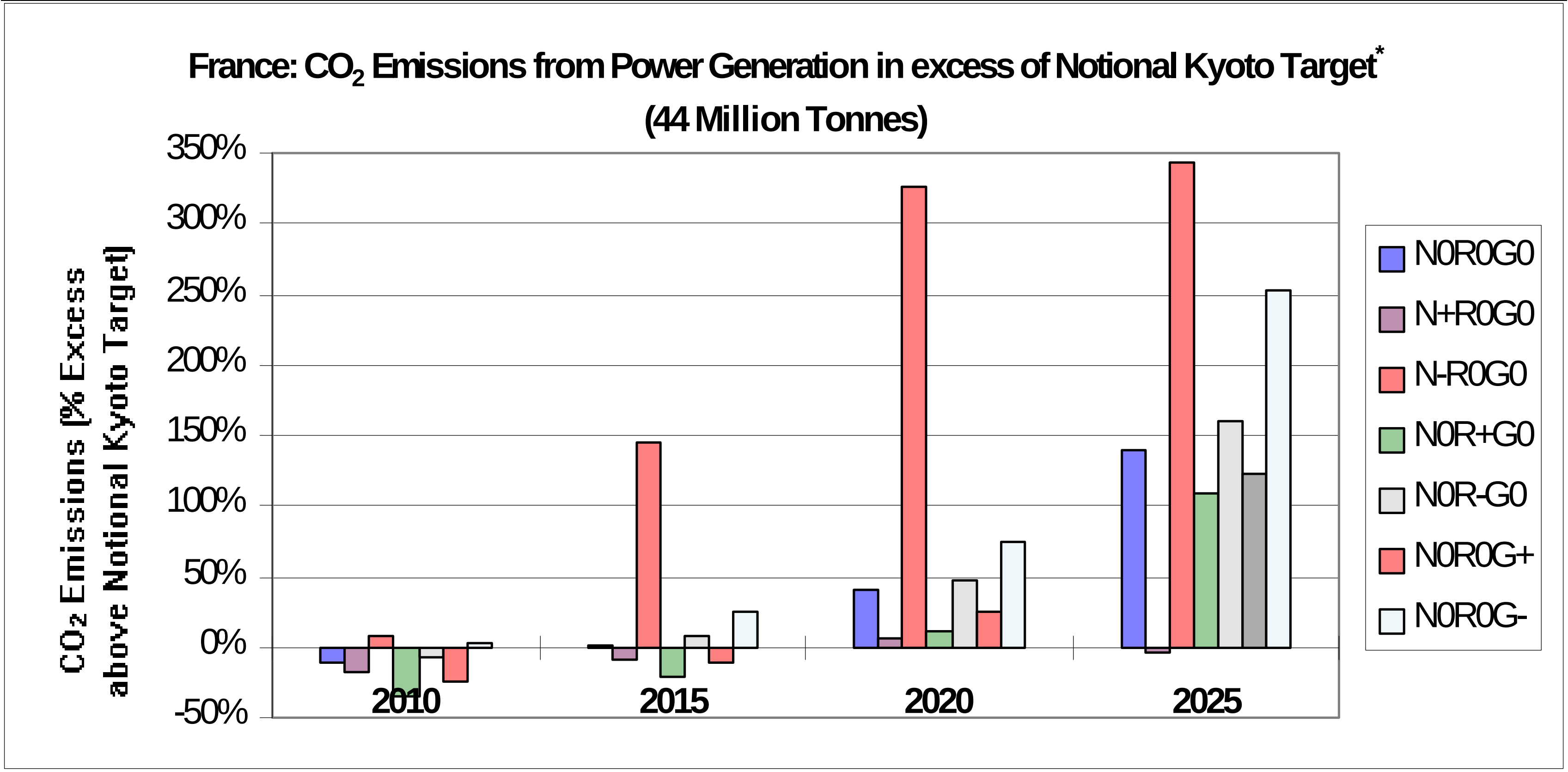


Figure 9.5 Spent Fuel Discharged

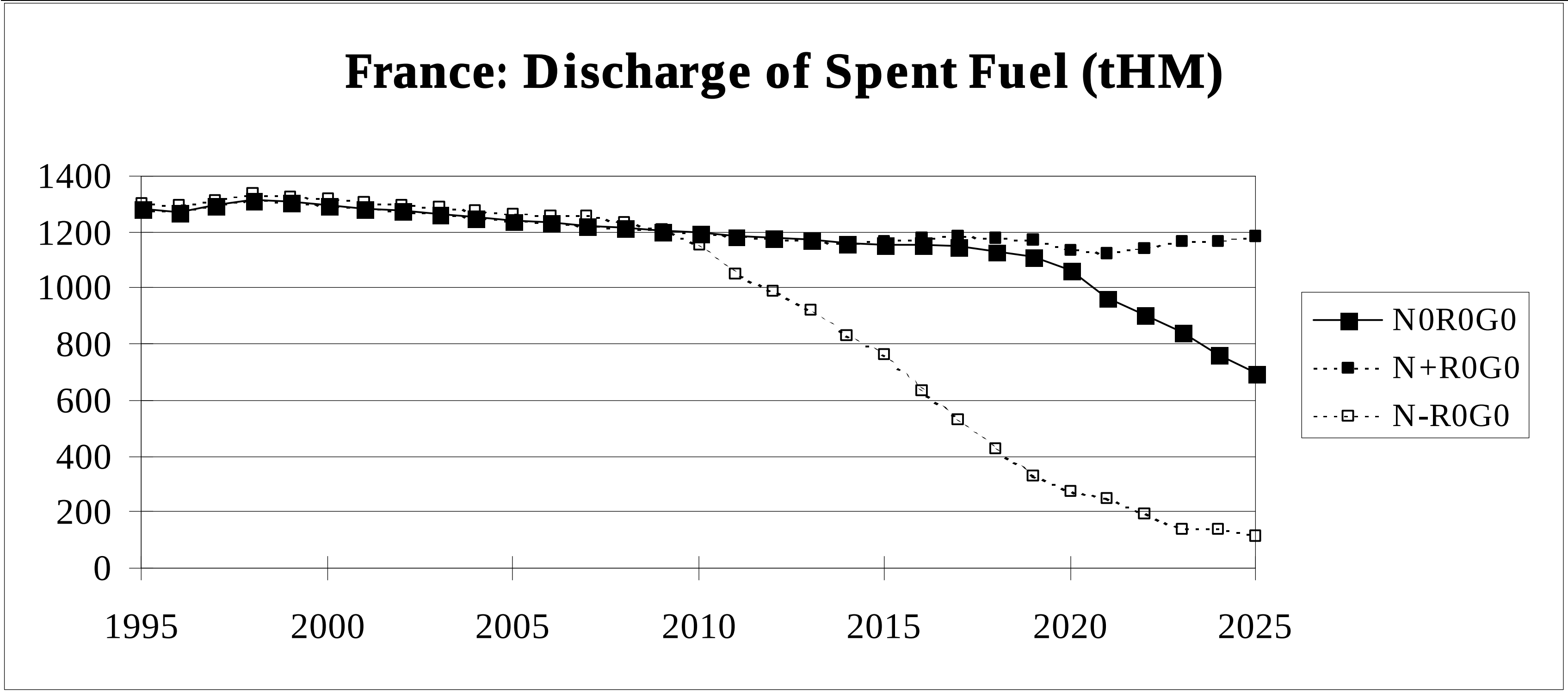


Figure 9.6 Low Level Waste (LLW/ILW)

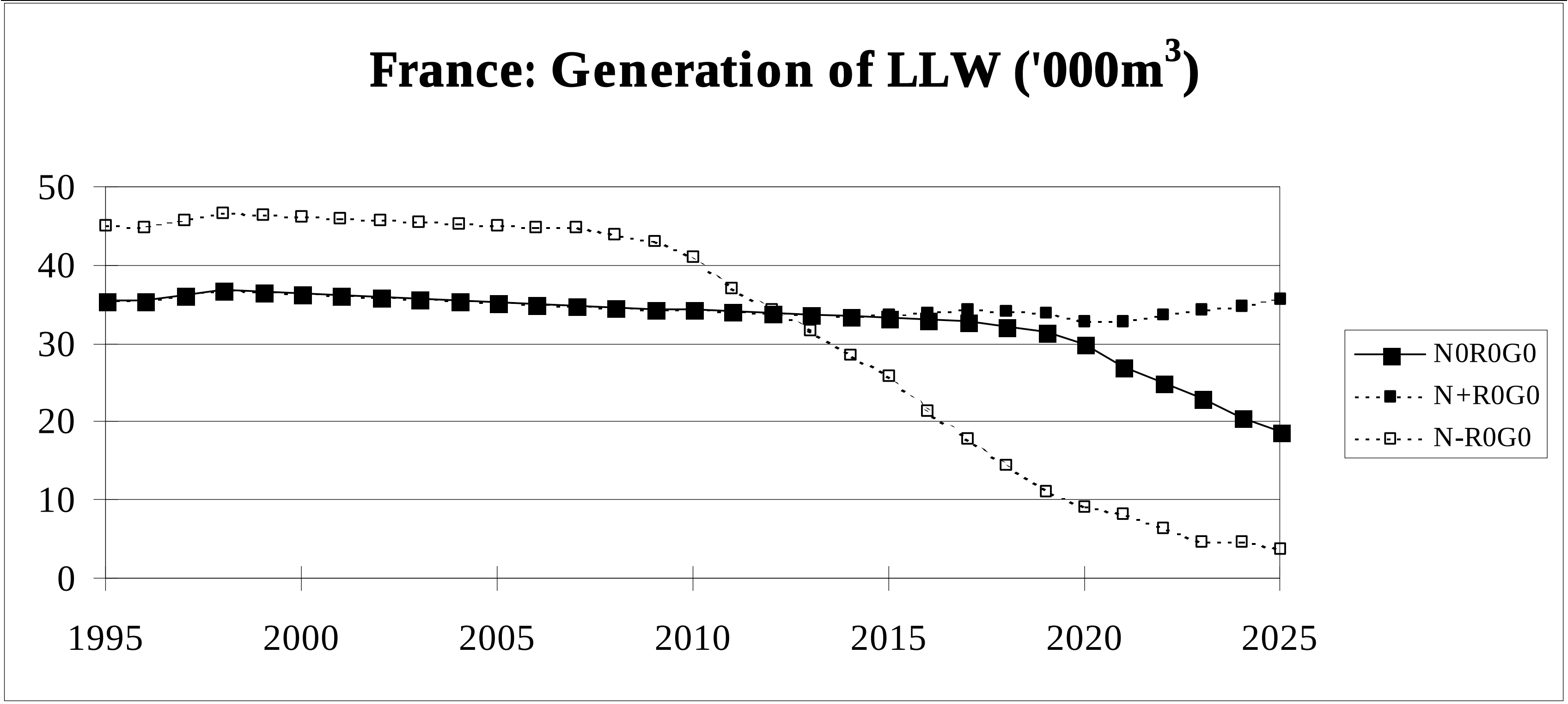


Figure 9.7 *Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025*

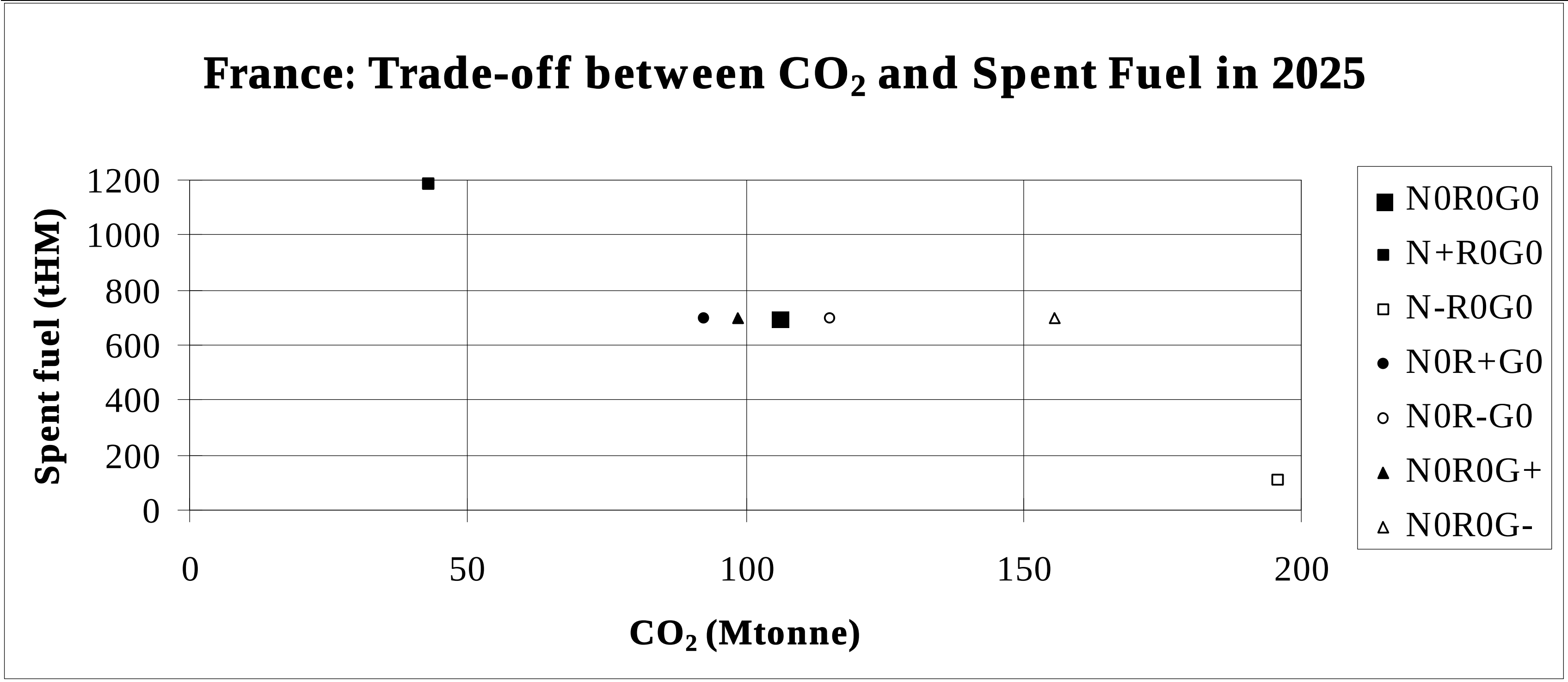
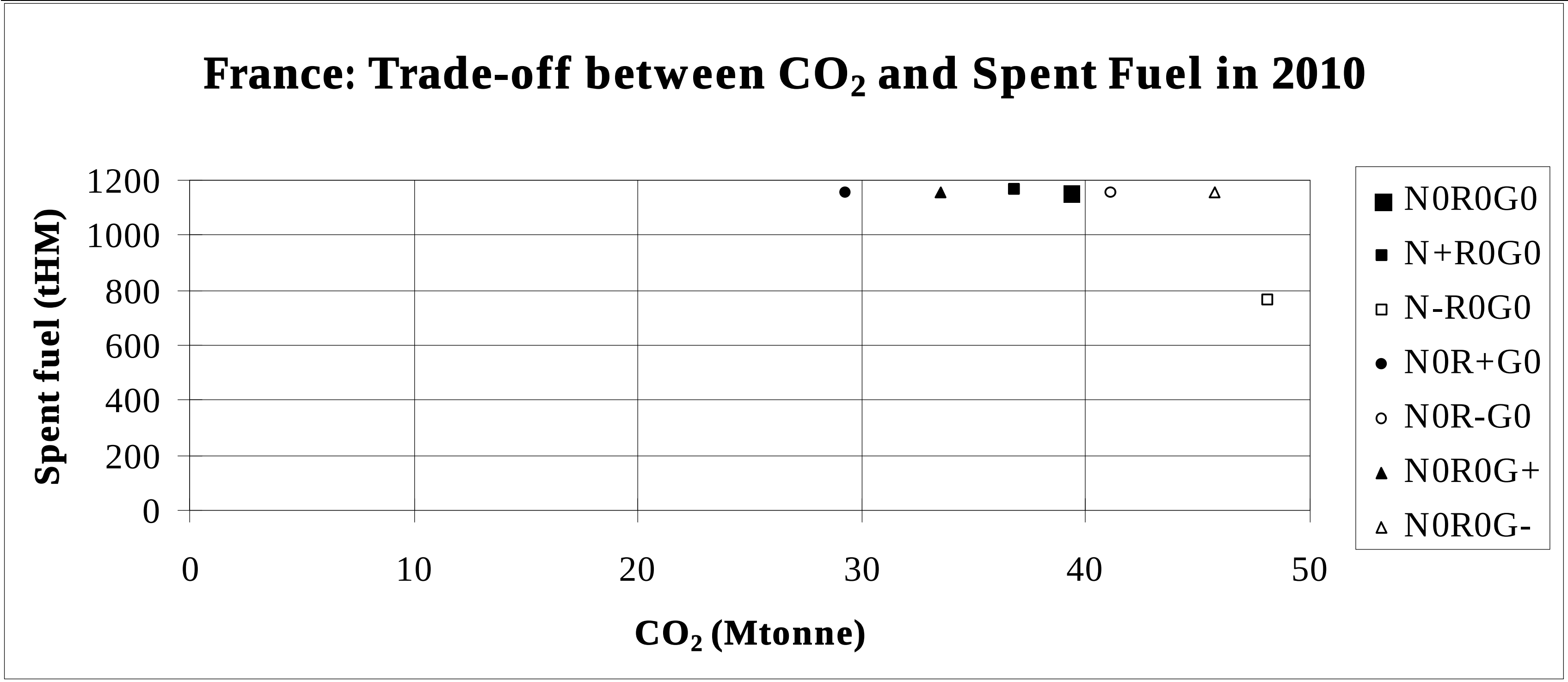


Figure 9.8 *Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010*


France: Trade-off between CO2 and Spent Fuel in 2010
Spent fuel (tHM)
1200
1000
800
600
400
200
0
0
10
20
30
40
50
CO2 (Mtonne)
N0R0G0
N+R0G0
N-R0G0
N0R+G0
N0R-G0
N0R0G+
N0R0G-

10 GERMANY

10.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4*.

The model has been calibrated against the actual performance of the German power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 303 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 323 million tonnes. The discrepancy is due to the model projecting higher electricity generation from nuclear plant. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 101*.

Table 10.1 Description of Scenarios

Scenario	**Description**	**Composition**
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 9.5% with large hydro and 7% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 21% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 12% with large hydro and 9.5% excluding large hydro in 2025, other factors as Base Scenario.

Scenario	Description	Composition
N0R-G0	Low RETs	Renewable generation amounts to 7% with large hydro and 4.5% excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

10.2 *RESULTS*

Electricity Generation in 2025 by Origin

Figure 10.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. Nuclear power accounted for 30% of electricity generation in 1995, but Coal dominates with 53% of generation. In all but the High Nuclear scenario (N+R0G0), nuclear generation falls to no more than 10% in 2025.

Gas replaces nuclear and a part of coal in the future. Gas generation is projected to range from 20-53% in 2025, with 40% of generation in the Base scenario (N0R0G0). Coal retains a significant share (over 40%) in this Base scenario but is subject to wide variations depending on whether Gas or Coal are favoured as new fossil fuel plant. In the High Gas / Low Coal scenario (N0R0G+), Coal's share of generation falls to 295 of the total in 2025; in the Low Gas / High Coal scenario (N0R0G-), this share is 61%. This wide range is explained by new plant being run high in the merit order.

There is some potential for renewable generation in Germany. Large hydro schemes are projected to generate only 2.5% of electricity in 2025, and it has been assumed that no new plant will be built. However Germany has resources of all renewables and could generate between 7-12% of its electricity from renewables in 2025 (Base scenario (N0R0G0) 9.3%).

Emissions of Carbon Dioxide

Figure 10.2 summarises the emissions of carbon dioxide from the German power system up to 2025 as forecast by this model.

The Base scenario (N0R0G0) shows CO_2 emissions declining to 310 Mtonne in 2015 from the 1990 value of 358 Mtonne. After 2015, the effects of nuclear retirement drive up CO_2 emissions to 375 Mtonne in 2025 (17 Mtonne, or 5%, above 1990 values).

Germany has 2 major options to reduce these emissions. Holding nuclear capacity at the 1995 value of 21% of the total (N+R0G0) would result in reductions in emissions relative to the Base scenario of almost 85 Mtonne in 2025. Encouraging Gas (N0R0G+) would lead to reductions of 60 Mtonne. Conversely, retiring nuclear plant early (N-R0G0) would add another 35

Mtonne to the emissions total and encouraging Coal (N0R0G-) would add 60 Mtonne to the total.

Renewables have a moderate effect on CO2 emissions, with a range in reductions relative to the Base of –15 to +15 Mtonne resulting from discouraging or encouraging their use.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, agreed to reduce emissions from 1990 levels by 21% in the year 2010. Total emissions in 1990 from all sectors were 978 Mtonne CO_2, of which 358 Mtonne (37%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 10.3* shows the difference between projected values and the Kyoto target. The reductions required are very large: 200 Mtonne represents over 20% of projected emissions. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to reduce emissions by 21% from the 1990 level to 283 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 10.4 shows how successful Germany will be in meeting this target under each of the seven scenarios. No scenarios meet the target in 2010, although High Nuclear (N+R0G0) and High Gas/Low Coal (N0R0G+) are close. These 2 scenarios meet the target in 2020 and 2025, but only High Nuclear gets close to the target in 2025. No other scenarios get close to meeting the target: the figure shows clearly that failing to encourage renewables and/or encouraging coal will exacerbate Germany's problems in meeting its Kyoto targets.

Spent Fuel from Nuclear Plants

Figure 10.5 shows the discharge of spent fuel from nuclear plant over the period. In the Base scenario (N0R0G0), spent fuel of 500 tHM/year arises until nuclear plant retires from 2015. By 2025, spent fuel arising is under 200 tHM. Because of nuclear capacity retaining its share of increasing capacity (and generation) in the High Nuclear scenario (N+R0G0), emissions rise to over 700 tHM in 2025. In the Low Nuclear scenario (N-R0G0), nuclear generation ends in 2020.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 10.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 34%, 115% and 0% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 10.7*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

Germany has considerable freedom when deciding on future emissions of CO_2 and spent fuel arising. Encouraging Coal rather than Gas would lead to extra emissions of 110 Mtonne in 2025. Indeed the Low Gas/High Coal scenario leads to higher CO_2 emissions in 2025 than the Low Nuclear scenario (N-R0G0).

The 2 nuclear scenarios (N+/N-R0G0) and the Base scenario (N0R0G0) lie on a straight line. 1 Mtonne of CO_2 can be saved for each 5.2 tHM extra spent fuel produced. Compared to the Base scenario (N0R0G0), High Nuclear (N+R0G0) leads to an extra 430 tHM spent fuel offset by CO_2 emissions reductions of 83 Mtonne.

Compared to the major reductions/increases from Nuclear and Fossil Fuel policy, Renewables policy has very little effect.

Figure 10.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

10.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. Nuclear power accounted for 30% of electricity generation in 1995, but Coal dominates with 53% of generation. In all but the High Nuclear scenario (N+R0G0), nuclear generation falls to no more than 10% in 2025.

2. Gas replaces nuclear and a part of coal in the future. Gas generation is projected to range from 20-53% in 2025, with 40% of generation in the Base scenario (N0R0G0).

3. Coal retains a significant share (over 40%) in this Base scenario but is subject to wide variations depending on whether Gas or Coal are favoured as new fossil fuel plant. In the High Gas / Low Coal scenario (N0R0G+), Coal's share of generation falls to 295 of the total in 2025; in the Low Gas / High Coal scenario (N0R0G-), this share is 61%. This wide range is explained by new plant being run high in the merit order.

4. Germany has resources of all renewables and could generate between 7-12% of its electricity from renewables in 2025 (Base scenario (N0R0G0) 9.3%).

5. The Base scenario (N0R0G0) shows CO_2 emissions declining to 310 Mtonne in 2015 from the 1990 value of 358 Mtonne. After 2015, the effects of nuclear retirement drive up CO_2 emissions to 375 Mtonne in 2025 (17 Mtonne, or 5%, above 1990 values).

6. No scenarios meet the Kyoto target for the power generation sector in 2010, although High Nuclear (N+R0G0) and High Gas / Low Coal (N0R0G+) are close. These 2 scenarios meet the target in 2020 and 2025, but only High Nuclear gets close to the target in 2025.

7. Failing to encourage renewables and / or encouraging coal will exacerbate Germany's problems in meeting its Kyoto targets.

8. In the Base scenario (N0R0G0), spent fuel of 500 tHM / year arises until nuclear plant retires from 2015. By 2025, spent fuel arising is under 200 tHM.

9. Germany has considerable freedom when deciding on future emissions of CO_2 and spent fuel arising. Encouraging Coal rather than Gas would lead to extra emissions of 110 Mtonne in 2025. Indeed the Low Gas / High Coal scenario leads to higher CO_2 emissions in 2025 than the Low Nuclear scenario (N-R0G0).

10. The 2 nuclear scenarios (N+ / N-R0G0) and the Base scenario (N0R0G0) lie on a straight line. 1 Mtonne of CO_2 can be saved for each 5.2 tHM extra

spent fuel produced. Compared to the Base scenario (N0R0G0), High Nuclear (N+R0G0) leads to an extra 430 tHM spent fuel offset by CO_2 emissions reductions of 83 Mtonne.

11. Compared to the major reductions / increases from Nuclear and Fossil Fuel policy, Renewables policy has very little effect.

Figure 10.1 Electricity Generation in 2025 by Origin

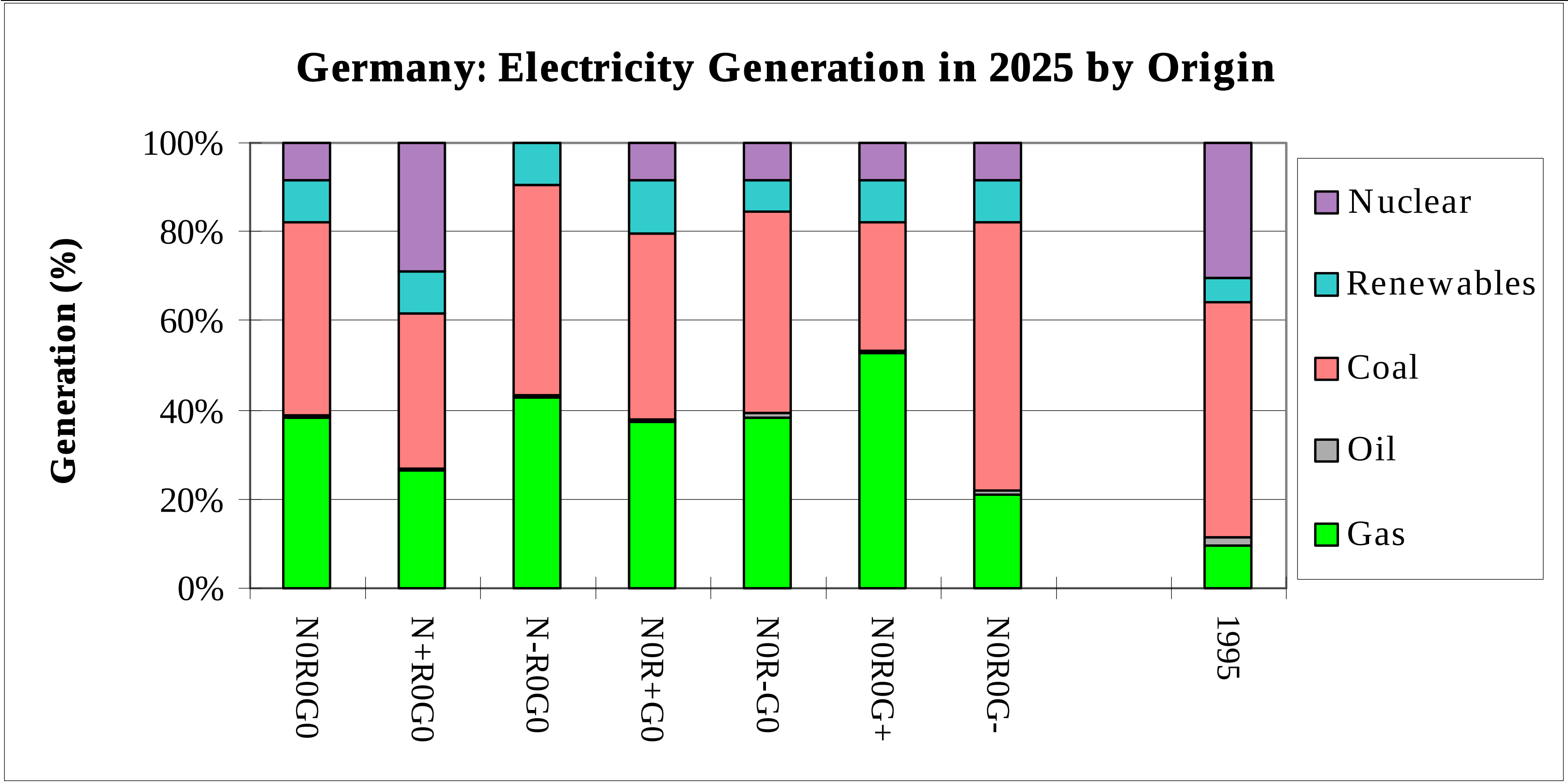


Figure 10.2 Carbon Dioxide Emissions from Power Generation

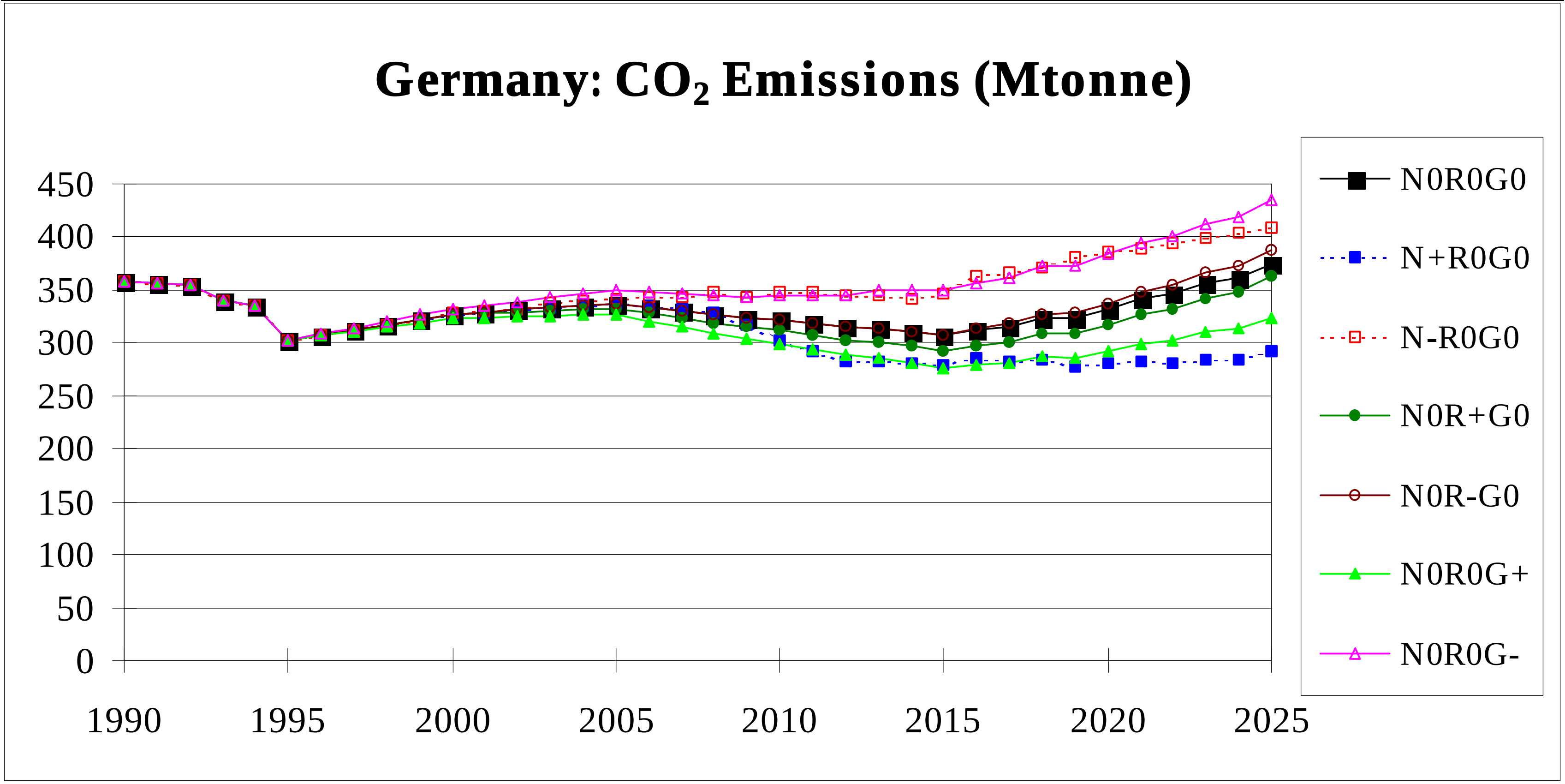


Figure 10.3 Notional Kyoto Target Reductions - All Sectors* (Assuming target in years post-2010 = target in 2010)

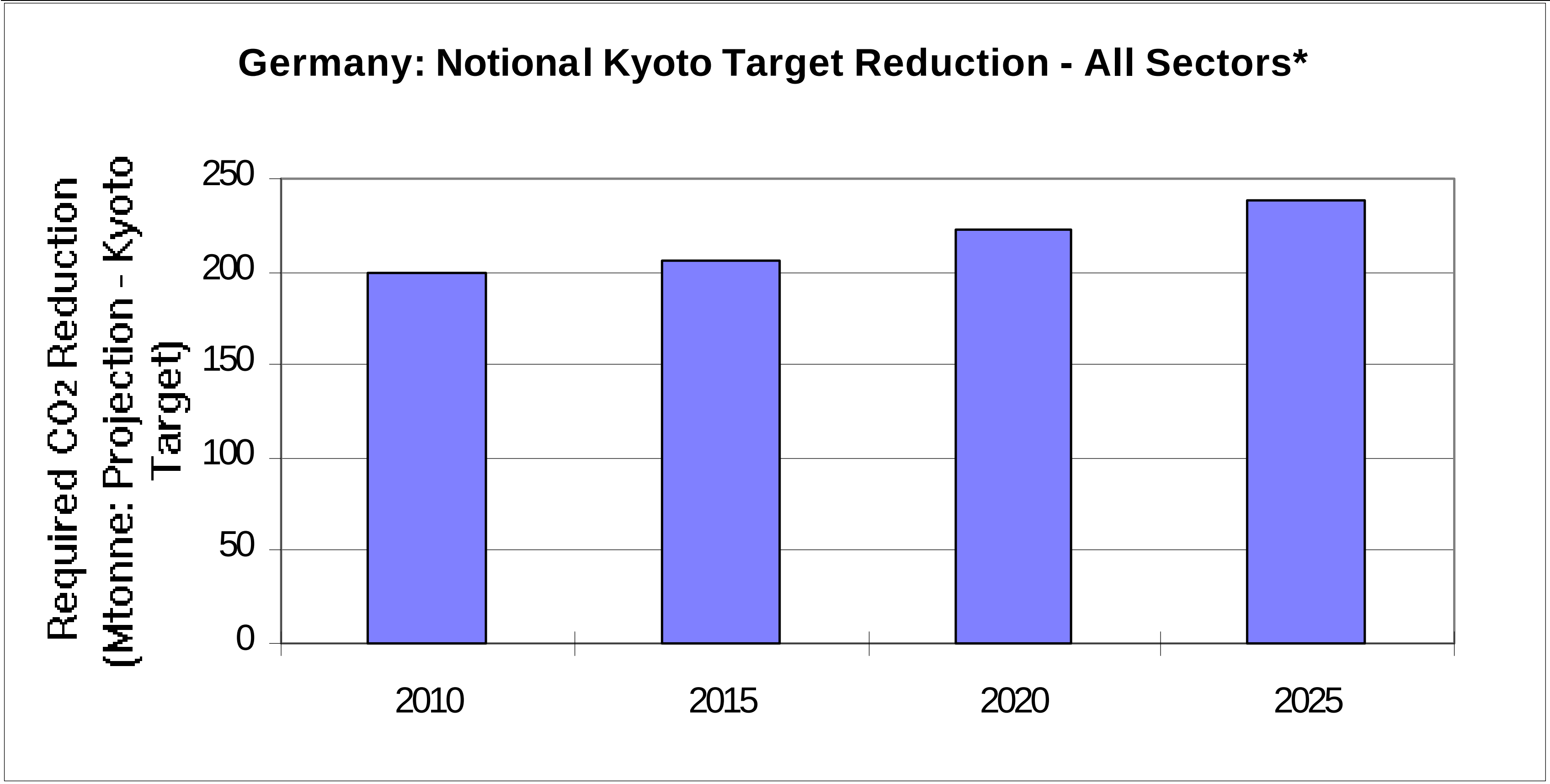


Figure 10.4 *Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target* (Assuming equal burdens on power generation sector and no-power generation sectors)*

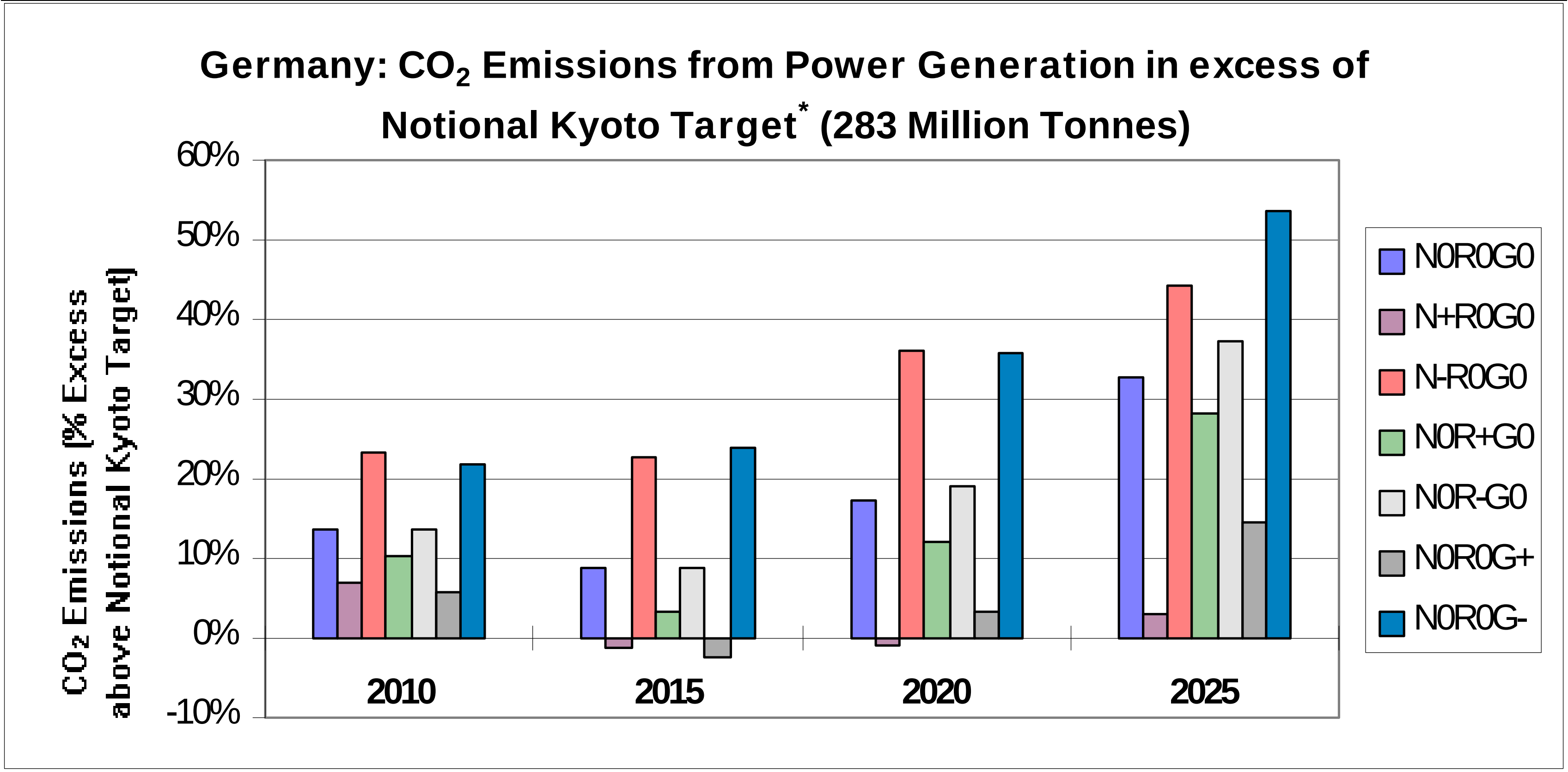


Figure 10.5 Spent Fuel Discharged

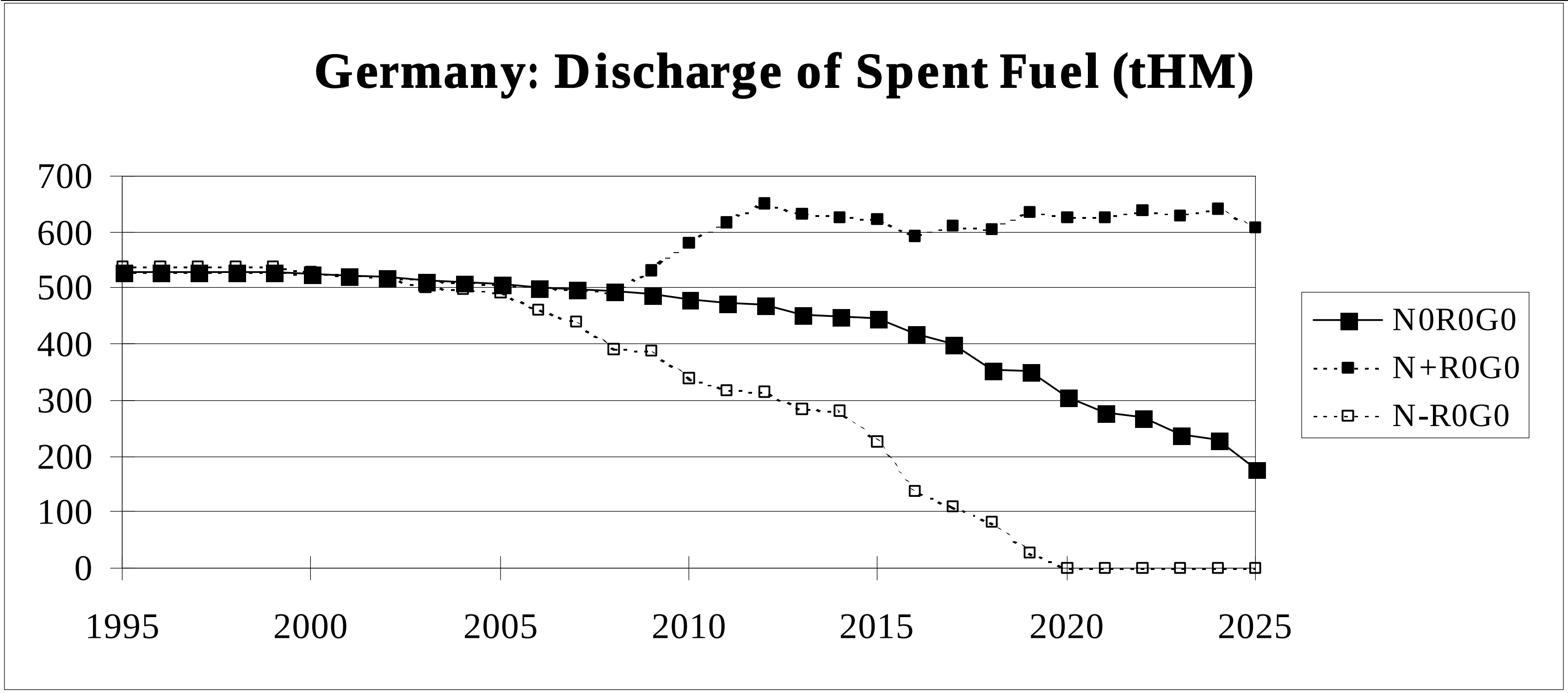


Figure 10.6 Low Level Waste (LLW/ILW)

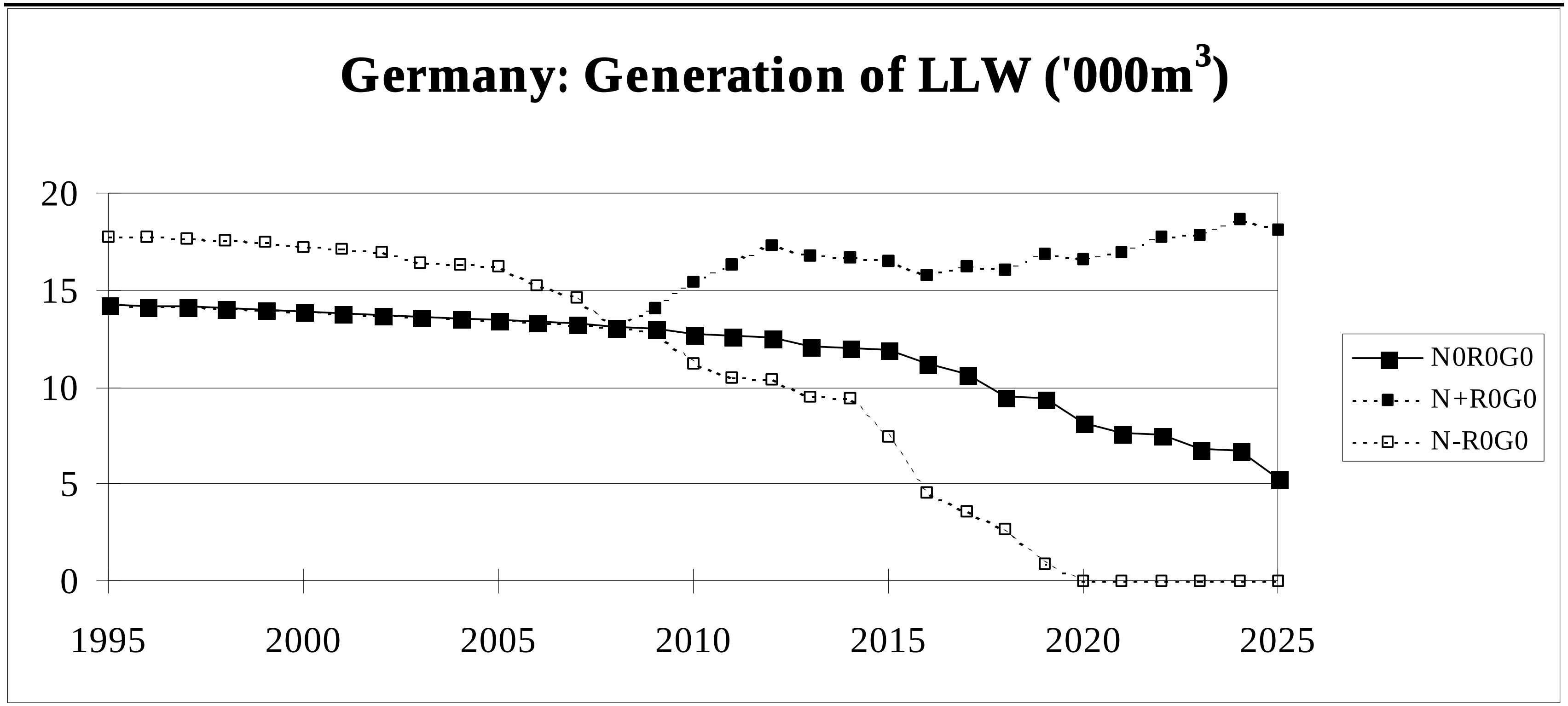


Figure 10.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

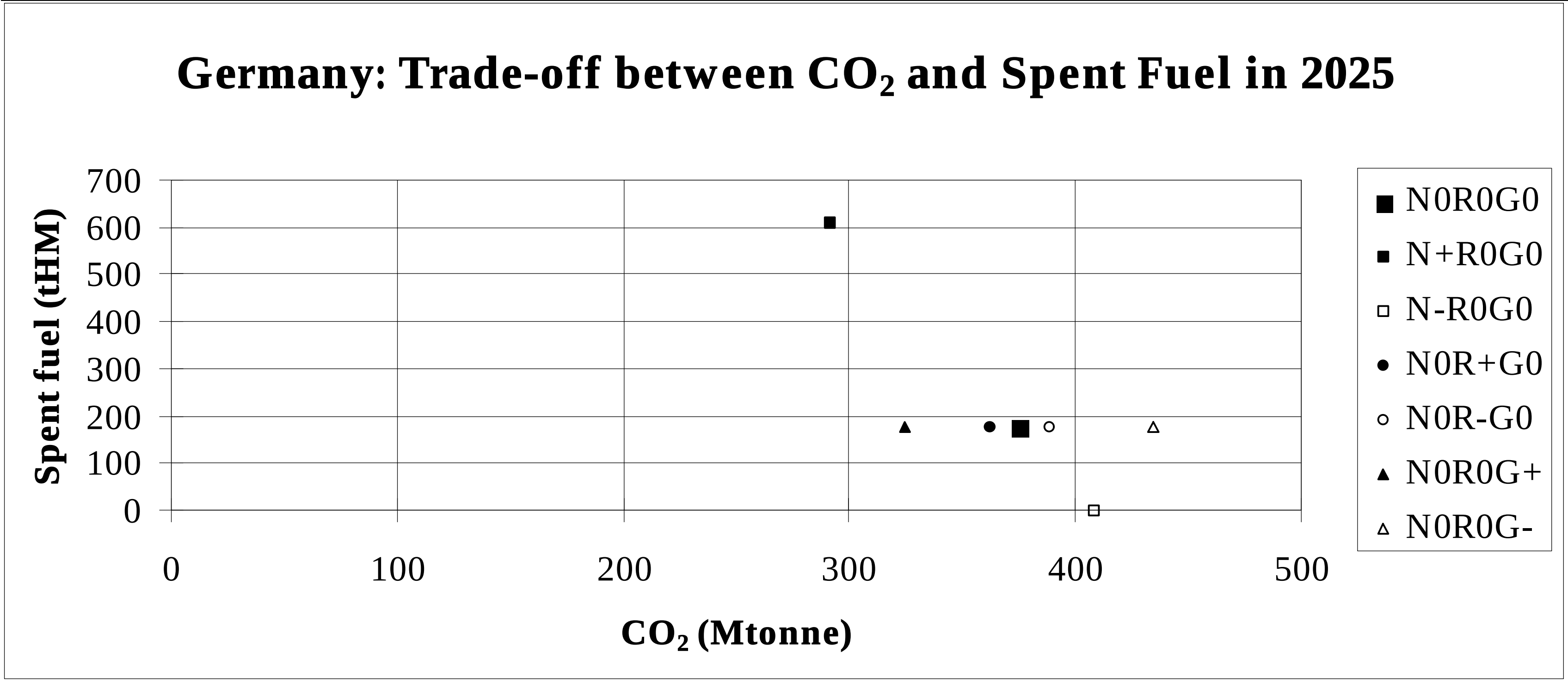
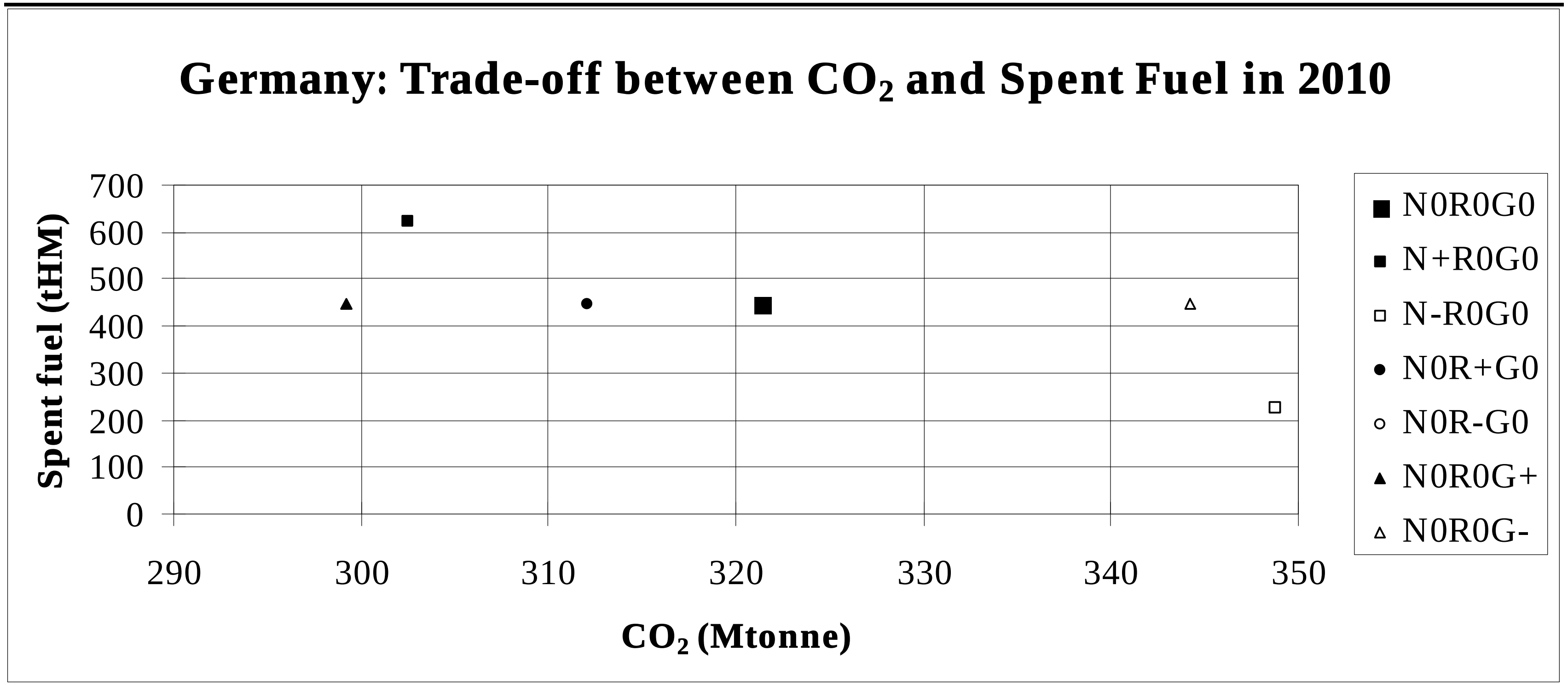


Figure 10.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010



Germany: Trade-off between CO2 and Spent Fuel in 2010
Spent fuel (tHM)
700
600
500
400
300
200
100
0
290
300
310
320
330
340
350
CO2 (Mtonne)
N0R0G0
N+R0G0
N-R0G0
N0R+G0
N0R-G0
N0R0G+
N0R0G-

11 NETHERLANDS

11.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4*.

The model has been calibrated against the actual performance of the Dutch power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 45 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 49 million tonnes. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 11.1*.

Table 11.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 5.3% with large hydro and 5.1% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 2% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 12.1% with large hydro and 12.0% excluding large hydro in 2025, other factors as Base Scenario.
N0R-G0	Low RETs	Renewable generation amounts to 3.6% with large hydro and 3.5%

Scenario	Description	Composition
		excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

11.2 *RESULTS*

Electricity Generation in 2025 by Origin

Figure 11.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. The Netherlands is not a major producer of nuclear electricity: nuclear power accounted for less than 5% of electricity generation in 1995. It is expected that this plant will be retired in the near future.

Gas is the preferred fuel for power generation. In 1995, it already accounted for 60% of power generated and this share is maintained in 2025 even in the Low Gas / High Coal scenario (N0R0G-). In all other scenarios, gas generation accounts for 77-92% of generation. Coal generation is projected to fall from its 1995 share of 27% to 14% in 2025 in the Base scenario (N0R0G0).

There is some potential for renewables in the Netherlands (principally based on Wind and Waste). There is a negligible amount of large hydro and no resources to increase this. However it is projected that renewable generation in 2025 will range from 3.5-12%, with a Base scenario value of 5.3%.

Emissions of Carbon Dioxide

Figure 11.2 summarises the emissions of carbon dioxide from the Dutch power system up to 2025 as forecast by this model.

The Base scenario (N0R0G0) shows CO_2 emissions stable at between 45-51 Mtonne throughout the period, with the peak in 2000 and a value of 47 Mtonne in 2025. Because of the low amount of nuclear capacity, the 2 nuclear scenarios have very little effect, although retiring nuclear plant early (N-R0G0) leads to increased emissions of 2.5 Mtonne in the important Kyoto target period 2008-2012.

The major differences are due to decisions regarding new fossil fuel plant. Favouring Gas (N0R0G+) leads to reductions of 6 Mtonne in 2025 relative to the base case; favouring Coal (N0R0G-) leads to an increase of 10 Mtonne (15%).

Actively encouraging renewables (N0R+G0) has a similar effect in 2025 as encouraging gas.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, the Netherlands agreed to reduce emissions from 1990 levels by 6% in the year 2010. Total emissions in 1990 from all sectors were 157 Mtonne CO_2, of which 45 Mtonne (29%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 11.3* shows the difference between projected values and the Kyoto target. The Netherlands will need to find reductions in the range of 18-23 Mtonne in 2010-25. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to reduce emissions by 6% from the 1990 level to 43 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 11.4 shows how successful the Netherlands will be in meeting this target under each of the seven scenarios. The target can only be met by encouraging gas (N0R0G+), however excesses are only of the order of 5 Mtonne (12%) in all other scenarios except for Low Gas / High Coal (N0R0G-), where excesses rise to 14 Mtonne (33%) by 2025.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 11.5 shows the discharge of spent fuel from nuclear plant over the period. Spent fuel of just over 15 tHm / year arises while nuclear plant is operational, with retirement occurring in 2004 in the Low Nuclear scenario (N-R0G0) and 2014 in the Base scenario (N0R0G0).

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW / LLW show a similar pattern to the discharges of spent fuel, (see *Figure 11.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are 0%, 0% and 100% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 11.7,* which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The Netherlands has very little freedom to control CO_2 emissions from the power generation. Encouraging Gas (N0R0G+) or Renewables (N0R+G0) would lead to reductions of 7 Mtonne and 6 Mtonne respectively relative to the base case in 2025 and would meet the Kyoto target for the power generation sector. Encouraging Coal would lead to extra emissions of 10 Mtonne.

Clearly an expansion of nuclear capacity would have a positive effect on CO_2 emissions, but this effect is not large. Retaining a 2% nuclear share of generating capacity reduces CO_2 emissions by just 0.17 Mtonne and is offset by an increase of 15.6 tHM of spent fuel in 2025.

Figure 11.8 shows that the trade-off between CO2 emissions and spent fule is almost identical in 2010 as it is in 2025 - this is due to the Netherlands having only one nuclear plant.

11.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. The Netherlands is not a major producer of nuclear electricity: nuclear power accounted for less than 5% of electricity generation in 1995. It is expected that this plant will be retired in the near future.

2. Gas is the preferred fuel for power generation. In 1995, it already accounted for 60% of power generated and this share is maintained in 2025 even in the Low Gas / High Coal scenario (N0R0G-). In all other scenarios, gas generation accounts for 77-92% of generation.

3. Coal generation is projected to fall from its 1995 share of 27% to 14% in 2025 in the Base scenario (N0R0G0).

4. There is some potential for renewables in the Netherlands (principally based on Wind and Waste). There is a negligible amount of large hydro and no resources to increase this. However it is projected that renewable generation in 2025 will range from 3.5-12%, with a Base scenario value of 5.3%.

5. The Base scenario (N0R0G0) shows CO_2 emissions stable at between 45-51 Mtonne throughout the period, with the peak in 2000 and a value of 47 Mtonne in 2025.

6. Because of the low amount of nuclear capacity, the 2 nuclear scenarios have very little effect, although retiring nuclear plant early (N-R0G0) leads to increased emissions of 2.5 Mtonne in the important Kyoto target period 2008-2012.

7. The major differences in CO_2 emissions are due to decisions regarding new fossil fuel plant. Favouring Gas (N0R0G+) leads to reductions of 6 Mtonne in 2025 relative to the base case; favouring Coal (N0R0G-) leads to an increase of 10 Mtonne (15%).

8. Actively encouraging renewables (N0R+G0) has a similar effect on CO_2 emissions in 2025 as encouraging gas.

9. Spent fuel of just over 15 tHm / year arises while nuclear plant is operational, with retirement occurring in 2004 in the Low Nuclear scenario (N-R0G0) and 2014 in the Base scenario (N0R0G0).

10. The Netherlands has very little freedom to control CO_2 emissions from the power generation. Encouraging Gas (N0R0G+) or Renewables (N0R+G0) would lead to reductions of 7 Mtonne and 6 Mtonne respectively relative to the base case in 2025 and would meet the Kyoto target for the power generation sector. Encouraging Coal would lead to extra emissions of 10 Mtonne.

11. Clearly an expansion of nuclear capacity would have a positive effect on CO_2 emissions, but this effect is not large. Retaining a 2% nuclear share of generating capacity reduces CO_2 emissions by just 0.17 Mtonne and is offset by an increase of 15.6 tHM of spent fuel in 2025.

Figure 11.1 Electricity Generation in 2025 by Origin

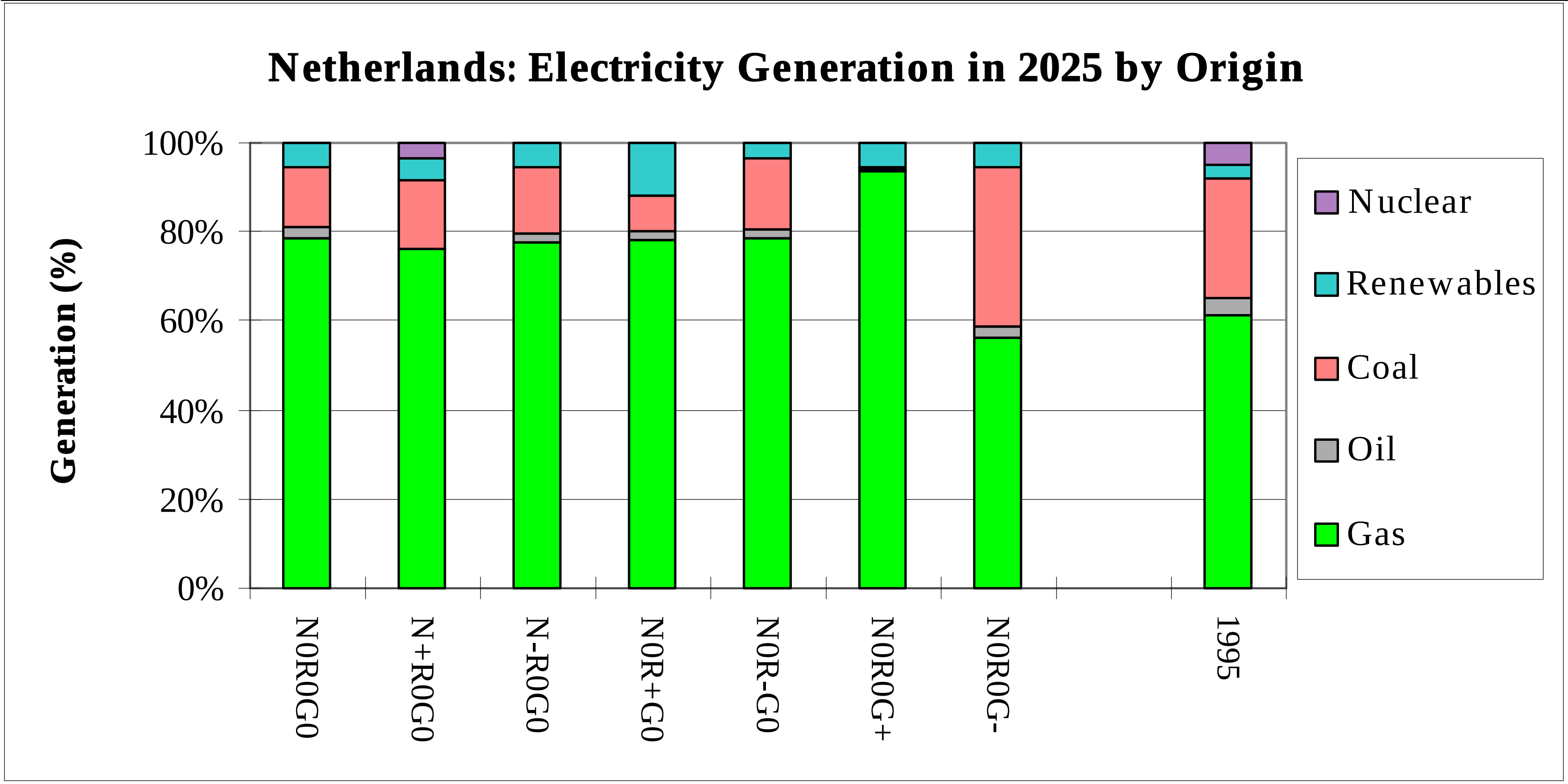


Figure 11.2 Carbon Dioxide Emissions from Power Generation

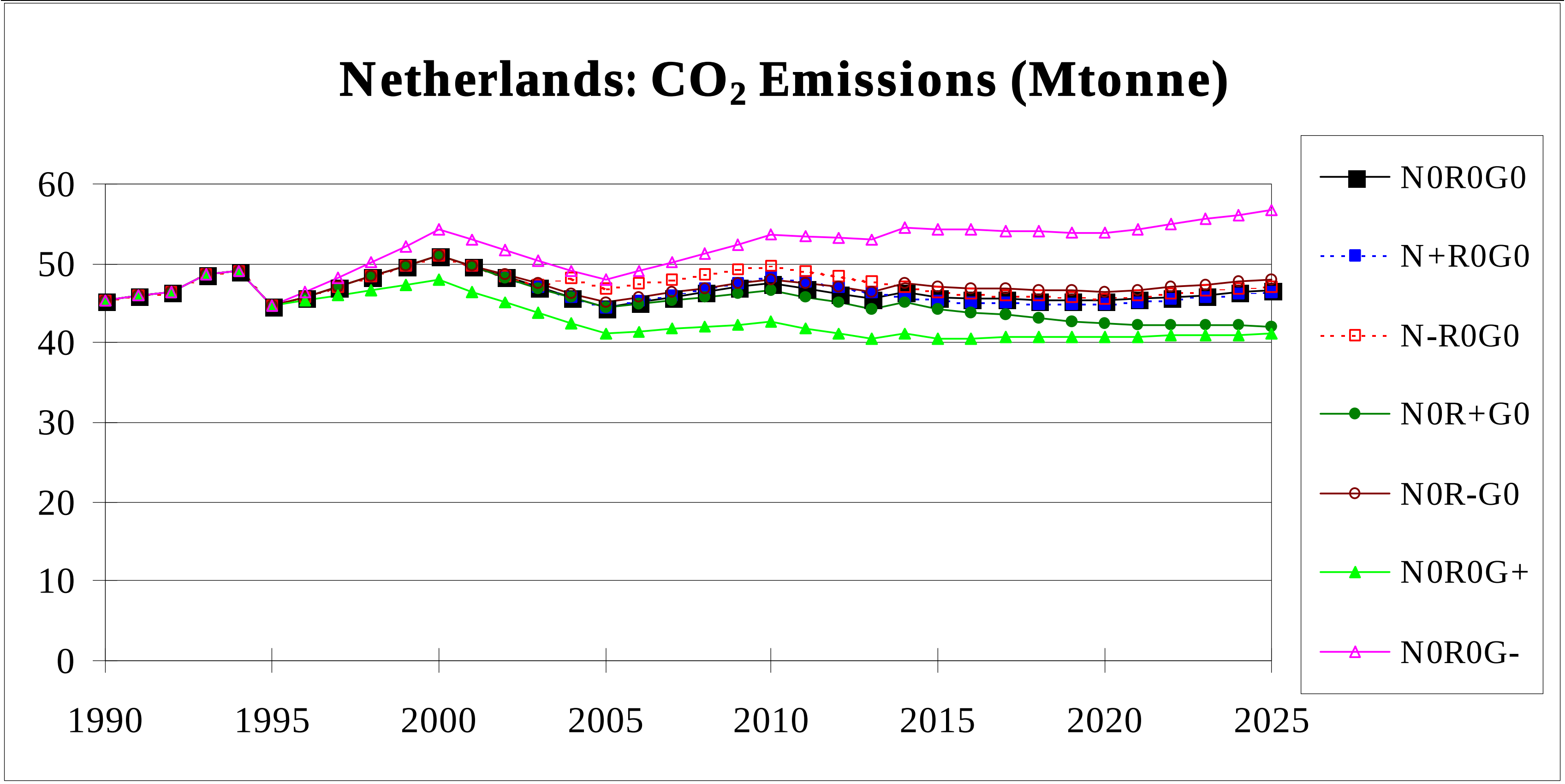


Figure 11.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

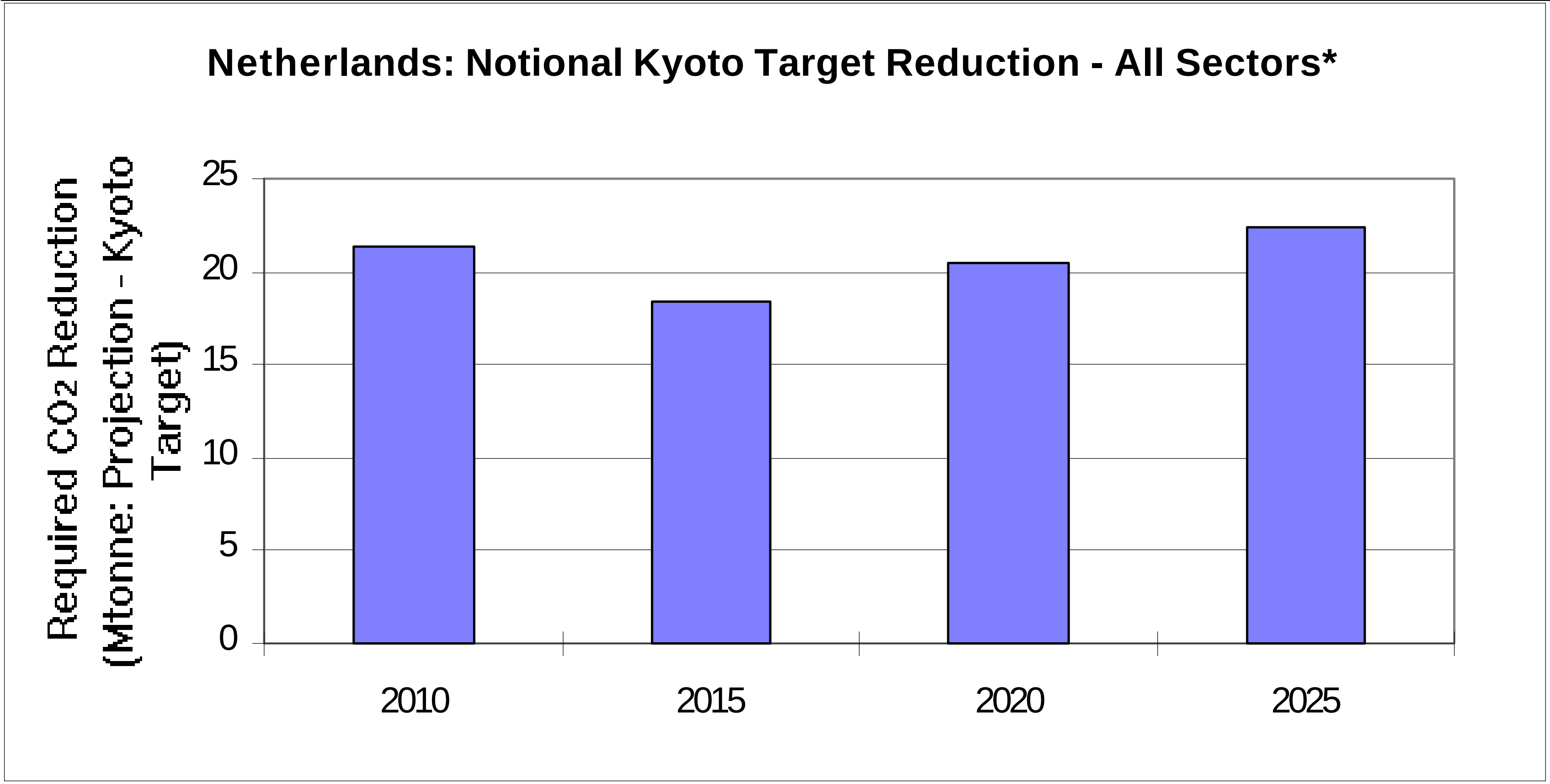


Figure 11.4 ***Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target* (Assuming equal burdens on power generation sector and non-power generation sectors)***

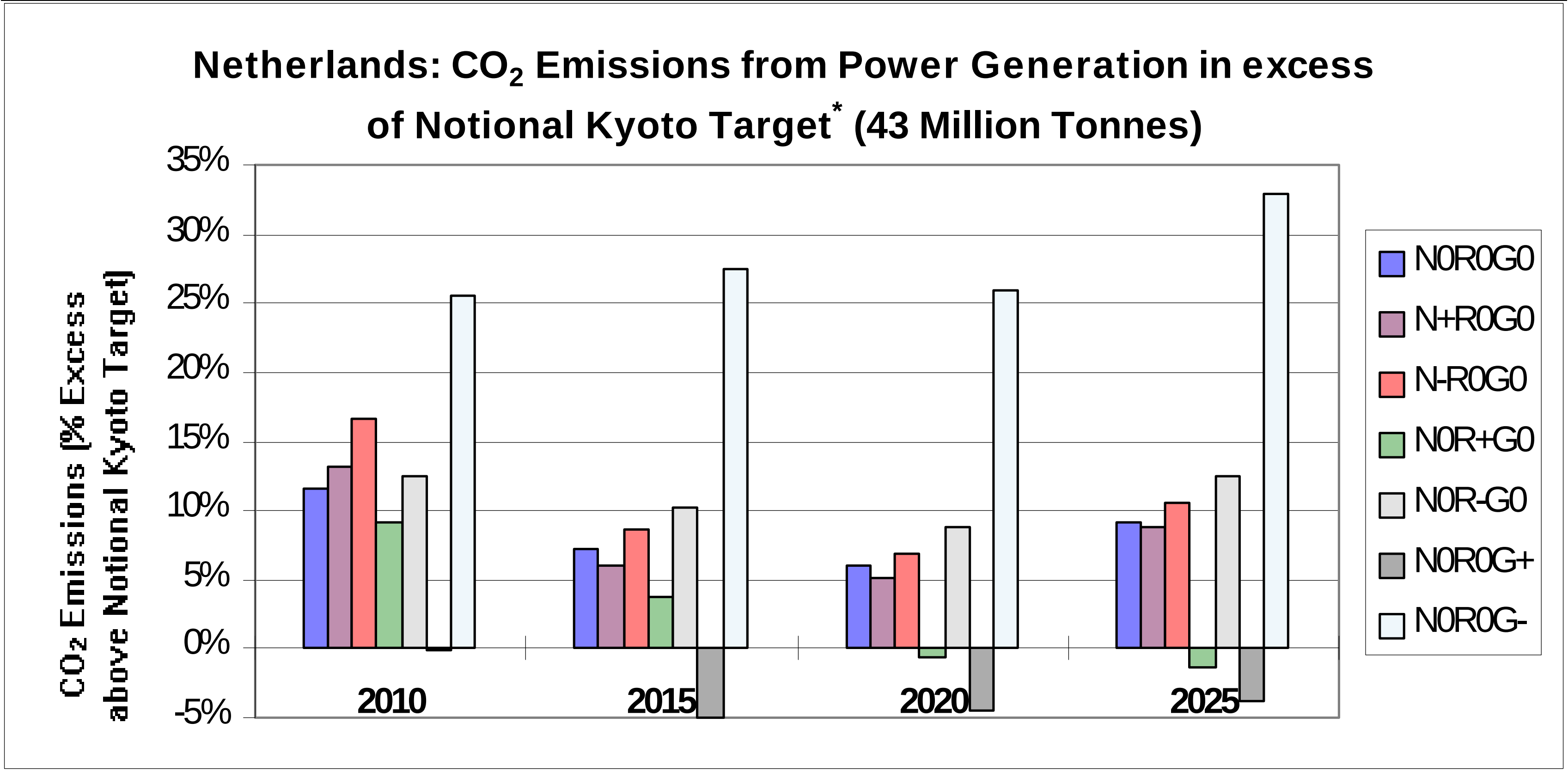


Figure 11.5 Spent Fuel Discharged

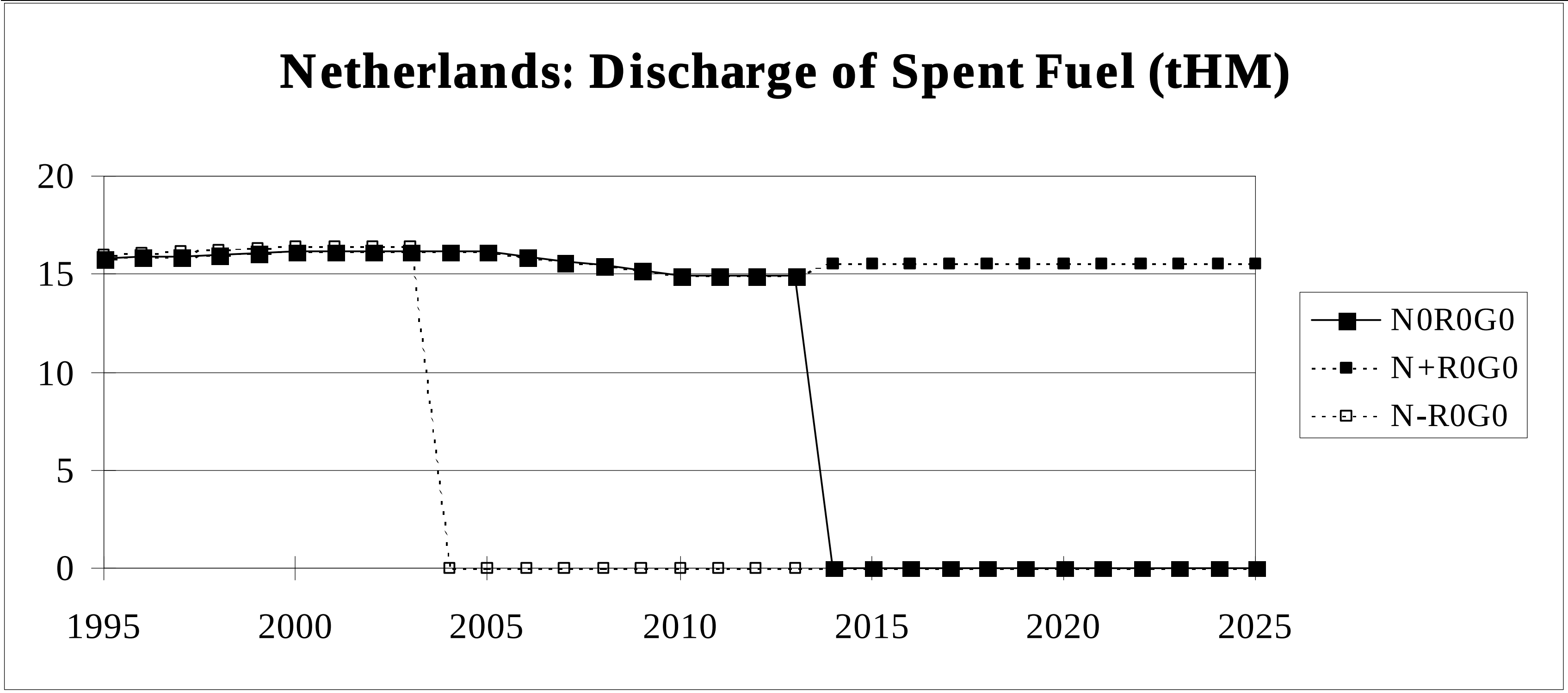


Figure 11.6 Low Level Waste (LLW/ILW)

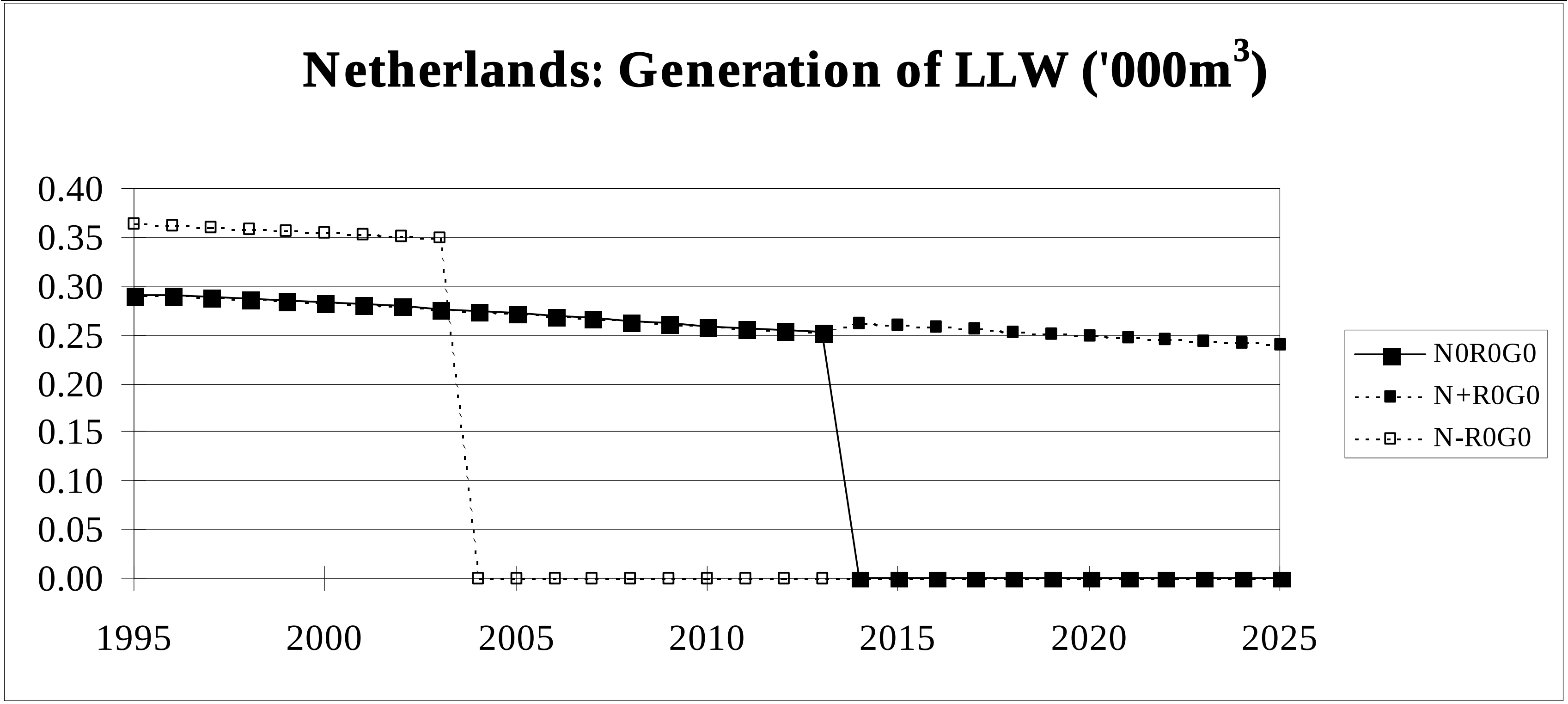


Figure 11.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

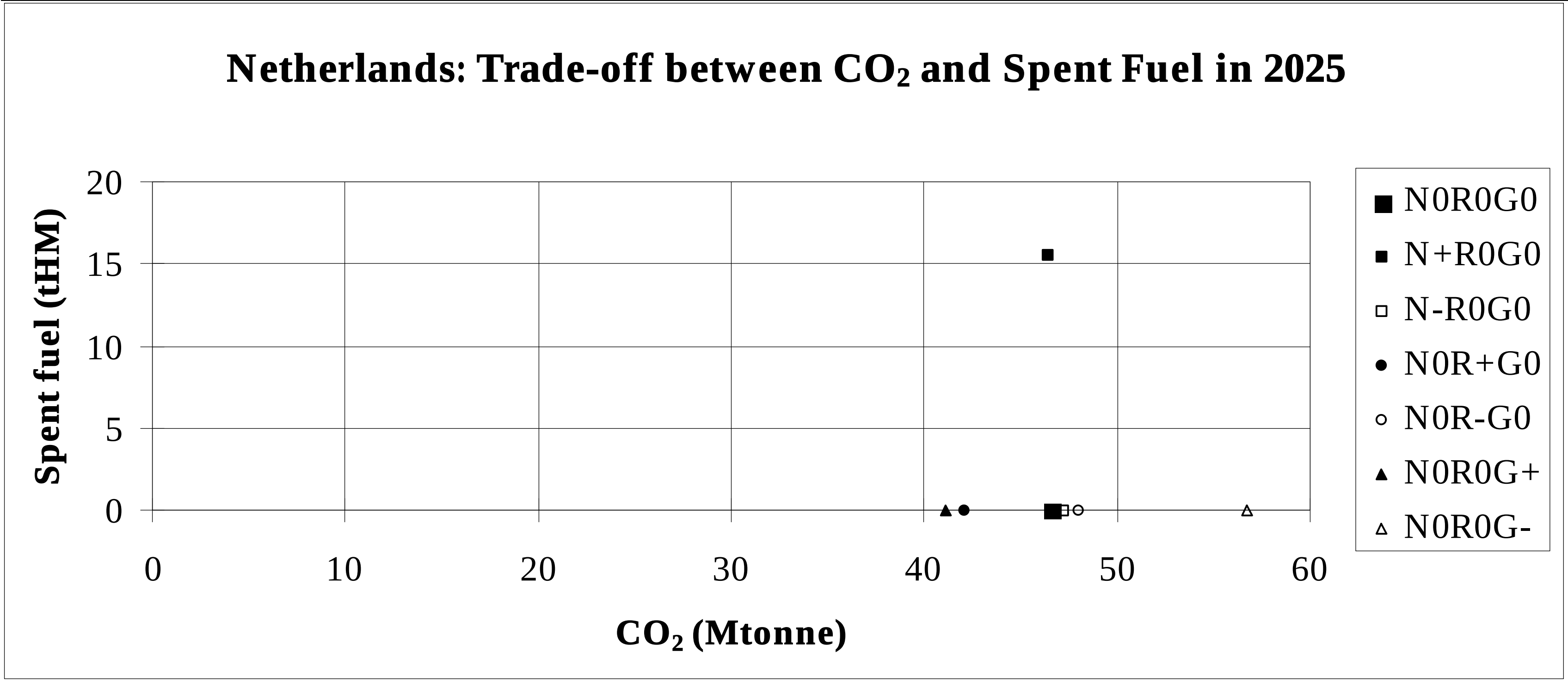
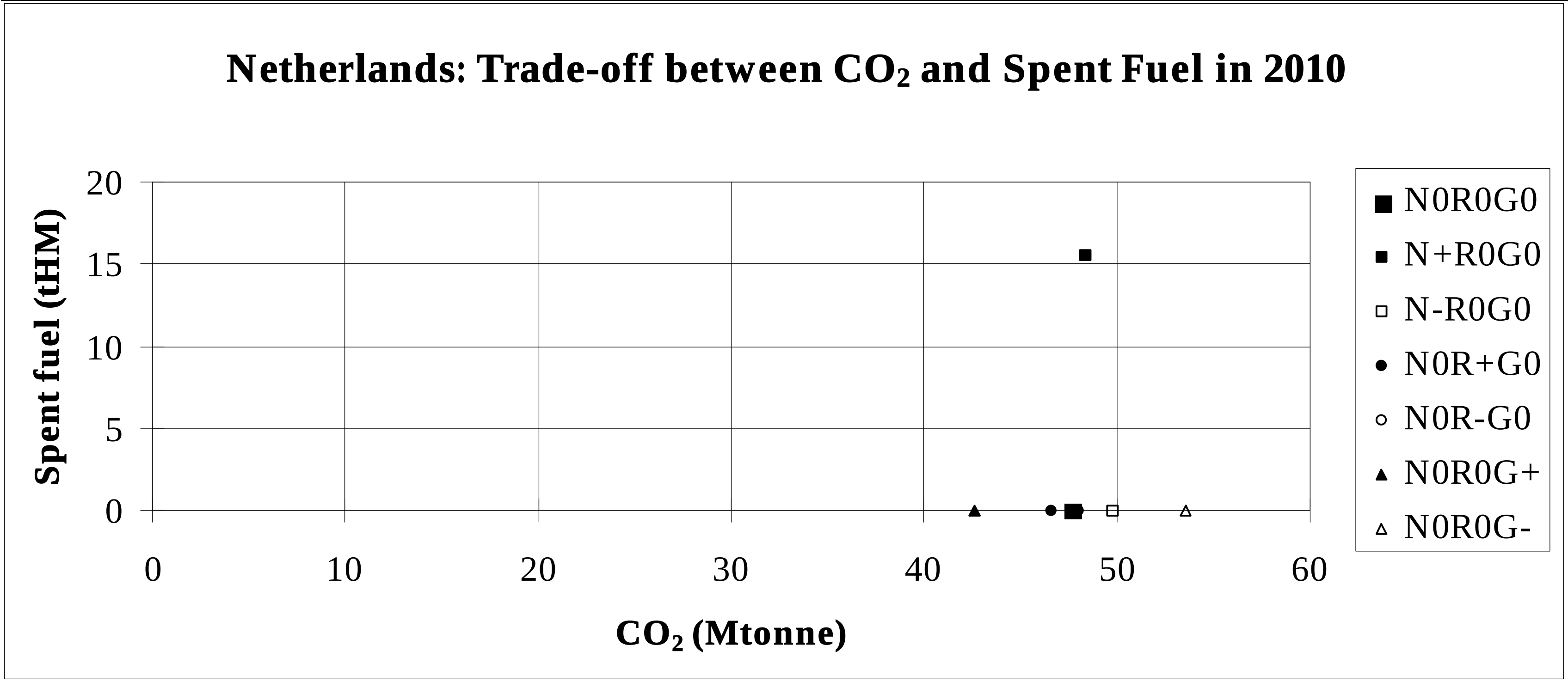


Figure 11.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010


Netherlands: Trade-off between CO2 and Spent Fuel in 2010
Spent fuel (tHM)
20
15
10
5
0
0
10
20
30
40
50
60
CO2 (Mtonne)
N0R0G0
N+R0G0
N-R0G0
N0R+G0
N0R-G0
N0R0G+
N0R0G-

12 SPAIN

12.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020').* The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4.*

The model has been calibrated against the actual performance of the Spanish power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 68 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 69.5 million tonnes. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 12.1.*

Table 12.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 20.5% with large hydro and 5% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 17% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 26.5% with large hydro and 11% excluding large hydro in 2025, other factors as Base Scenario.
N0R-G0	Low RETs	Renewable generation amounts to 18.5% with large hydro and 3%

Scenario	Description	Composition
		excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

12.2 RESULTS

Electricity Generation in 2025 by Origin

Figure 12.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995. Spanish generation in 1995 relied predominantly on nuclear (36%) and Coal (34%). Without new build, nuclear's share will decline to below 15% in 2025.

The share of coal remains relatively constant. The shortfall due to declining nuclear capacity is projected to be made up from natural gas, which also replaces the 13% generated by oil in 1995. Gas generation is projected to account for 32% of generation in 2025 in the Base scenario (N0R0G0) and between 22% and 40% in the Low Gas / High Coal (N0R0G-) and High Gas / Low Coal (N0R0G+) scenarios.

There is significant renewables potential in Spain. In 1995, 14.3% of electricity was generated from renewables, including 13.6% from large hydro. It is assumed that no more large hydro schemes will be built in Spain. However, there is strong potential for Biomass, Wind and other renewables technologies in Spain. The High Renewables scenario (N0R+G0) shows 27% of electricity generation from renewables. The Base (N0R0G0) and Low Renewables (N0R-G0) have 20% and 19% respectively.

Emissions of Carbon Dioxide

Figure 12.2 summarises the emissions of carbon dioxide from the Spanish power system up to 2025 as forecast by this model.

CO_2 emissions remain close to their 1990 value of 65 Mtonne to 2005, in all scenarios. After this, emissions rise steadily to 2020 and the sharply in the period 2020-2025. The base scenario (N0R0G0) shows emissions of 88 Mtonne in 2020 and 111 Mtonne in 2025, respectively 35% and 70% above the 1990 value. Spanish electricity demand is projected to rise strongly.

Both the Low Nuclear (N-R0G0) and Low Gas / High Coal (N0R0G-) add an extra 15 Mtonne to this total in 2025.

Spain can reduce it projected emissions by 15 Mtonne in 2025 by either supporting renewables (N0R+G0) or gas (N0R0G+). The high nuclear scenario (N+R0G0) would lead to reductions of over 20 Mtonne.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, Spain agreed to limit increases in emissions from 1990 levels to 15% in the year 2010. Total emissions in 1990 from all sectors were 202 Mtonne CO_2, of which 65 Mtonne (32%) came from the power generation sector.

Assuming that 1990 levels plus 15% must be met not only in 2010 but also in subsequent years, *Figure 12.3* shows the difference between projected values and the Kyoto target. Target reductions in 2010 and 2015 are relatively modest, but over 50 Mtonne of reductions are needed in 2020 and over 80 Mtonne in 2025. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to limit emissions to 15% above the 1990 level, i.e. to 75 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 12.4 shows that all scenarios can meet the Kyoto target for power generation in 2010, and there are no serious problems in 2015. However the problems will increase with time. Even supporting new nuclear build will not meet the target in 2020, and Low Nuclear (N-R0G0) is projected to given an excess of 40 Mtonne. In 2025, the scenarios supporting nuclear, renewables and gas lead to excesses of 35-50 Mtonne.

Spain will need a concerted effort to meet its CO_2 targets in 2025.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 12.5 shows the discharge of spent fuel from nuclear plant over the period. Spanish nuclear plant is steadily retired in the Base scenario (N0R0G0). Spent fuel arising decreases from 230 tHM in 1995 to 130 tHM in 2020 and 70 tHM in 2025. In the High Nuclear scenario (N+R0G0), spent fuel stabilises at 190 tHM/year. Nuclear plant is fully retired by 2019 in the Low Nuclear scenario (N-R0G0).

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 12.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 31%, 80% and 0% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 12.7*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The Kyoto target for the power generation sector is 75 Mtonnes in 2025. None of the scenarios meets this. The figure shows that encouraging renewables (N0R+G0) and Gas (N0R0G+) is almost as successful in reducing CO_2 emissions in 2025 as is supporting nuclear power (N+R0G0).

Conversely, supporting coal generation (N0R0G-) would add an extra 13 Mtonne to CO_2 emissions, which is almost as high as retiring nuclear plant after 30 years (N-R0G0).

The 2 nuclear scenario and base scenario lie on a straight line, where 1 Mtonne of CO_2 emissions can be saved if an extra 5.0 tHM of spent fuel are produced. The nigh nuclear scenario (N+R0G0) leads to reductions of 21 Mtonne and an increase of 113 tHM relative to the base scenario (N0R0G0) in 2025.

Figure 12.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

12.3 *SUMMARY AND CONCLUSIONS*

The major conclusions are as follows:

1. Spanish generation in 1995 relied predominantly on nuclear (36%) and Coal (34%). Without new build, nuclear's share will decline to below 15% in 2025.

2. The share of coal remains relatively constant. The shortfall due to declining nuclear capacity is projected to be made up from natural gas, which also replaces the 13% generated by oil in 1995.

3. There is significant renewables potential in Spain. In 1995, 14.3% of electricity was generated from renewables, including 13.6% from large hydro. It is assumed that no more large hydro schemes will be built in Spain. However, there is strong potential for Biomass, Wind and other renewables technologies in Spain. The High Renewables scenario (N0R+G0) shows 27% of electricity generation from renewables. The Base (N0R0G0) and Low Renewables (N0R-G0) have 20% and 19% respectively.

4. CO_2 emissions remain close to their 1990 value of 65 Mtonne to 2005, in all scenarios. After this, emissions rise steadily to 2020 and the sharply in the period 2020-2025. The base scenario (N0R0G0) shows emissions of 88 Mtonne in 2020 and 111 Mtonne in 2025, respectively 35% and 70% above the 1990 value.

5. Both the Low Nuclear (N-R0G0) and Low Gas/High Coal (N0R0G-) add an extra 15 Mtonne to this total in 2025.

6. Spain can reduce it projected emissions by 15 Mtonne in 2025 by either supporting renewables (N0R+G0) or gas (N0R0G+). The High Nuclear scenario (N+R0G0) would lead to reductions of over 20 Mtonne.

7. All scenarios can meet the Kyoto target for power generation in 2010, and there are no serious problems in 2015. However the problems will increase with time. Even supporting new nuclear build will not meet the target in 2020, and Low Nuclear (N-R0G0) is projected to given an excess of 40 Mtonne. In 2025, the scenarios supporting nuclear, renewables and gas lead to excesses of 35-50 Mtonne.

8. Spent fuel arising decreases from 230 tHM in 1995 to 130 tHM in 2020 and 70 tHM in 2025. In the High Nuclear scenario (N+R0G0), spent fuel stabilises at 190 tHM/year. Nuclear plant is fully retired by 2019 in the Low Nuclear scenario (N-R0G0).

9. The 2 nuclear scenario and base scenario lie on a straight line, where 1 Mtonne of CO_2 emissions can be saved if an extra 5.0 tHM of spent fuel are produced. The nigh nuclear scenario (N+R0G0) leads to reductions of 21 Mtonne and an increase of 113 tHM relative to the base scenario (N0R0G0) in 2025.

Figure 12.1 Electricity Generation in 2025 by Origin

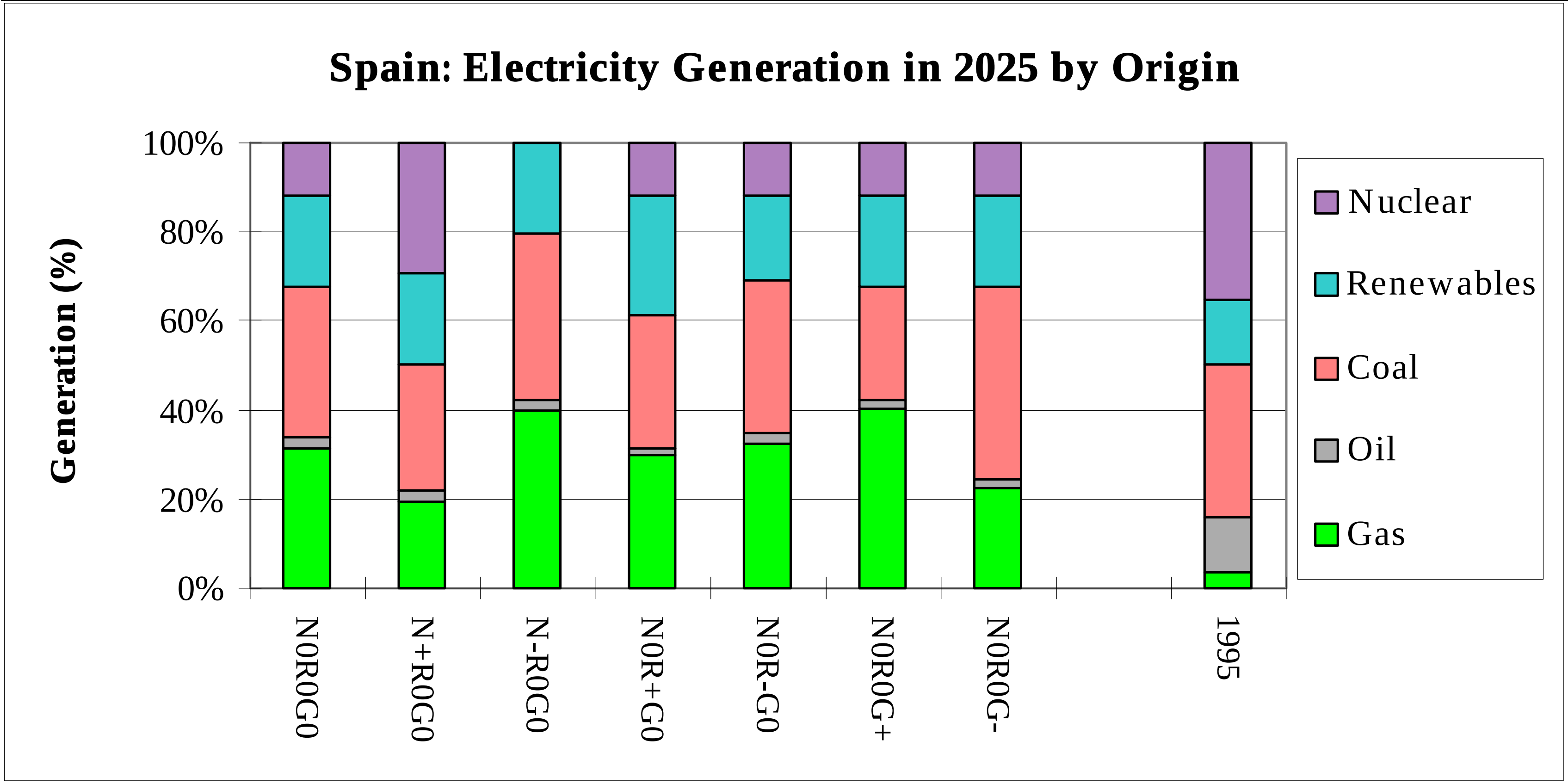


Figure 12.2 Carbon Dioxide Emissions from Power Generation

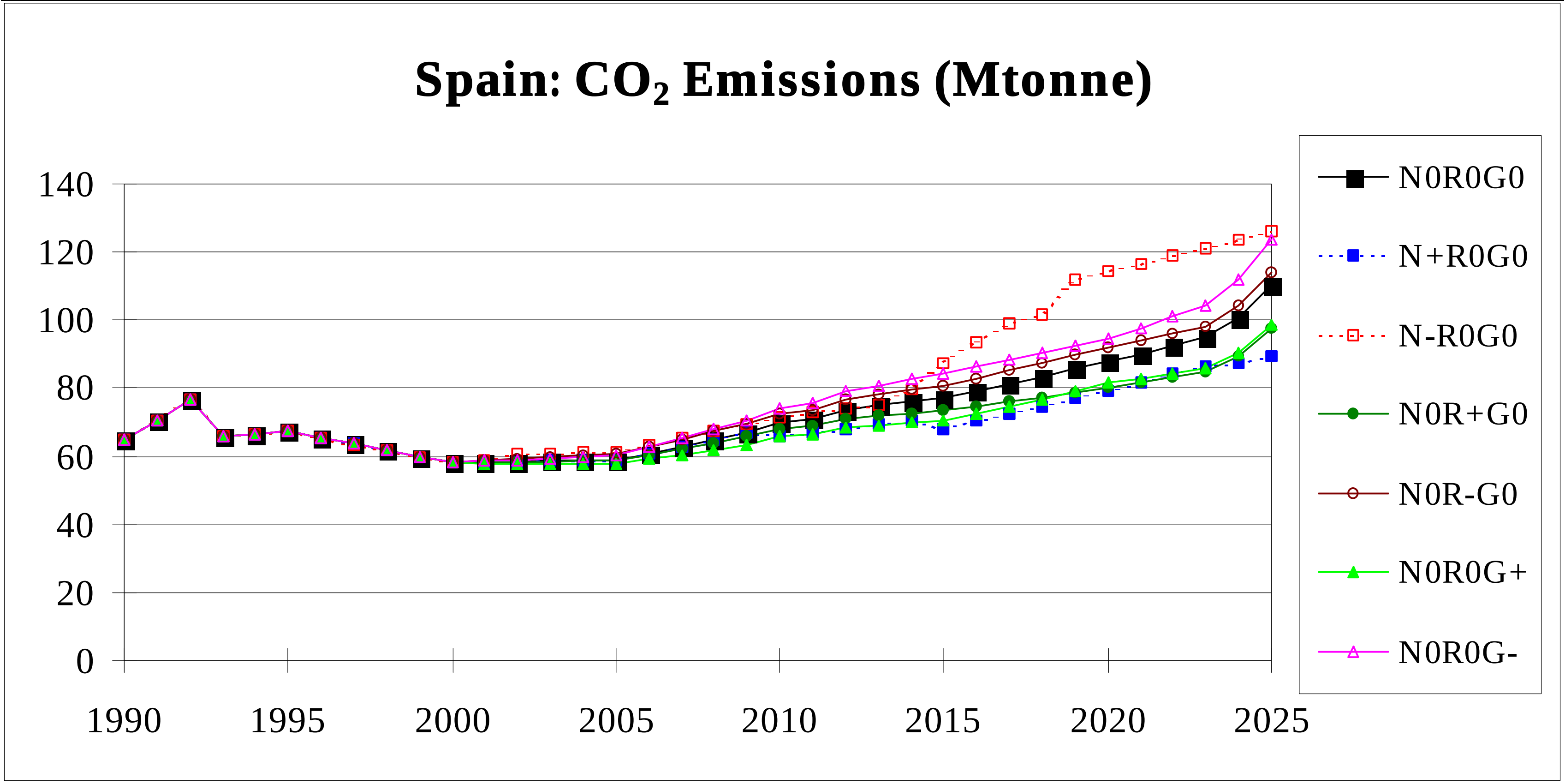


Figure 12.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

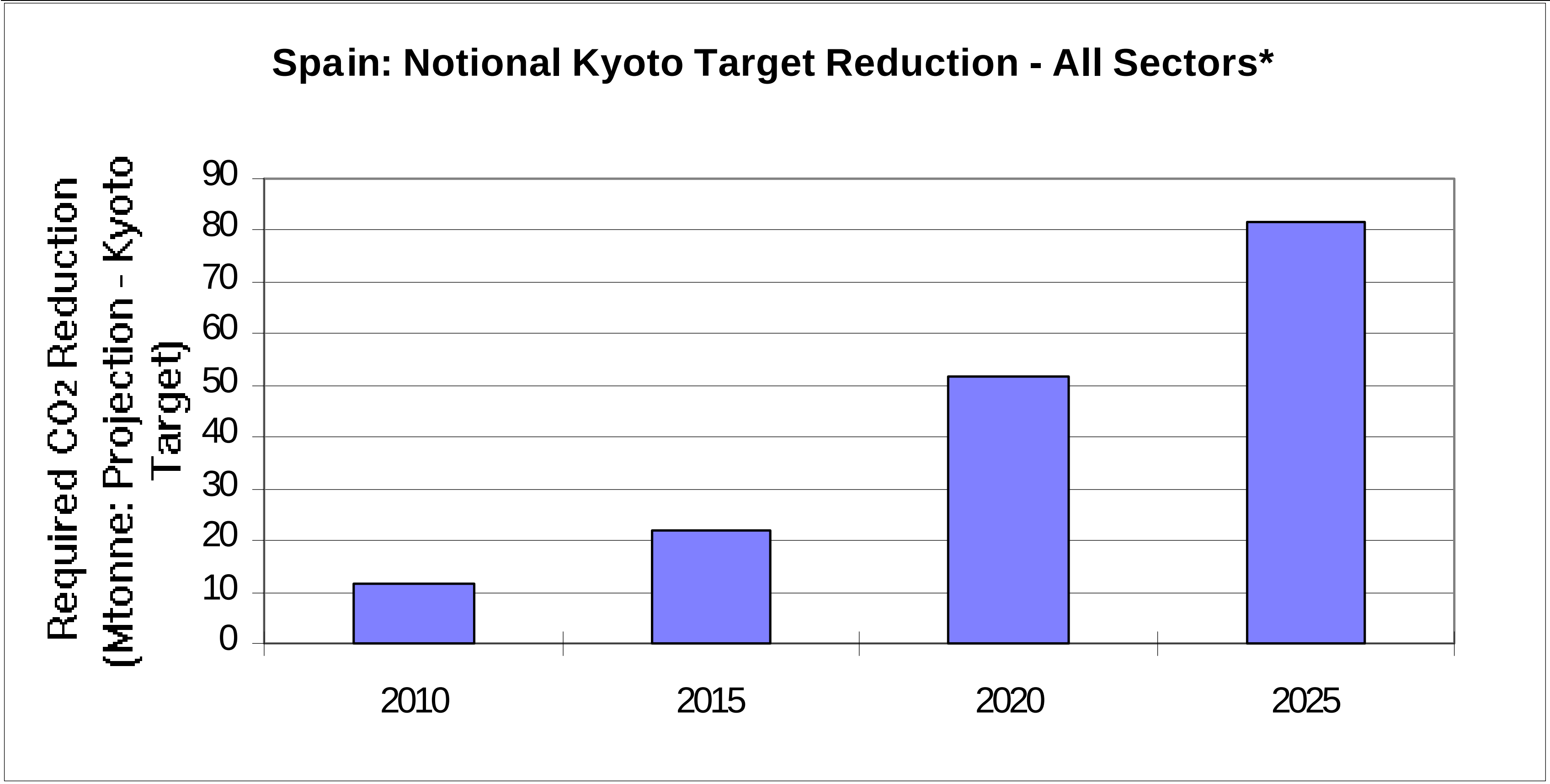


Figure 12.4 Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target (Assuming equal burdens on power generation sector and non-power generation sectors)*

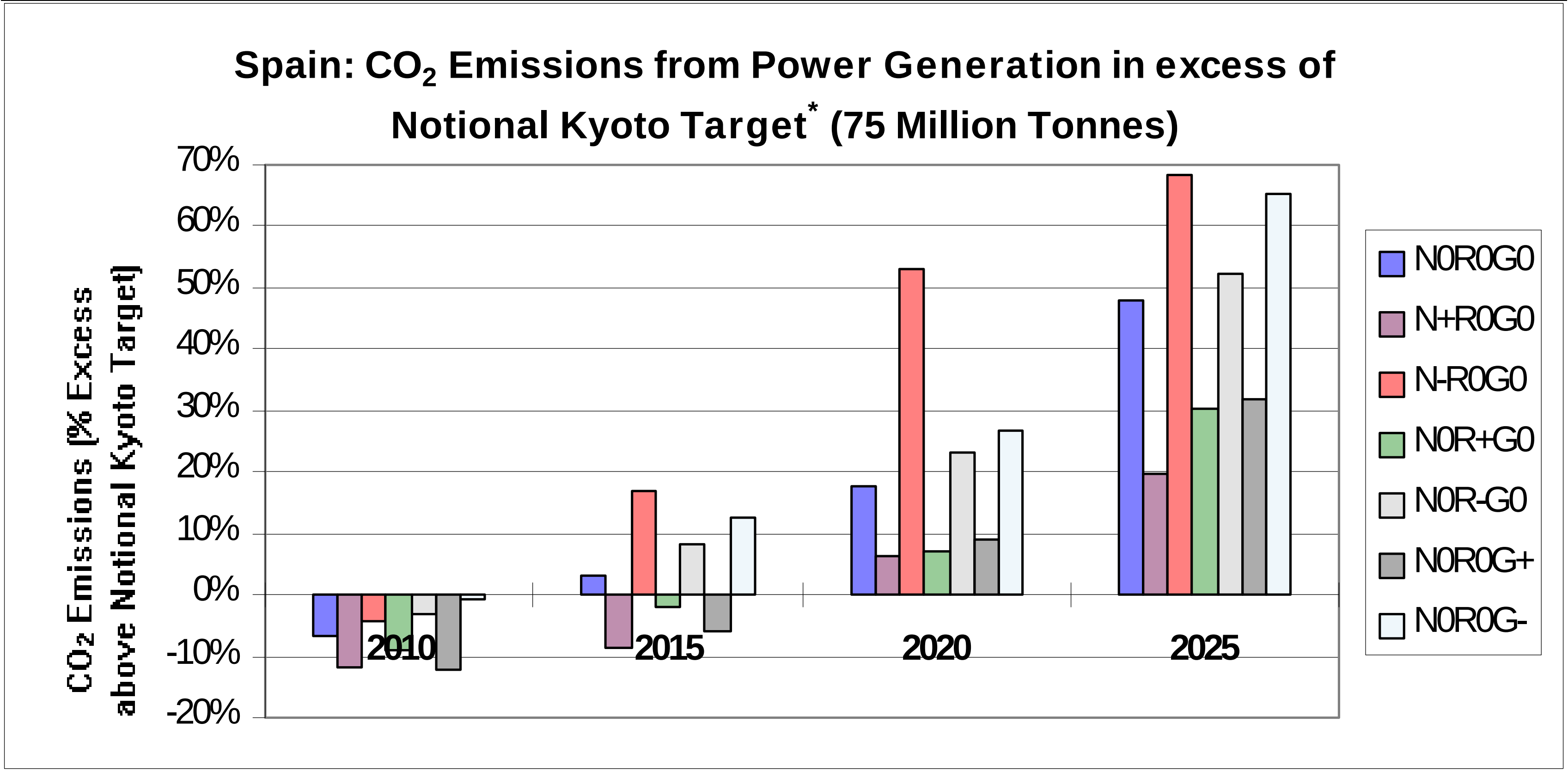


Figure 12.5 Spent Fuel Discharged

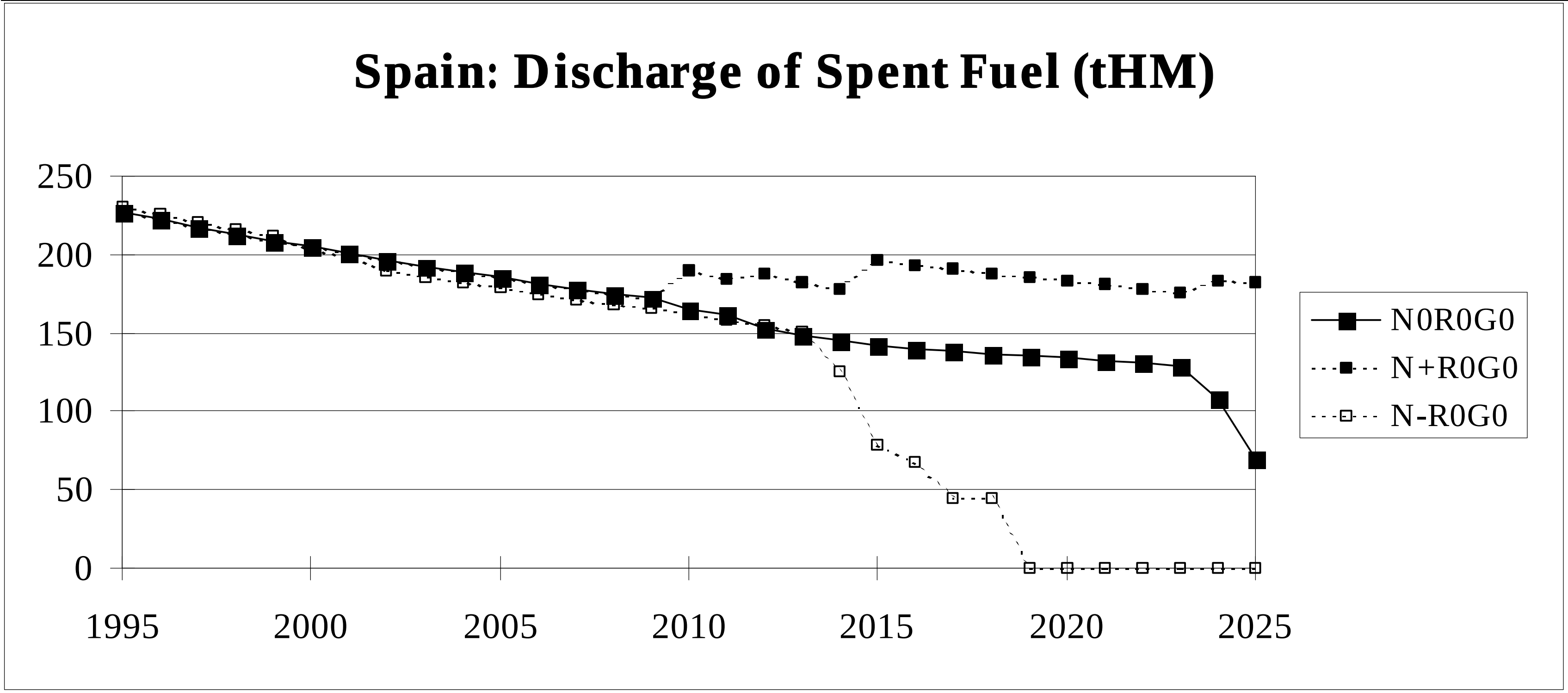


Figure 12.6 Low Level Waste (LLW/ILW)

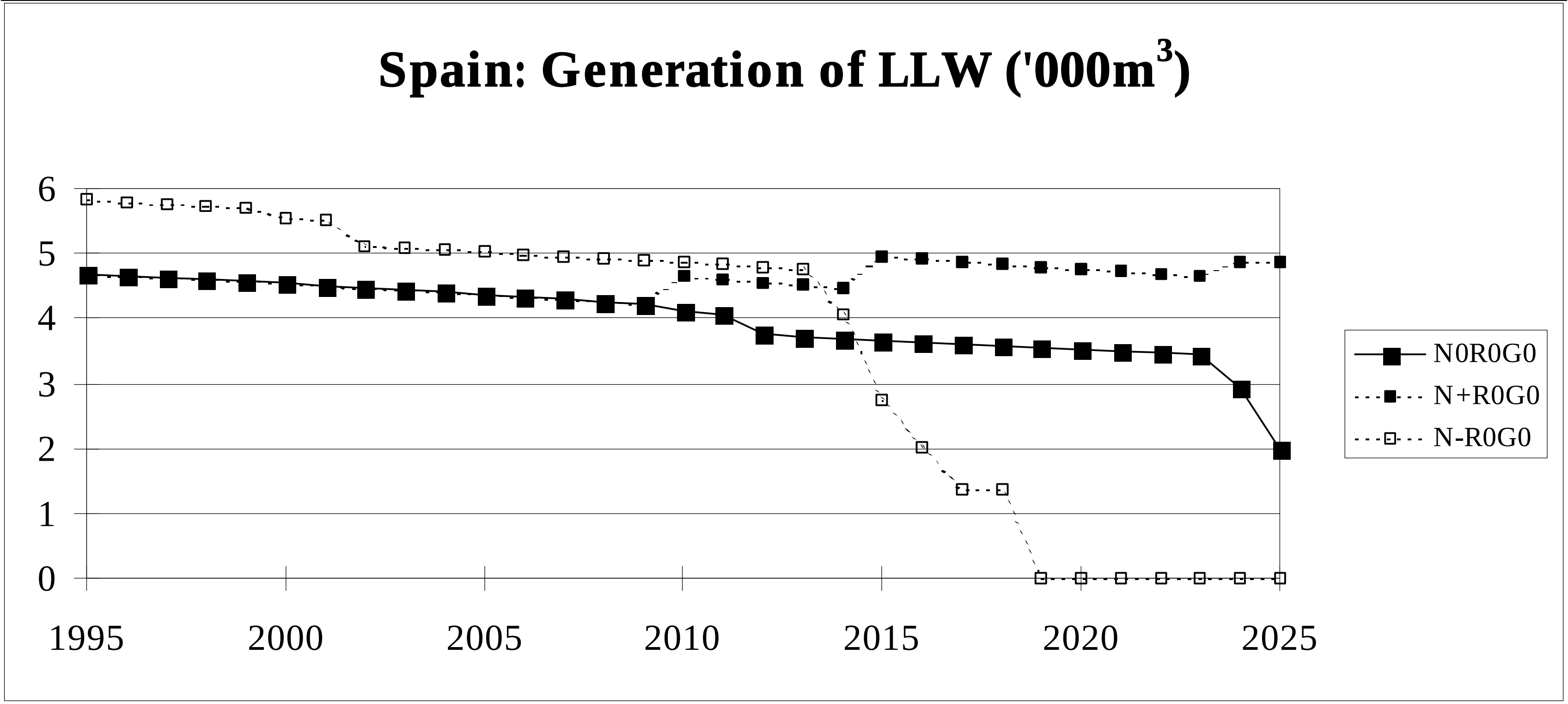


Figure 12.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

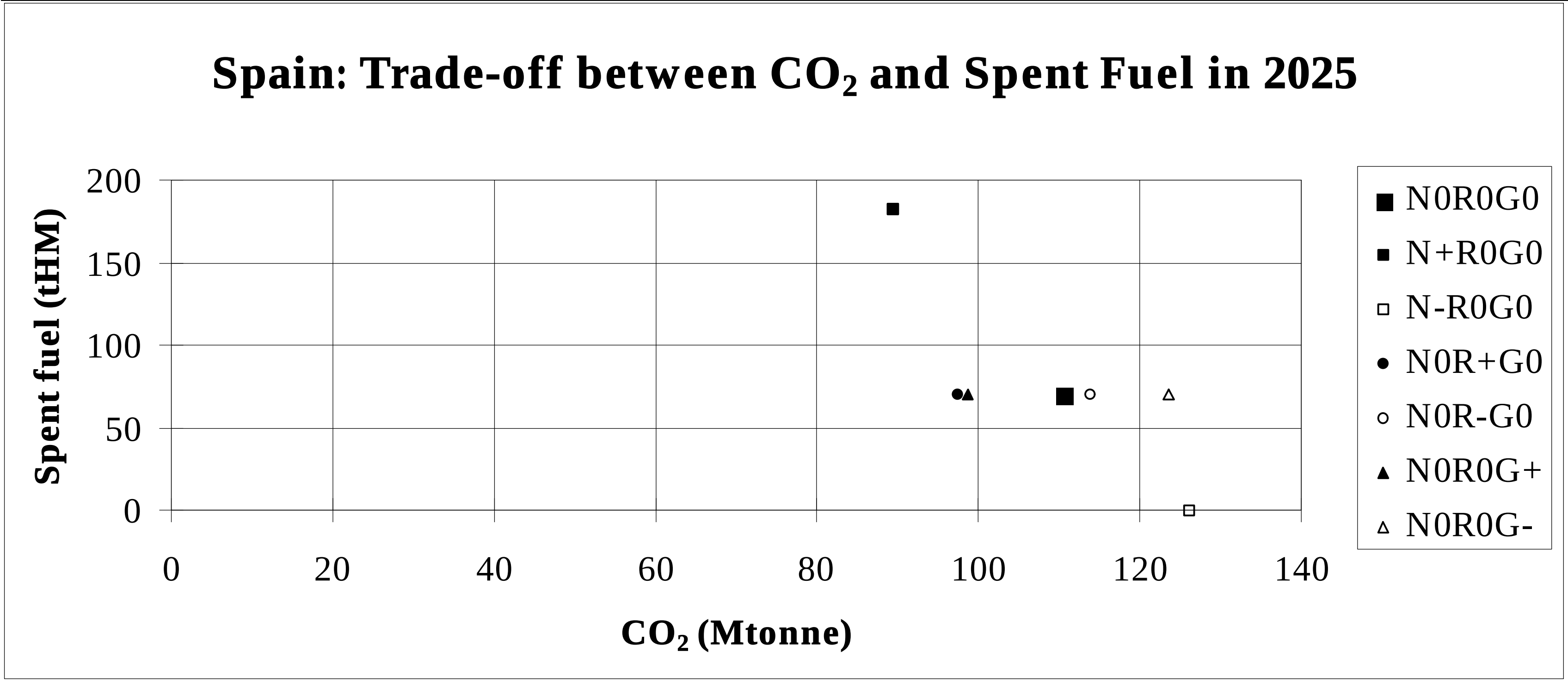
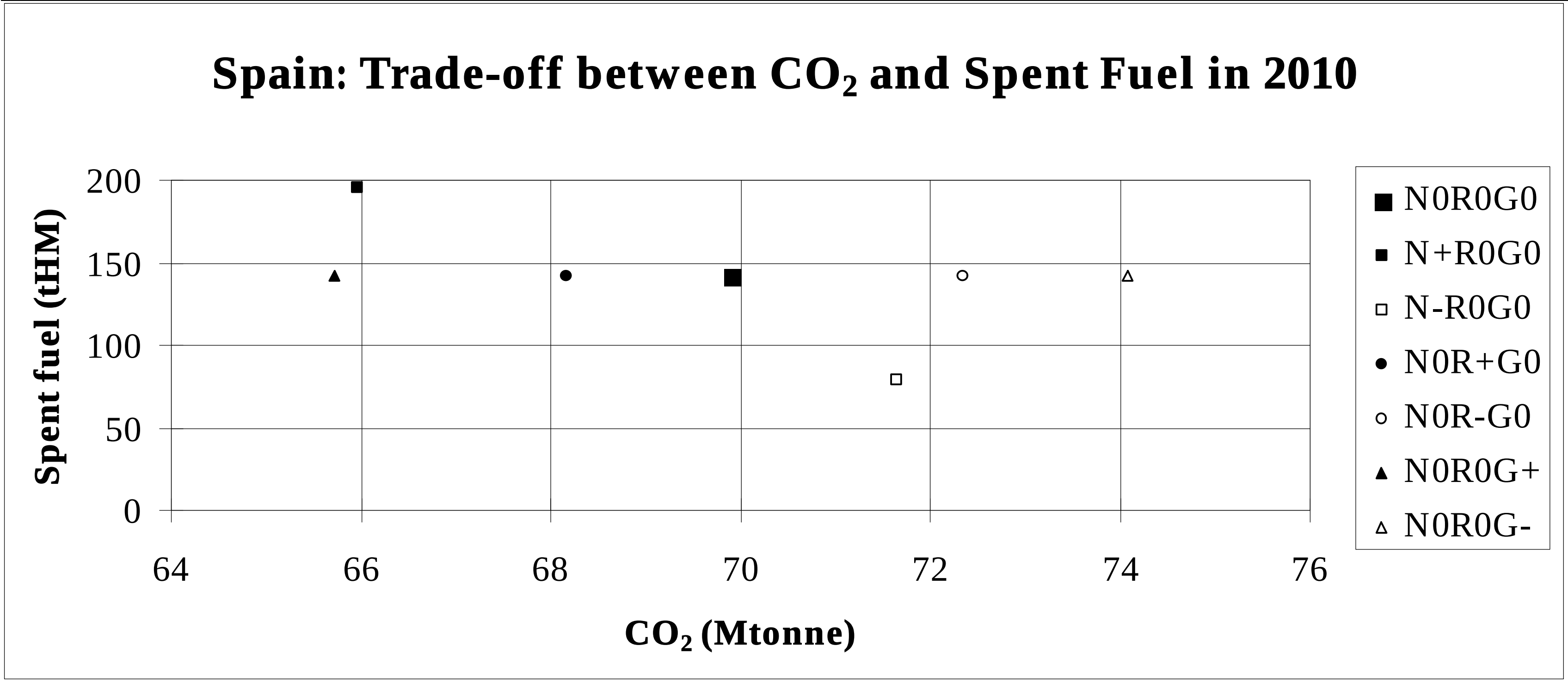


Figure 12.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010


Spain: Trade-off between CO2 and Spent Fuel in 2010
Spent fuel (tHM)
200
150
100
50
0
64
66
68
70
72
74
76
CO2 (Mtonne)
N0R0G0
N+R0G0
N-R0G0
N0R+G0
N0R-G0
N0R0G+
N0R0G-

13 SWEDEN

13.1 CALIBRATION OF MODEL AND CHOICE OF SCENARIOS

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4*.

The model has been calibrated against the actual performance of the Swedish power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 6 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 6 million tonnes. The discrepancy is due to the model projecting higher electricity generation from nuclear plant. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 13.1*.

Table 13.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 55.5% with large hydro and 7.5% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 31% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 65% with large hydro and 17% excluding large hydro in 2025, other factors as Base Scenario.

Scenario	Description	Composition
N0R-G0	Low RETs	Renewable generation amounts to 53.5% with large hydro and 5.5% excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

13.2 RESULTS

Electricity Generation in 2025 by Origin

Figure 13.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995.

Over 95% of Sweden's generation in 1995 was fuelled by nuclear (48%) and renewables (48%). CO_2 emissions were thus very low (6 Mtonne).

Sweden is currently detailing the future of its nuclear plant, with some groups advocating retiring nuclear plants before its normal lifetime. The base scenario (N0R0G0) assumes that plant is not retired early (40 year lifetime). Under this scenario, 9% of electricity is generated by nuclear power in 2025. In the high nuclear scenario, nuclear generation retains 34% of the total in 2025.

Sweden has very large renewables resources. Large scale hydro accounted for 46% of generation in 1995. Assuming that the 1995 capacity remains, 48% of electricity generation will be from large hydro in the Base scenario (N0R0G0). The potential for other renewable generation is high is Sweden and is strongly politically supported. Biomass, wind and waste all offer significant potential for development. The High Renewable scenario (N0R+G0) projects that renewables will account for 65% of all generation in 2025, with non-hydro schemes representing 17% of all generation. In the Base scenario (N0R0G0) renewables are projected to account for 56% of generation in 2025 and even in the low nuclear scenario (N0R-G0) they generate 53%.

If nuclear and renewables are not supported, Sweden will have to make up its generation shortfall with fossil fuel plant. As with all countries it has been assumed that new fossil fuel plant will be built in the ratio 2:1 gas : coal in the base scenario (N0R0G0). It should also be noted that Sweden plans to significantly increase CHP development, where coal / waste dual-fired plant represents an economic solution. Thus coal generation rises to 15% in the Base scenario (N0R0G0) and 23% in the Low Gas / High Coal scenario. Gas accounts for between 19% and 29% in all scenarios except for High Nuclear (N+R0G0) and Low Gas / High Coal (N0R0G-).

Emissions of Carbon Dioxide

Figure 13.2 summarises the emissions of carbon dioxide from the Swedish power system up to 2025 as forecast by this model.

Sweden's emissions in 1990 were just 5 Mtonne. The model projects that these will have to increase strongly in the future as fossil fuels meet an increasing share of the system. CO_2 emissions rise to 15 Mtonne prior to the main period of nuclear plant retirement (2005 in the low nuclear scenario (N-R0G0) and 2015 in all other scenarios). Post 2015, Base scenario (N0R0G0) emissions rise strongly to 36 Mtonne in 2025.

Sweden's major means of affecting CO_2 emissions is nuclear power. The High nuclear scenario stabilises emissions at 15 Mtonne (40% of base scenario emissions). Under early retirement of nuclear plants (N-R0G0), emissions exceed 45 Mtonne from 2015.

Decisions regarding renewables are the next most important method to reduce CO_2, with the High Renewables scenario (N0R+G0) showing reductions of 32% relative to the base scenario in 2025. Conversely, Low Renewables (N0R-G0) adds 9%.

Supporting gas over coal (N0R0G+) sees a reduction of 20% relative to the base scenario in 2025; supporting coal (N0R0G-) leads to an increase of 21% (8 Mtonnes).

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, Sweden agreed to limit emissions to no more than 4% of 1990 levels by year 2010. Total emissions in 1990 from all sectors were 50 Mtonne CO_2, of which 5 Mtonne (10%) came from the power generation sector.

Assuming that 1990 levels plus 4% must be met not only in 2010 but also in subsequent years, *Figure 13.3* shows the difference between projected values and the Kyoto target. Sweden must reduce its projected emissions by 43 Mtonne in 2010, declining to 35 Mtonne in 2025. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to limit emissions to no more than 4% above the 1990 level, i.e. to 5 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 13.4 shows how successful Sweden will be in meeting this target under each of the seven scenarios. The very low emissions from the power generation sector of 5 Mtonne in 1990 mean that the power generation sector will lead to increased CO_2 emissions in the future and thus cannot contribute to the limit of 4% increases required from all sectors. All scenarios except for Low Nuclear (N-R0G0) show excesses of 10 Mtonne in 2010 and 2015. Following the low nuclear path leads to excesses of 28 Mtonne in 2010, rising to 28 Mtonne in 2015. Sweden will experience serious problems meeting its Kyoto targets if it follows this scenario.

By 2025, Sweden can remain within 10 Mtonne of its targets if it replaces its nuclear plant and within 25 Mtonne if it supports renewables or favours gas for new fossil fuel generation plant.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 13.5 shows the discharge of spent fuel from nuclear plant over the period. Under the High Nuclear scenario (N+R0G0) spent fuel decreases from 235 tHM in 1995 to 200 tHM in 2025. Under the Low Nuclear scenario, (N-R0G0), plant is progressively retired from 2005 - 2016. In the Base scenario, (N0R0G0) this process takes place 10 years later and spent fuel of 40tHM is produced in 2025.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 13.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 17%, 82% and 0% of the values in 1995.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 13.7*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The figure shows a very wide range of possible outcomes in 2025. The difference between High Nuclear (N+R0G0) and Low Nuclear (N-R0G0) is 31 Mtonne CO_2 emissions; between High Nuclear and Base (N0R0G0) there is a difference of 22 Mtonne CO_2 emissions and 155 tHM of spent fuel. The importance of encouraging renewables and natural gas are clearly illustrated.

Figure 13.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

13.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. Over 95% of Sweden's generation in 1995 was fuelled by nuclear (48%) and renewables (48%). CO_2 emissions were thus very low (6 Mtonne).

2. Sweden is currently detailing the future of its nuclear plant, with some groups advocating retiring nuclear plants before its normal lifetime. The base scenario (N0R0G0) assumes that plant is not retired early (40 year lifetime). Under this scenario, 9% of electricity is generated by nuclear power in 2025. In the high nuclear scenario, nuclear generation retains 34% of the total in 2025.

3. Sweden has very large renewables resources. Large scale hydro accounted for 46% of generation in 1995. The High Renewable scenario (N0R+G0) projects that renewables will account for 65% of all generation in 2025, with non-hydro schemes representing 17% of all generation. In the Base scenario (N0R0G0) renewables are projected to account for 56% of generation in 2025 and even in the low nuclear scenario (N0R-G0) they generate 53%.

4. If nuclear and renewables are not supported, Sweden will have to make up its generation shortfall with fossil fuel plant. It should also be noted that Sweden plans to significantly increase CHP development, where coal/waste dual-fired plant represents an economic solution. Thus coal generation rises to 15% in the Base scenario (N0R0G0) and 23% in the Low Gas/High Coal scenario.

5. Sweden's emissions in 1990 were just 5 Mtonne. The model projects that these will have to increase strongly in the future as fossil fuels meet an increasing share of the system. CO_2 emissions rise to 15 Mtonne prior to

the main period of nuclear plant retirement (2005 in the low nuclear scenario (N-R0G0) and 2015 in all other scenarios). Post 2015, Base scenario (N0R0G0) emissions rise strongly to 36 Mtonne in 2025.

6. Sweden's major means of affecting CO_2 emissions is nuclear power. The High nuclear scenario stabilises emissions at 15 Mtonne (40% of base scenario emissions). Under early retirement of nuclear plants (N-R0G0), emissions exceed 45 Mtonne from 2015.

7. Decisions regarding renewables are the next most important method to reduce CO_2, with the High Renewables scenario (N0R+G0) showing reductions of 32% relative to the base scenario in 2025. Conversely, Low Renewables (N0R-G0) adds 9%.

8. The very low emissions from the power generation sector of 5 Mtonne in 1990 mean that the power generation sector will lead to increased CO_2 emissions in the future and thus cannot contribute to the limit of 4% increases required from all sectors. All scenarios except for Low Nuclear (N-R0G0) show excesses of 10 Mtonne in 2010 and 2015. Following the low nuclear path leads to excesses of 28 Mtonne in 2010, rising to 28 Mtonne in 2015. Sweden will experience serious problems meeting its Kyoto targets if it follows this scenario.

9. Under the High Nuclear scenario (N+R0G0) spent fuel decreases from 235 tHM in 1995 to 200 tHM in 2025. Under the Low Nuclear scenario, (N-R0G0), plant is progressively retired from 2005 - 2016. In the Base scenario, (N0R0G0) this process takes place 10 years later and spent fuel of 40tHM is produced in 2025.

10. There a very wide range of possible outcomes in 2025. The difference between High Nuclear (N+R0G0) and Low Nuclear (N-R0G0) is 31 Mtonne CO_2 emissions; between High Nuclear and Base (N0R0G0) there is a difference of 22 Mtonne CO_2 emissions and 155 tHM of spent fuel. The importance of encouraging renewables and natural gas are clearly illustrated.

Figure 13.1 Electricity Generation in 2025 by Origin

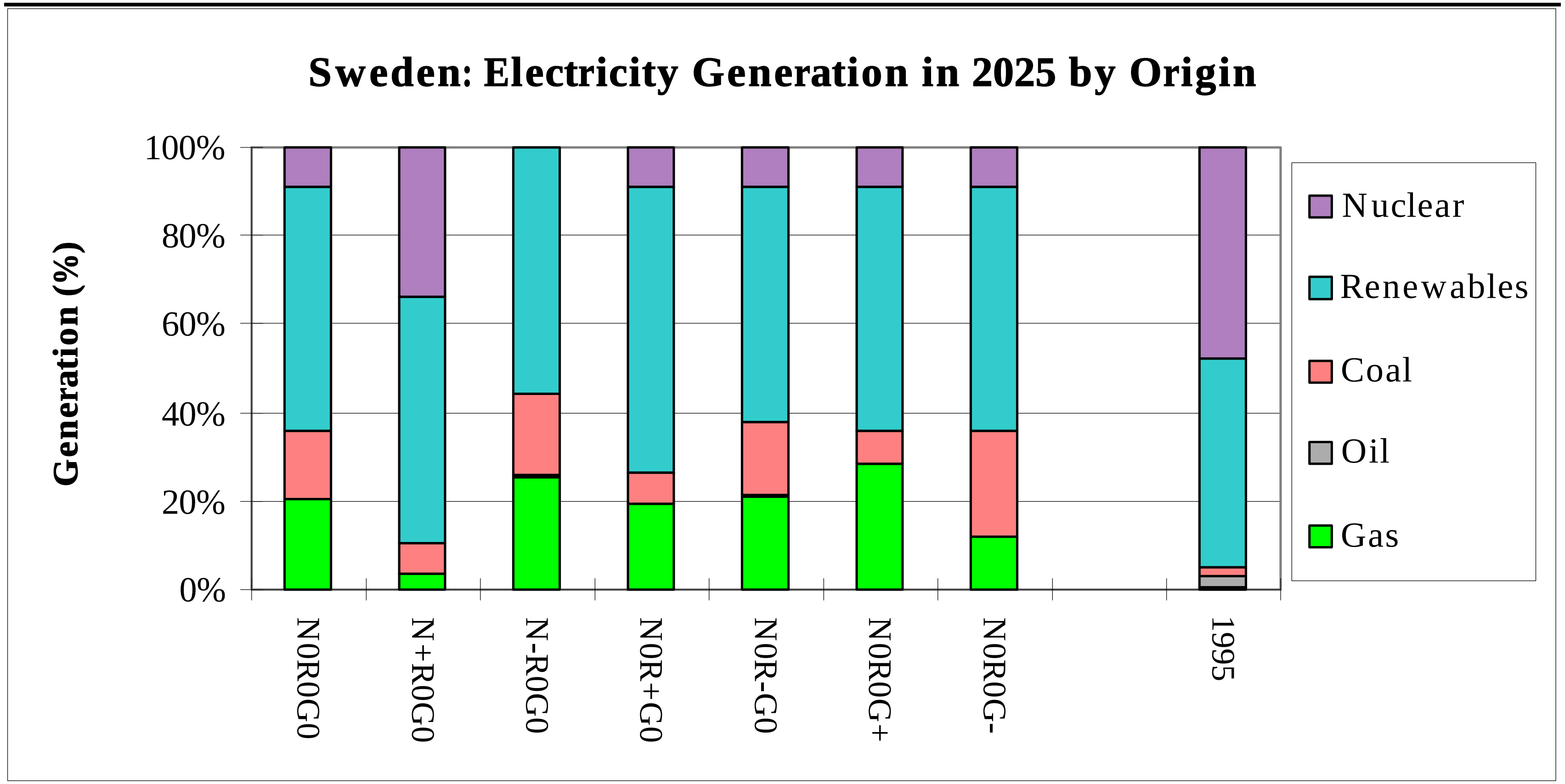


Figure 13.2 Carbon Dioxide Emissions from Power Generation

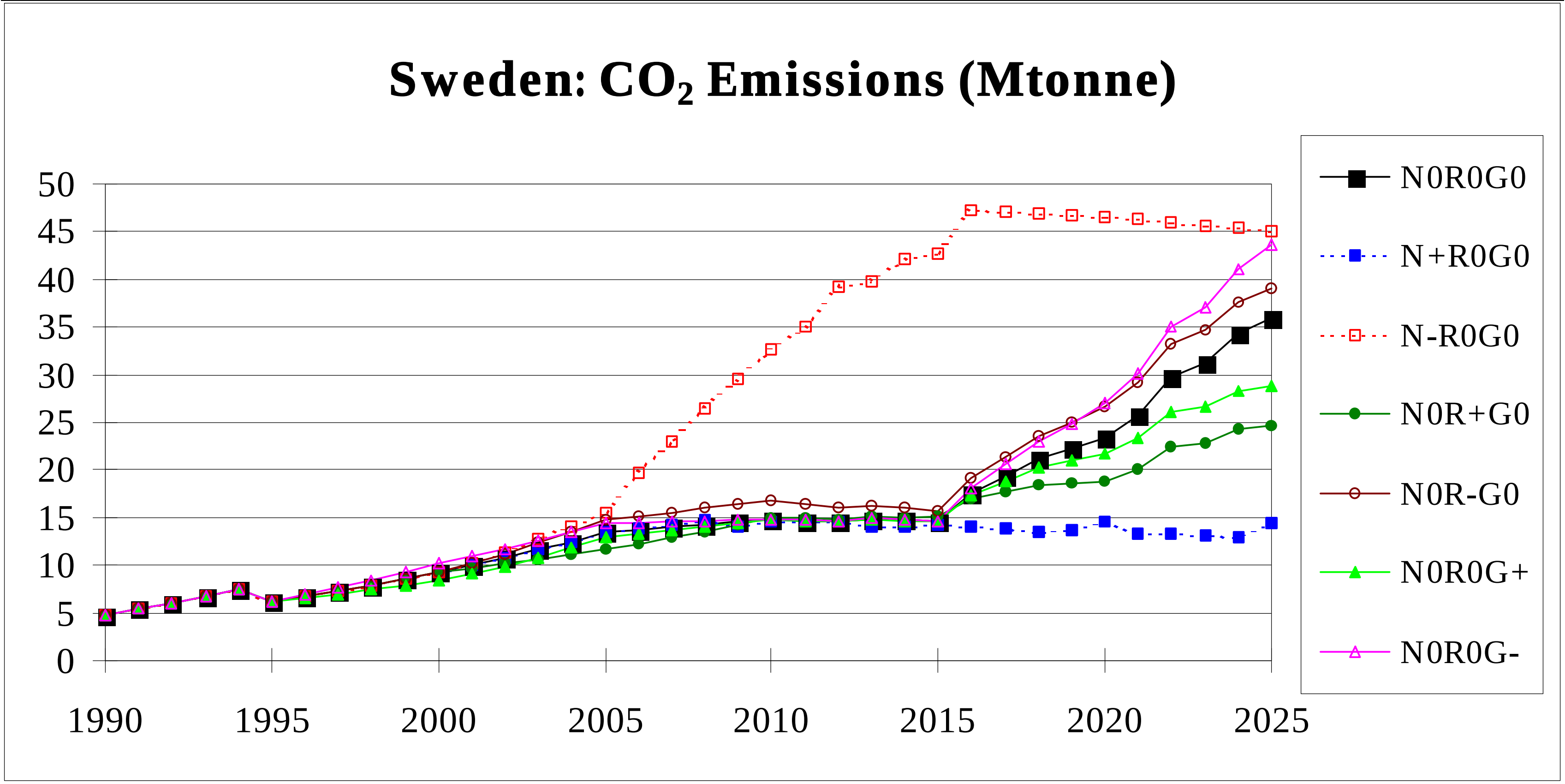


Figure 13.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

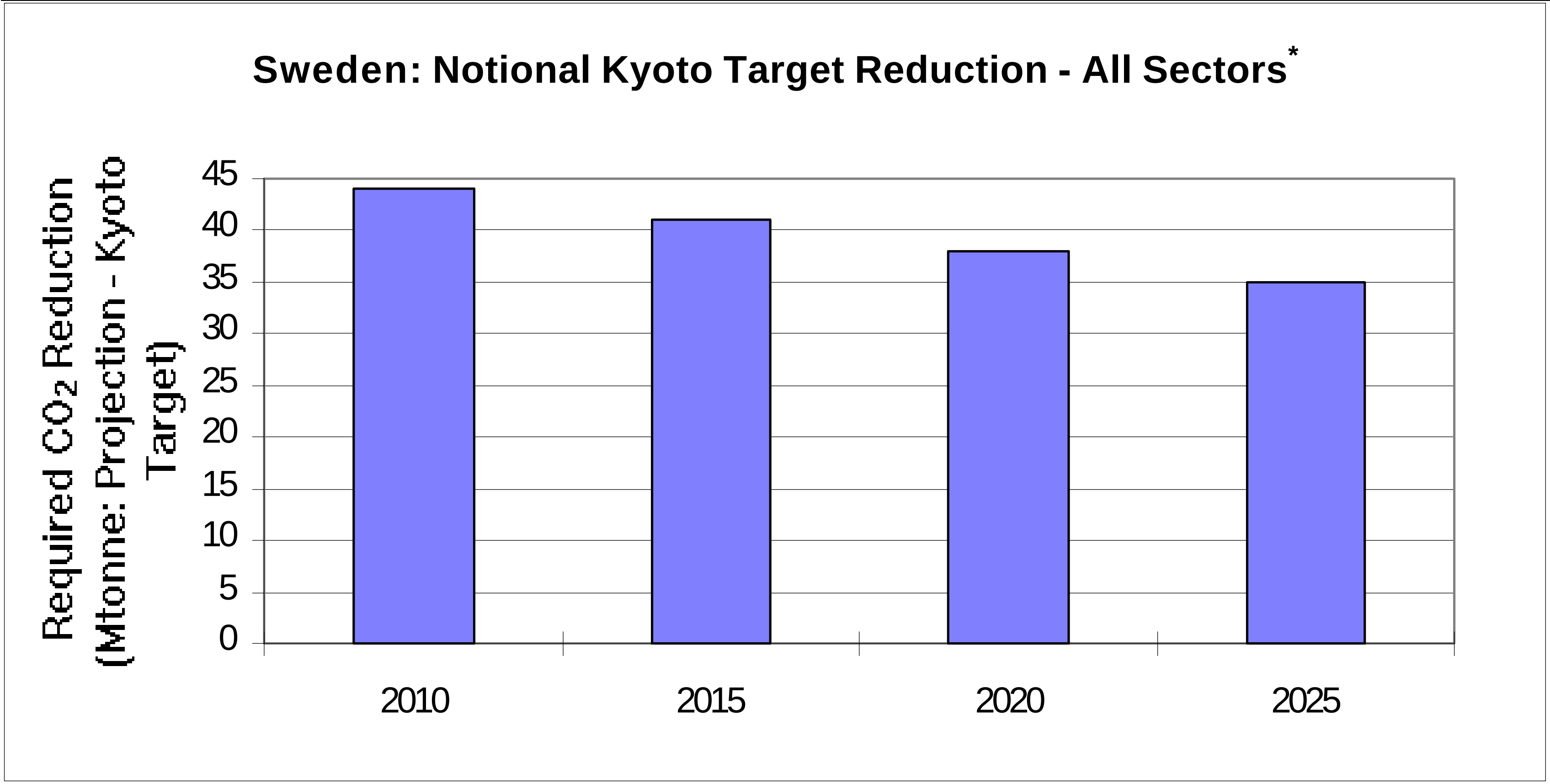


Figure 13.4 Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target (Assuming equal burdens on power generation sector and non-power generation sectors)*

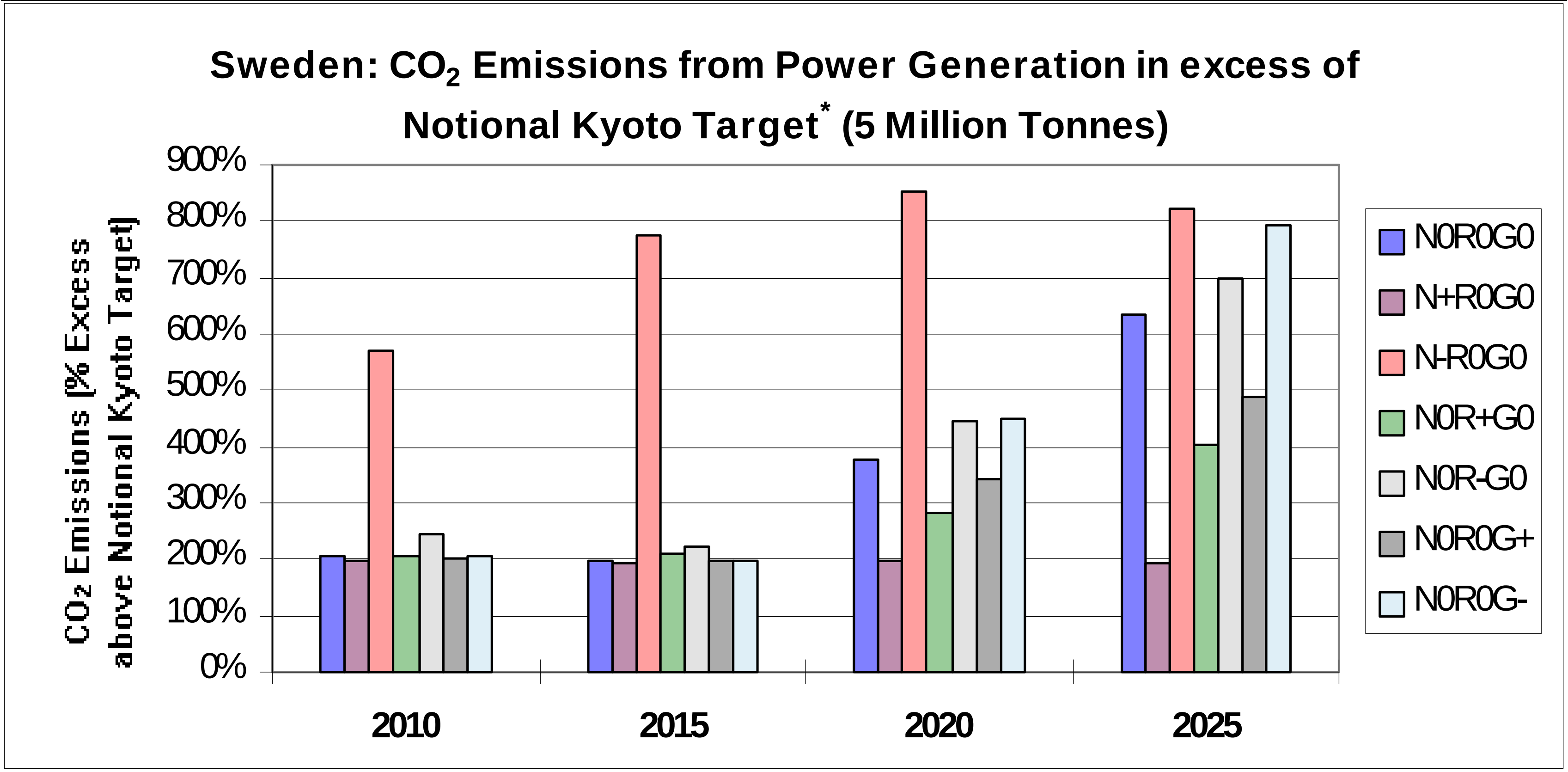


Figure 13.5 Spent Fuel Discharged

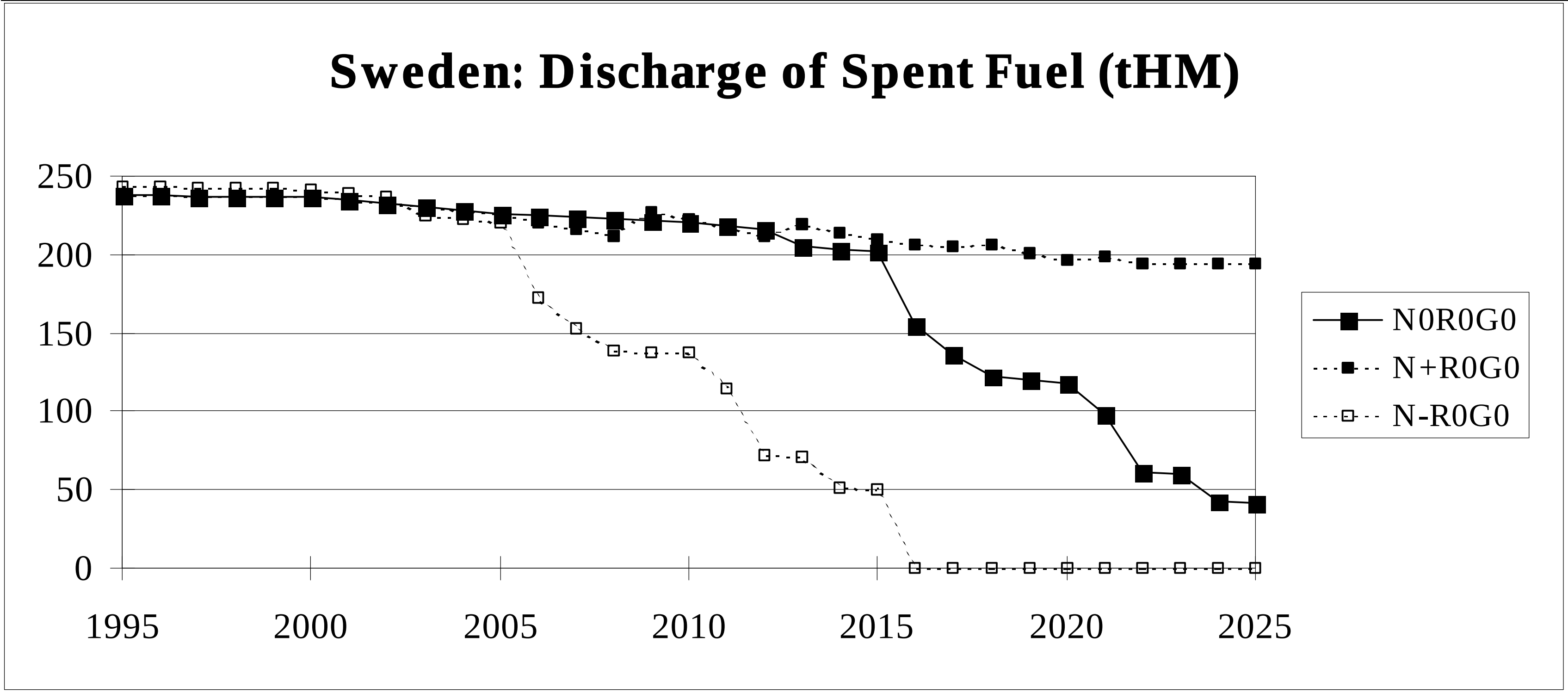


Figure 13.6 Low Level Waste (LLW/ILW)

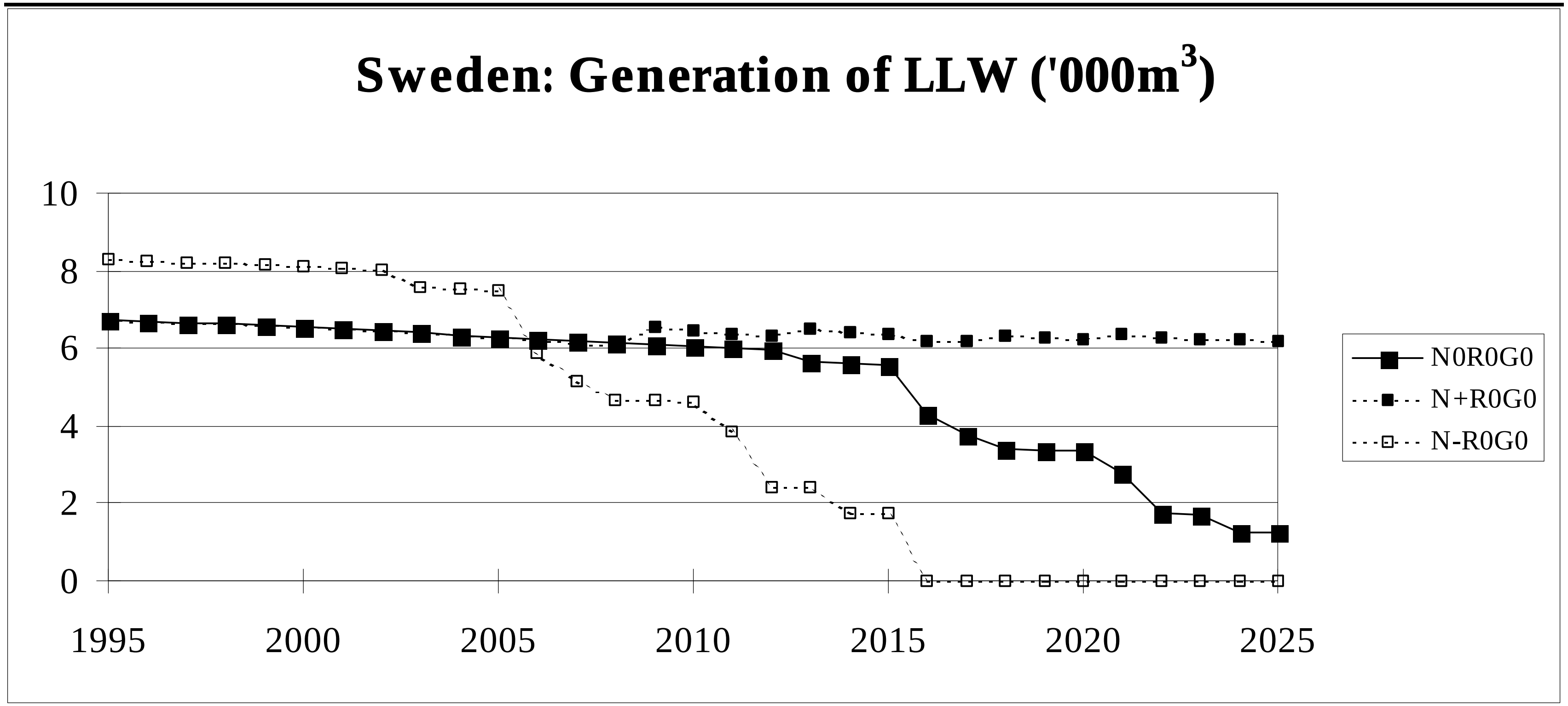


Figure 13.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

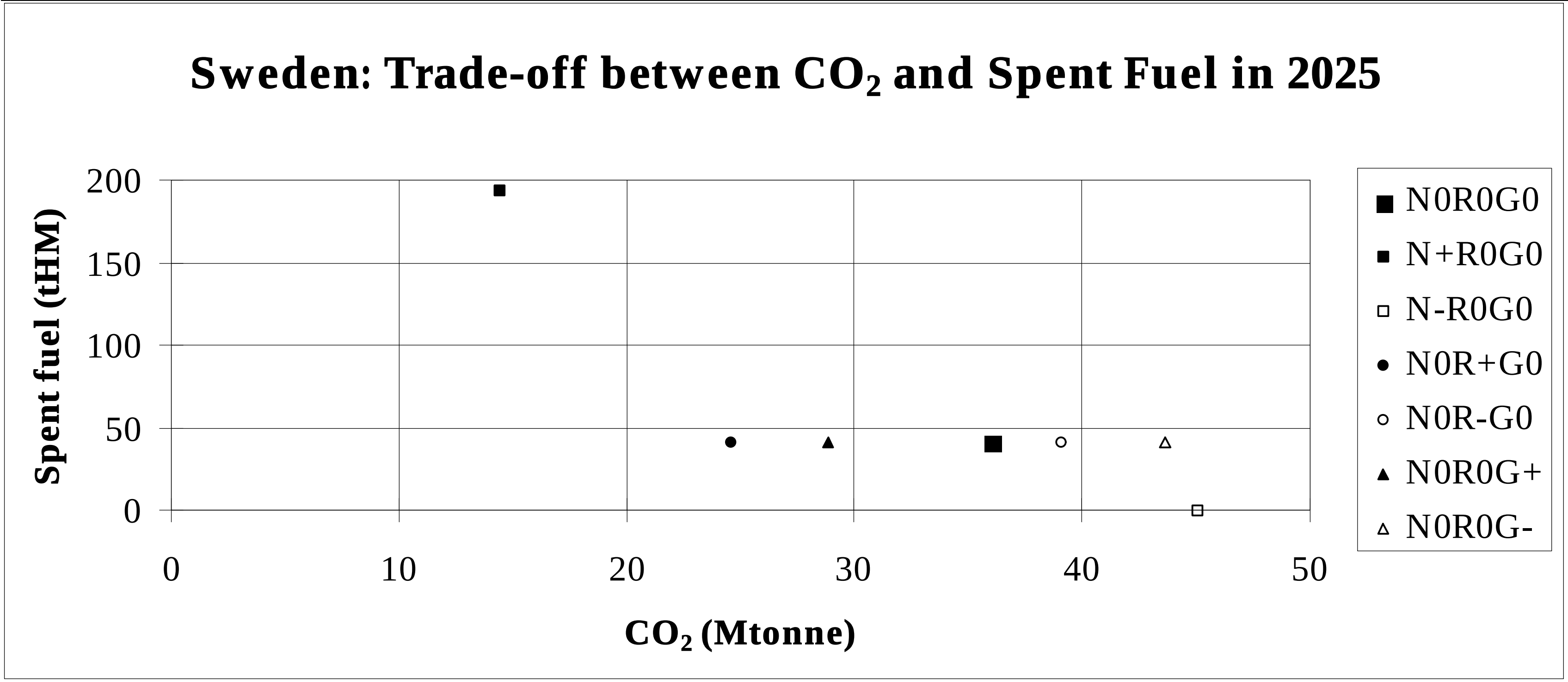
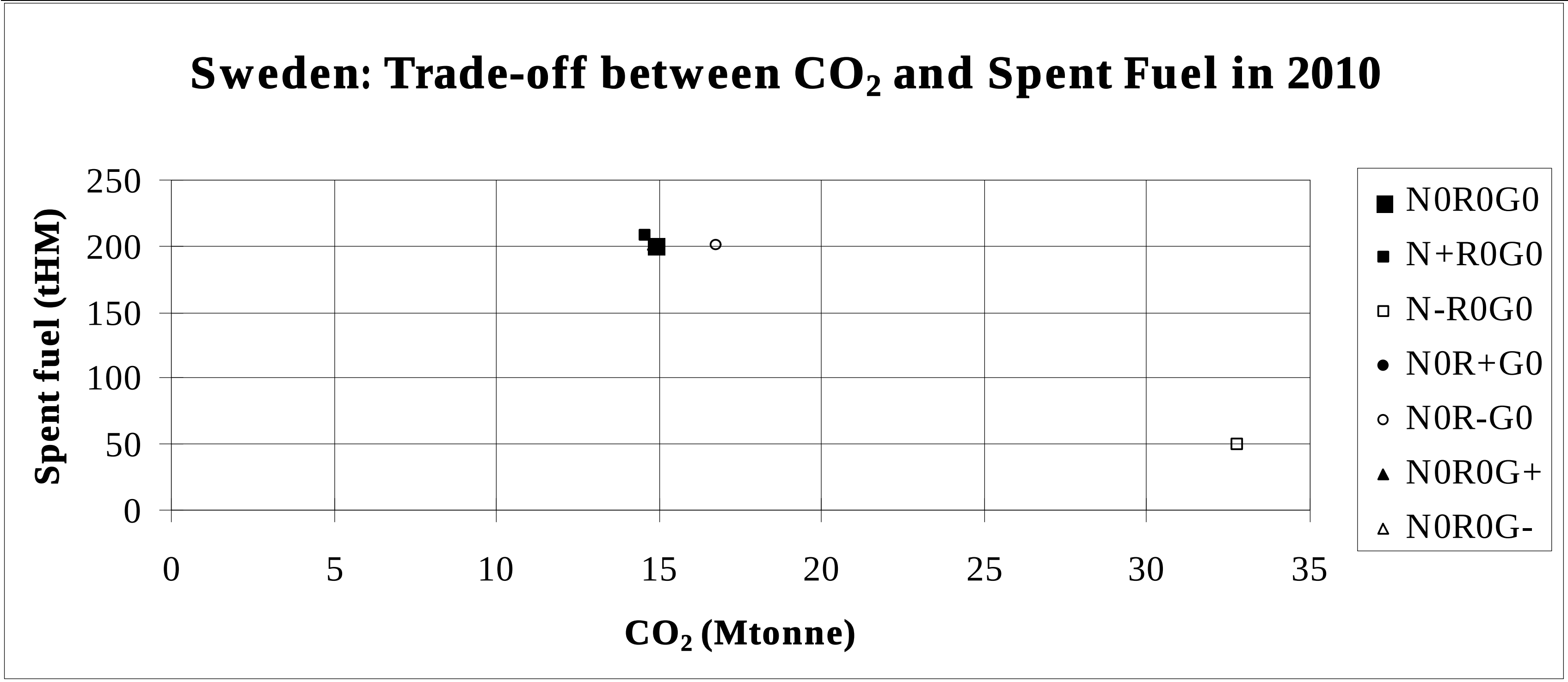


Figure 13.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010



14 UK

14.1 Calibration of Model and Choice of Scenarios

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020').* The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain. Further scenario details are described in *Section 3.2.4.*

The model has been calibrated against the actual performance of the UK power system in 1995. No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 174 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 174 million tonnes. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios are shown in *Table 14.1*.

Table 14.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas, renewable generation amounts to 8.5% with large hydro and 7.5% excluding large hydro in 2025.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 16% of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation amounts to 12.5% with large hydro and 11.5% excluding large hydro in 2025, other factors as Base Scenario.

Scenario	Description	Composition
N0R-G0	Low RETs	Renewable generation amounts to 7% with large hydro and 6% excluding large hydro in 2025, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

14.2 RESULTS

Electricity Generation in 2025 by Origin

Figure 14.1 shows the share of electricity generation in 2025 by origin in each of the seven scenarios, plus the share in 1995.

Coal is the most important source of generation in the UK and coal generated over 45% of the UK's electricity in 1995. The rapid introduction of CCGT Plant has recent past has resulted in gas accounting for almost 20% of generation in 1995.

The UK's nuclear plant varies widely by both technology and age. Nuclear was the second largest generation in 1995, with 27% of the total. It is projected that this share will fall to 10% in the base scenario (N0R0G0) and to between 2% and 23% in the Low Nuclear (N-R0G0) and High Nuclear (N+R0 G0) scenarios respectively.

Much of the UK's coal plant is old and will be retired In the near future. If 100% of new fossil fuel plant is gas (N0R0G+), no coal generation capacity will exist in 2025. In the Base Scenario (N0R0G0), Coal's share of generation reduces to 16%; the Low Gas / High Coal scenario sees coal retaining a 31% share of generation in 2025. Gas becomes dominant, accounting for 60% of generation in the Base scenario (N0R0G0) in 2025.

Renewables offer limited potential in the UK. Large hydro schemes contributed only 1.5% to electricity generation in 1995. However, there is significant wind and waste potential and there is a Government target to increase the share of electricity generation to 10% by 2010 (this has been modelled as the High renewable scenario (N0R+G0) where renewables have a 12.5% share of generation in 2025. The Low Renewables (N0R-G0) and Base (N0R0G0) scenarios project shares of 7% and 10% in 2025 from renewables respectively.

Emissions of Carbon Dioxide

Figure 14.2 summarises the emissions of carbon dioxide from the UK power system up to 2025 as forecast by this model.

The UK's historical dependence on coal for power generation has meant that CO_2 emissions declined by over 25% from 220 Mtonne in 1990 to 175 Mtonne in 1995. Availability and load factors of nuclear plant also increased significantly during this period.

Emissions are projected to remain at 1995 levels to 2010 under the Base scenario (N0R0G0). The effects of increase electricity demand are offset by gas plant replacing coal. 2010 - 2015 sees further reductions of 25 Mtonne as further coal plant is retired, with emissions stabilising at approximately 159 Mtonne to 2025 in the Base scenario. 2025 emissions are 25% lower than those in 1990.

The UK has some flexibility to influence this outcome. Renewables policy has only limited effect. Relative to the Base scenario projection for 2025, encouraging gas (N0R0G+) leads to projected reductions of 23 Mtonne, while favouring Coal leads to increased emissions of 29 Mtonne. Nuclear policy has similar effects, with reductions in 2025 of 23 Mtonne under the High Nuclear scenario (N+R0G0) and increases of 19 Mtonne under Low Nuclear (N-R0G0).

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, UK agreed to reduce emissions from 1990 levels by 12.5% in the year 2010. Total emissions in 1990 from all sectors were 579 Mtonne CO_2, of which 219 Mtonne (38%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 14.3* shows the difference between projected values and the Kyoto target. The UK needs to make reductions of 100 Mtonne/year CO_2 in the period from 2010 to meet its Kyoto commitments. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to reduce emissions by 12.5% from the 1990 level to 191 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 14.4 shows how successful UK will be in meeting this target under each of the seven scenarios. The power generation sector will be able to conform to the targeted reductions of 12.5% in all scenarios for all years (other than Gas/High Coal (N0R0G-) in 2010). From 2020, Base scenario (N0R0G0) reductions of 35 Mtonne can be increased by a further 20 Mtonne by encouraging either Nuclear (N+R0G0) or Gas (N0R0G+).

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 14.5 shows the discharge of spent fuel from nuclear plant over the period. UK spent fuel arising was almost 1000 tHM in 1995. This decreases to no more than 400 tHM by 2008 as the UK's AGR reactors are retired. Spent fuel arising stabilises at 400 tHM in the High Nuclear scenario (N+R0G0). Base scenario (N0R0G0) emissions stabilise at just over 200 tHM by 2020. In the Low Nuclear scenario (N-R0G0) they decrease from 1995 as the older AGR units are immediately retired. By 2020, only the PWR units at Sizewell remain operational.

Low and Intermediate Level Waste from Nuclear Plant

LLW/ILW does not decrease in the same was as spent fuel as AGR plant creates similar waste as PWR. The discharges of LLW show a similar pattern to the discharges of spent fuel, (see *Figure 14.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 22%, 37% and 2% of the values in 1995. The High Nuclear scenario (N+R0G0) sees waste stabilising at its 1990 value of 7000m^3/year. Base scenario (N0R0G0) arising are of the order of 3500m^3/year in 2025.

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2025 can be summarised as in *Figure 14.7,* which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The most important decision facing the UK is the choice of new fossil fuel plant. Building 100% gas (N0R0G+) would lead to CO_2 reductions of 23 Mtonne relative to the base scenario (No, Ro, Go); building 67% coal would increase emissions by 29 Mtonnes (17%). Renewables policy is projected to lead to deductions/increases of approximately 25% of these figures. Nuclear policy is less important. High Nuclear (N+R0G0) would not decrease emissions in comparison to High Gas/Low Coal (N0R0G+); Low Nuclear (N-R0G0) CO_2 emissions leads to increases in line with Low Gas/High Coal (N0R0G-).

The UK can reduce/increase CO_2 by 1 Mtonne at the cost of increasing/reducing spent fuel by 8 tHM. The high nuclear scenario (N+R0G0) leases to a reduction in 2025 of 23 Mtonne CO_2 relative the to Base scenario (N0R0G0) and an increase in spent fuel of 150 tHM.

Figure 14.8 shows that a unit of CO_2 reduction would cost more units of spent fuel in 2010 than in 2025. The scope for reducing CO_2 emissions using nuclear power generation is also lower.

14.3 SUMMARY AND CONCLUSIONS

The major conclusions are as follows:

1. Coal is the most important source of generation in the UK and coal generated over 45% of the UK's electricity in 1995. The rapid introduction of CCGT Plant has recent past has resulted in gas accounting for almost 20% of generation in 1995.

2. The UK's nuclear plant varies widely by both technology and age. Nuclear was the second largest generation in 1995, with 27% of the total. It is projected that this share will fall to 10% in the base scenario (N0R0G0) and to between 2% and 23% in the Low Nuclear (N-R0G0) and High Nuclear (N+R0 G0) scenarios respectively.

3. Much of the UK's coal plant is old and will be retired In the near future. Gas becomes dominant, accounting for 60% of generation in the Base scenario (N0R0G0) in 2025.

4. Renewables offer limited potential in the UK.

5. The UK's historical dependence on coal for power generation has meant that CO_2 emissions declined by over 25% from 220 Mtonne in 1990 to 175 Mtonne in 1995. Availability and load factors of nuclear plant also increased significantly during this period.

6. Emissions are projected to remain at 1995 levels to 2010 under the Base scenario (N0R0G0). The effects of increase electricity demand are offset by gas plant replacing coal. 2010 - 2015 sees further reductions of 25 Mtonne as further coal plant is retired, with emissions stabilising at approximately 159 Mtonne to 2025 in the Base scenario. 2025 emissions are 25% lower than those in 1990.

7. The power generation sector will be able to conform to the targeted reductions of 12.5% in all scenarios for all years (other than Gas / High Coal (N0R0G-) in 2010). From 2020, Base scenario (N0R0G0) reductions of 35 Mtonne can be increased by a further 20 Mtonne by encouraging either Nuclear (N+R0G0) or Gas (N0R0G+).

8. UK spent fuel arising was almost 1000 tHM in 1995. This decreases to no more than 400 tHM by 2008 as the UK's AGR reactors are retired. Spent fuel arising stabilises at 400 tHM in the High Nuclear scenario (N+R0G0). Base scenario (N0R0G0) emissions stabilise at just over 200 tHM by 2020.

9. The most important decision facing the UK is the choice of new fossil fuel plant. Building 100% gas (N0R0G+) would lead to CO_2 reductions of 23 Mtonne relative to the base scenario (No, Ro, Go); building 67% coal would increase emissions by 29 Mtonnes (17%).

10. The UK can reduce / increase CO_2 by 1 Mtonne at the cost of increasing / reducing spent fuel by 8 tHM. The high nuclear scenario (N+R0G0) leases to a reduction in 2025 of 23 Mtonne CO_2 relative the to Base scenario (N0R0G0) and an increase in spent fuel of 150 tHM.

Figure 14.1 Electricity Generation in 2025 by Origin

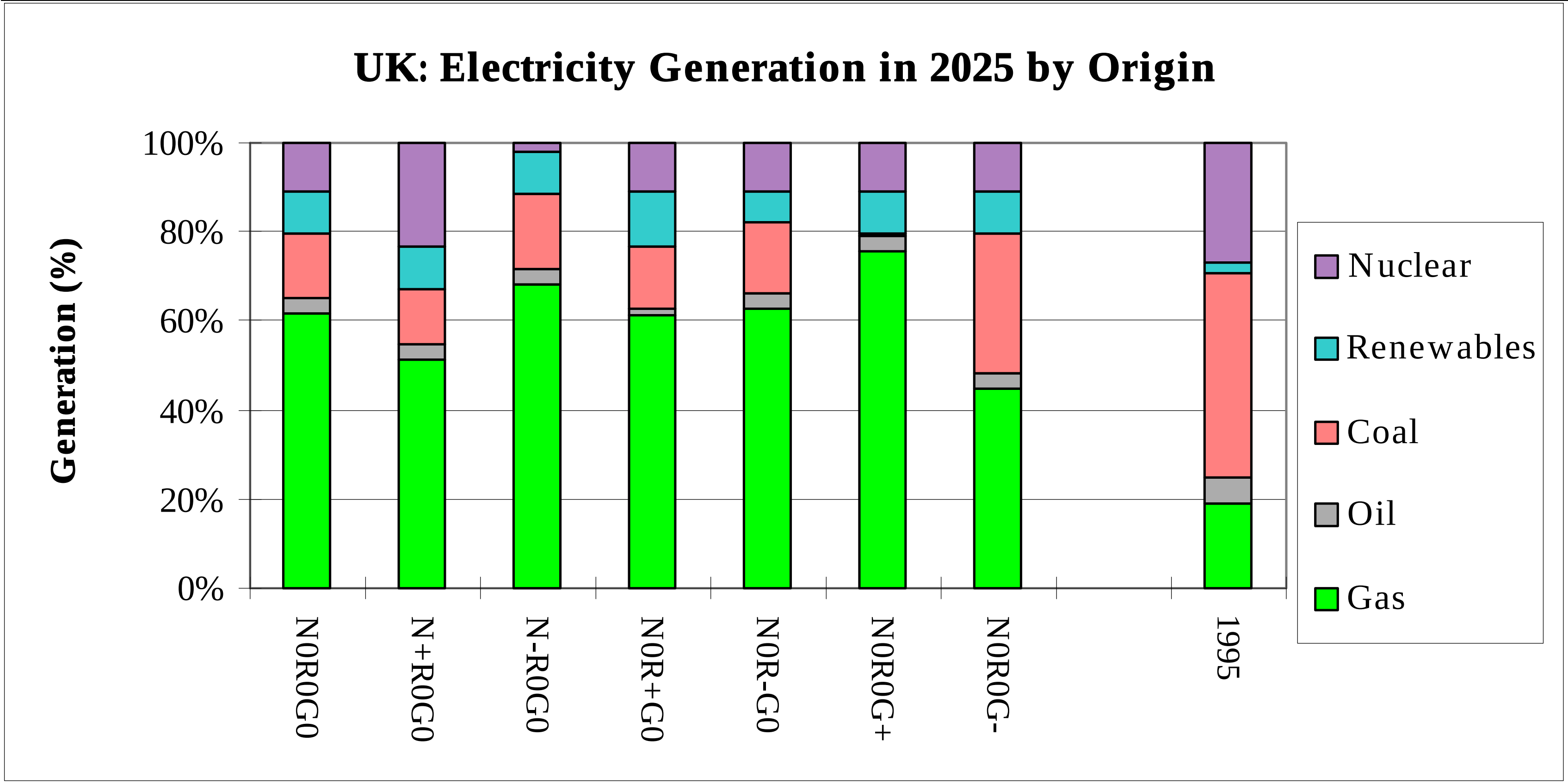


Figure 14.2   Carbon Dioxide Emissions from Power Generation

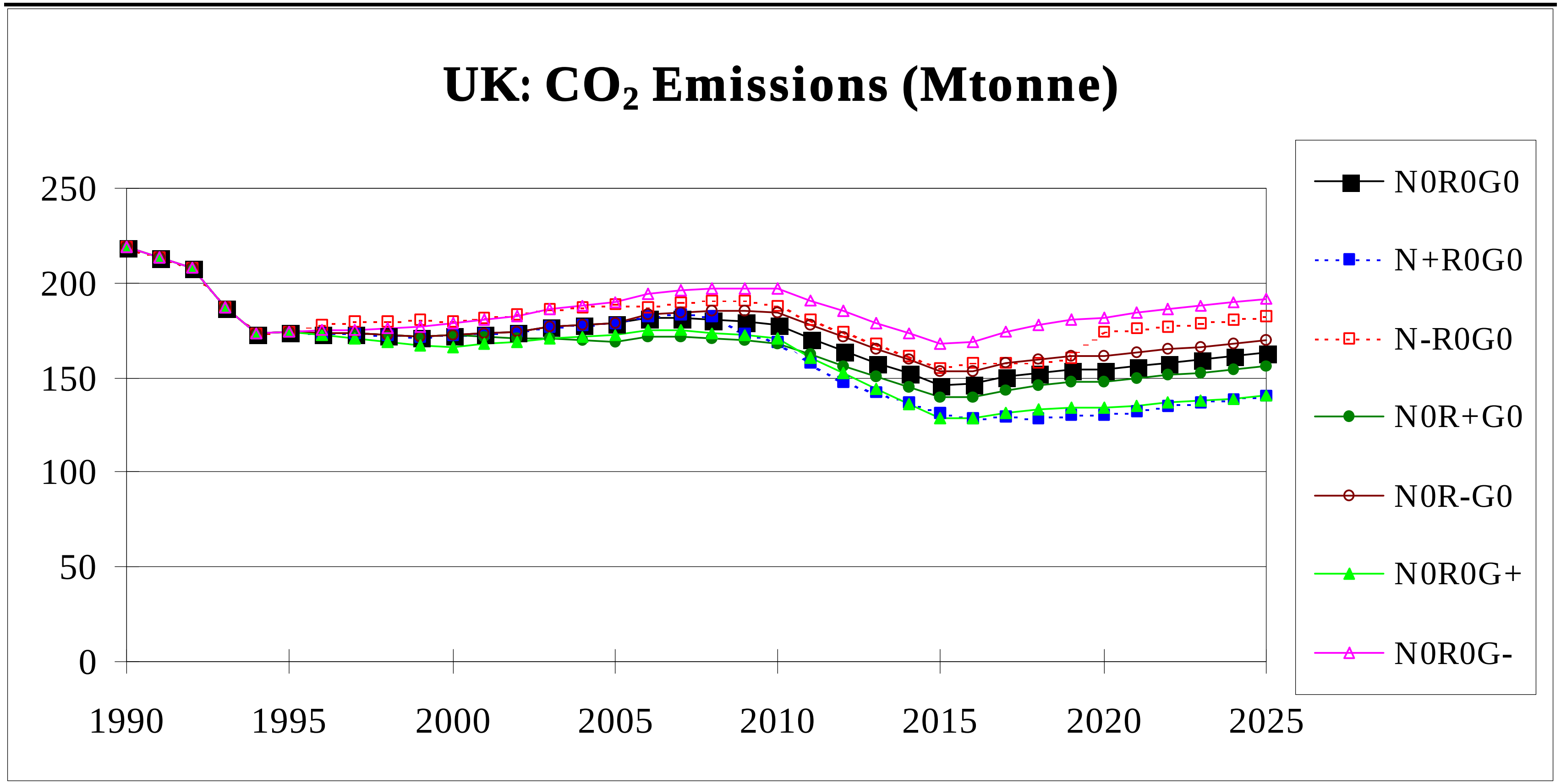


Figure 14.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

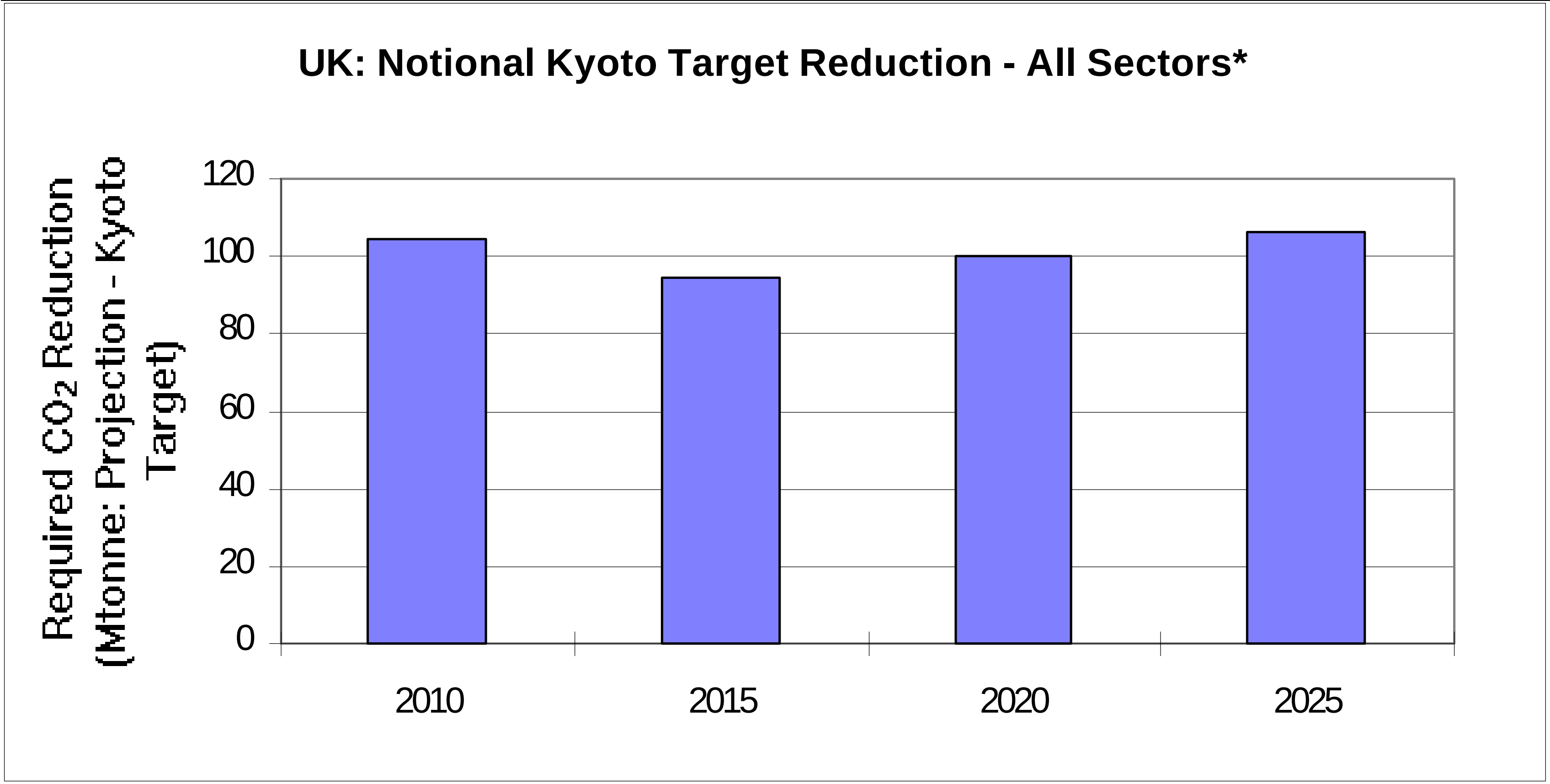


Figure 14.4 Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target (Assuming equal burdens on power generation sector and non-power generation sectors)*

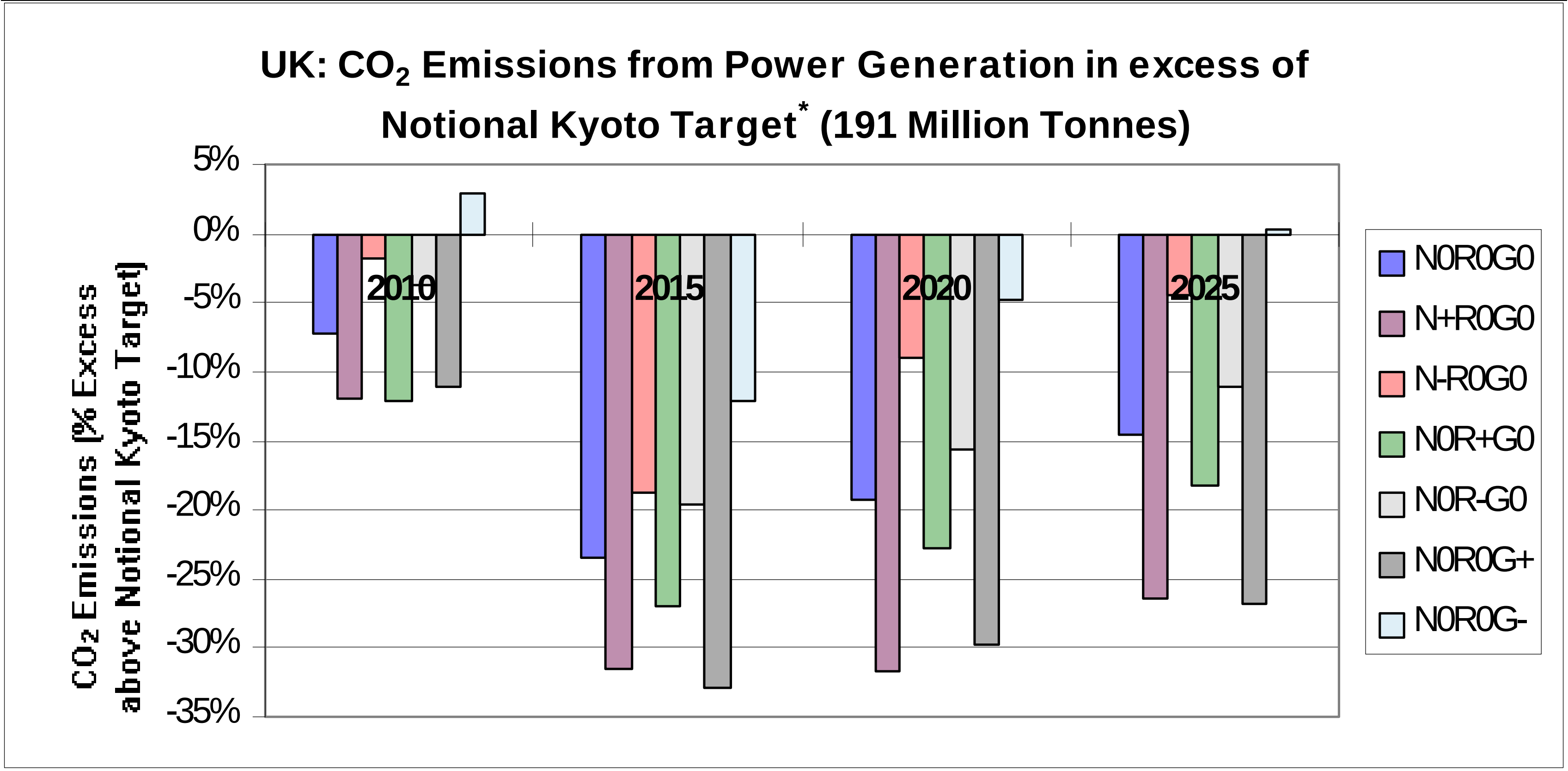


Figure 14.5 Spent Fuel Discharged

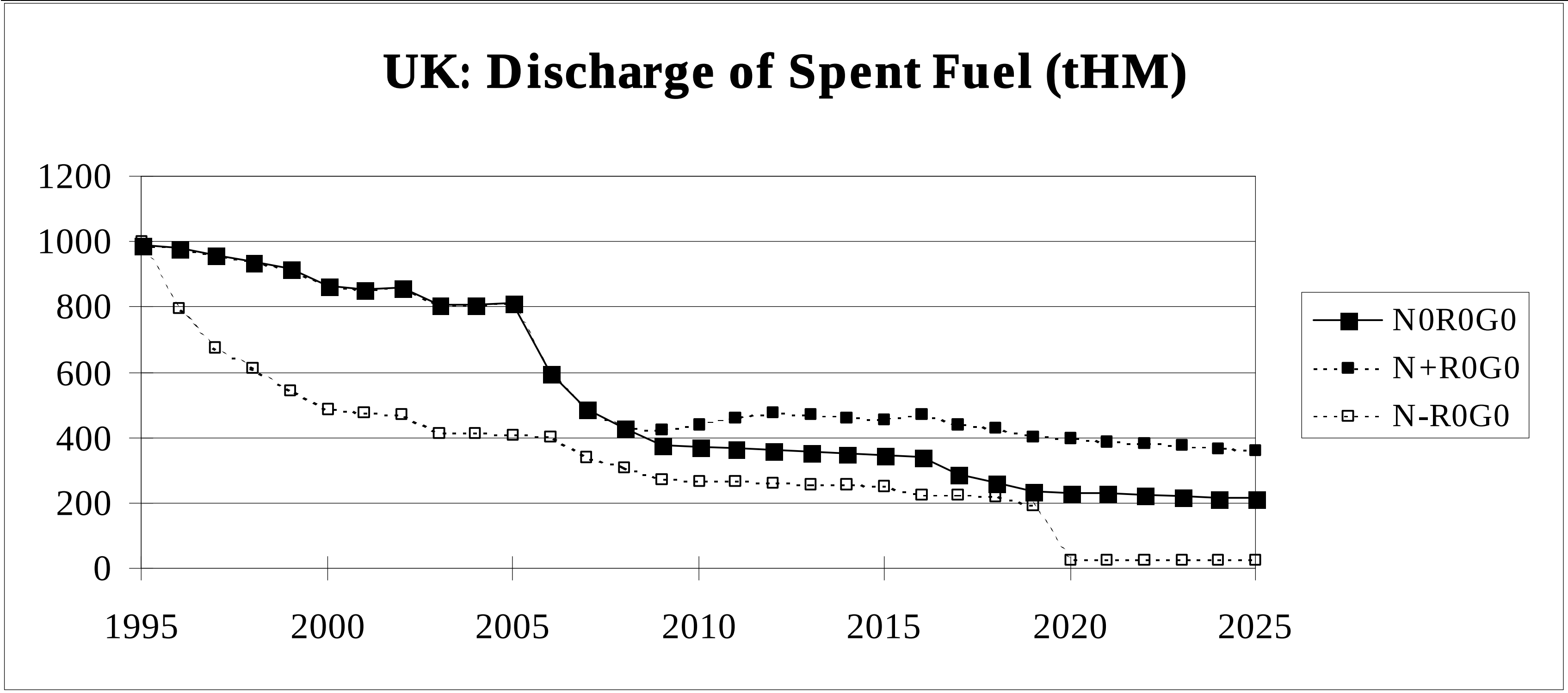


Figure 14.6 Low Level Waste (LLW/ILW)

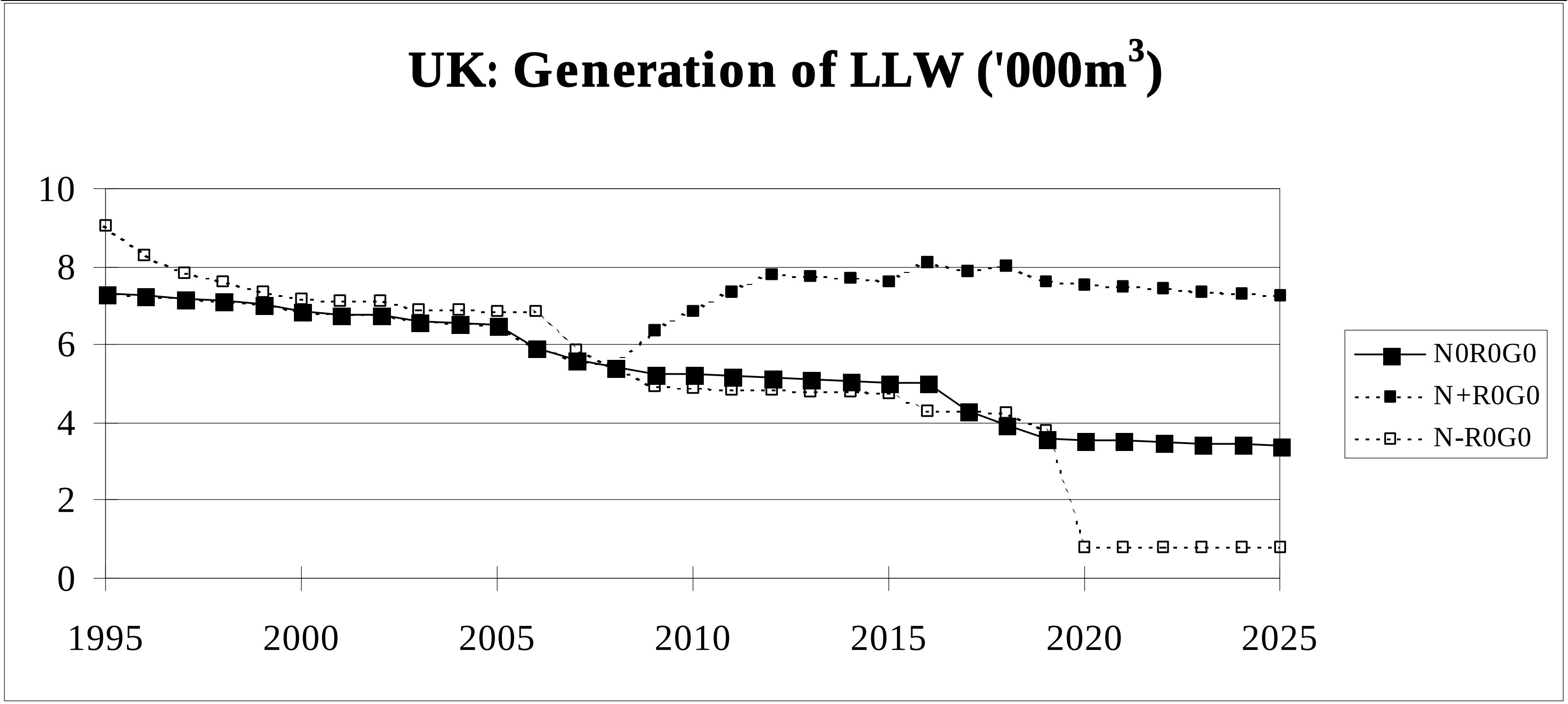


Figure 14.7 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2025

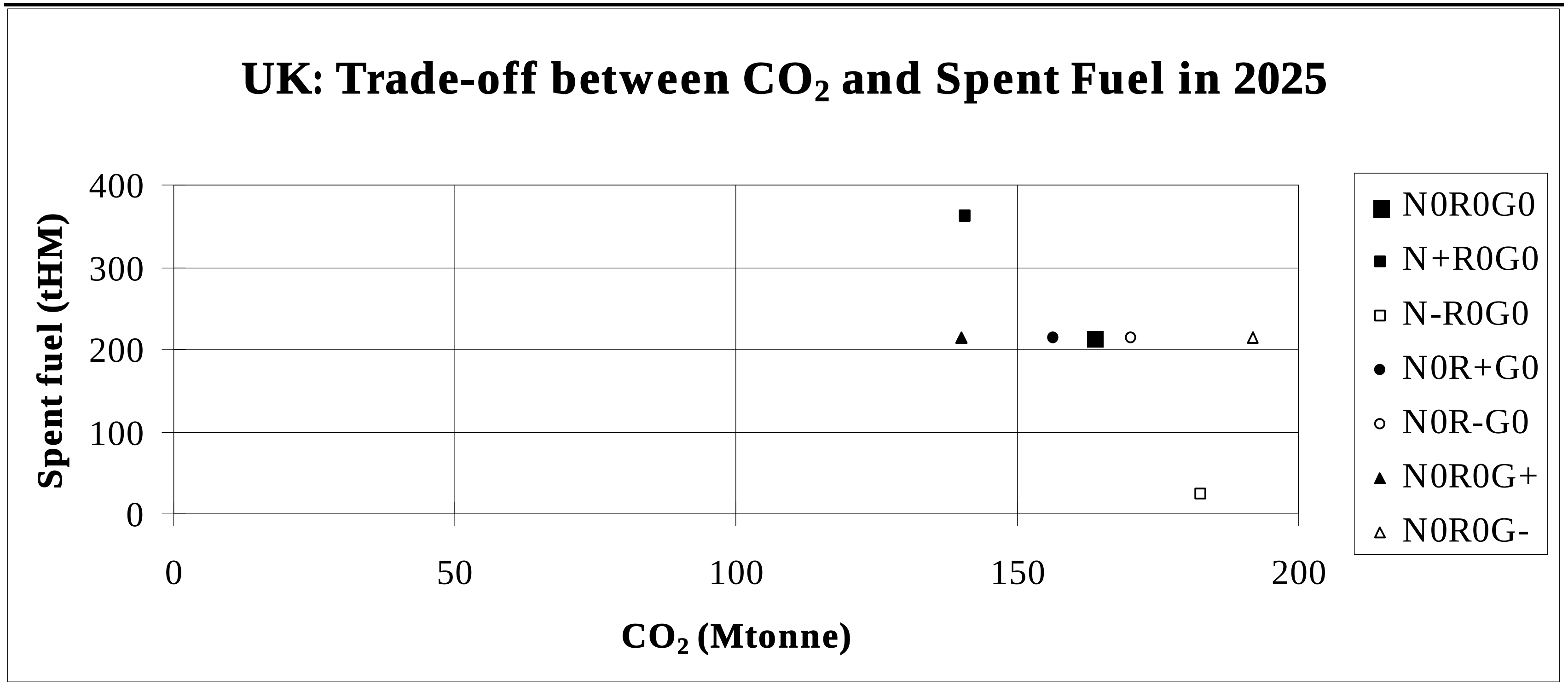
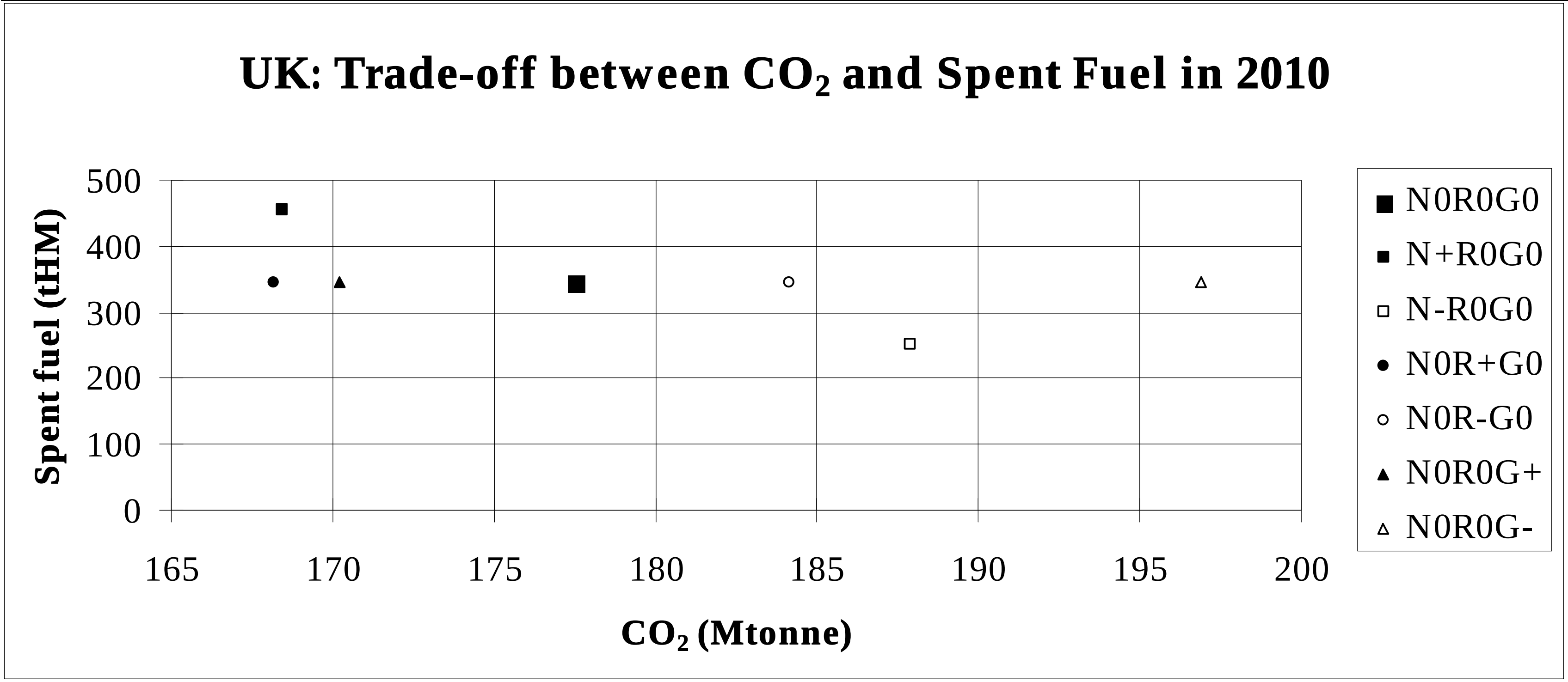


Figure 14.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel 2010



15 REPROCESSING

15.1 INTRODUCTION

Reprocessing of spent nuclear fuel has the potential significantly to reduce the volume of highly radioactive material that must be stored. Reprocessing will increase the amount of plutonium that is separated from the highly radioactive fission products and will make it conceivably more accessible to diversion. The plutonium can also be used as a nuclear fuel in mixed oxide fuel elements and this in turn reduces the inventory of free plutonium. Spent MOx fuel can be reprocessed and again recycled, but the plutonium becomes steadily contaminated with high isotopes and eventually is unusable either for commercial or military purposes. MOx recycle therefore has the advantage that plutonium is eventually made less accessible to diversion for military purposes.

Annex 1 details the methodology and assumptions concerning reprocessing and recycle of plutonium in MOx. These assumptions have been used as inputs to a model to consider reprocessing for the EU as a whole. The major assumptions made are:-

- Reprocessing capacity in the EU is 2300 tHM/year, and will remain at this level to 2025. It is further assumed that all of this capacity is available for the reprocessing of EU spent fuel;
- MOx fuel reaches 30% of fuel use by 2025;
- 0.15 m3 of vitrified fission products are produced for every tonne of heavy metal reprocessed; this figure is calculated from figures given in the ExternE report discussed and referenced in *Annex 1*;
- LLW/ILW wastes arising from reprocessing are only 0.4 m^3/TWh. This is considered to be negligible in comparison to the production of LLW/ILW from normal operation and decommissioning activities.

15.2 RESULTS

The model has been used to estimate the consequences of reprocessing and MOx use for each of three scenarios:-

1. Low Nuclear (N-R0G0);
2. Base Scenario (N0R0G0);
3. High Nuclear (N+R0G0).

Figure 15.1 shows the effects of reprocessing on spent fuel arising. Reprocessing has a highly significant effect, and reduces the cumulative spent fuel arising in 2025 from between 58,000-94,000 tHM to under 20,000 tHM in all scenarios. In the Low Nuclear scenario (N-R0G0), the accumulation of spent fuel arising is zero from 2020, this is because the back-log of spent fuel is fully reprocessed in this scenario by this date In the Base case the accumulation of spent fuel begins to fall after about 2015, suggesting that the present capacity of reprocessing would be sufficient to manage all spent fuel within the period. In the High Nuclear Scenario the accumulation of spent fuel rises steadily suggesting that more reprocessing capacity would be needed.

Figure 15.2 shows the effects of MOx use on the cumulative inventory of free plutonium, assuming that fuel is reprocessed to the limit of available reprocessing capacity. The cumulative total of plutonium arising if MOx fuel is not used, ranges from 550 to 900 tonne in 2025 depending on the scenario. If MOX is used as a fuel source, starting at 5% of the total fuel requirement and moving progressively to 30% by 2025, then the inventory of free plutonium is drastically reduced to less than 100 tonnes in the low case and effectively to zero in the base and high cases. The proportional impact is greater in the latter cases because the utilisation of plutonium in MOx is growing faster than the output from reprocessing.

Although not an intention of the modelling exercise, it is interesting to note the implications for MOx reprocessing capacity; in the Low Case the required capacity by 2025 is about 45 tonnes per year and in the High Case it is more like 800 tonnes per year. These numbers simply reflect the nuclear fuel needed in the two extremes.

The amounts of vitrified HLW produced within the period are identical in the Base and High cases, because the reprocessing activity is limited in both cases and all years by the installed capacity of reprocessing plant. The activity is always conducted at the same level and the arisings of HLW are therefore the same. The amount is estimated at between 10 and 11 thousand cubic metres, roughly equivalent in volume to a small office block. There is a slight reduction in the Low case, because eventually the reprocessing capacity works through the accumulated back-log of fuel and then reprocesses only the small annual arisings from the Low case; the production of HLW is correspondingly smaller at around 9,000 m3 over the period.

Figure 15.1 Effects of Reprocessing on Spent Fuel Arising

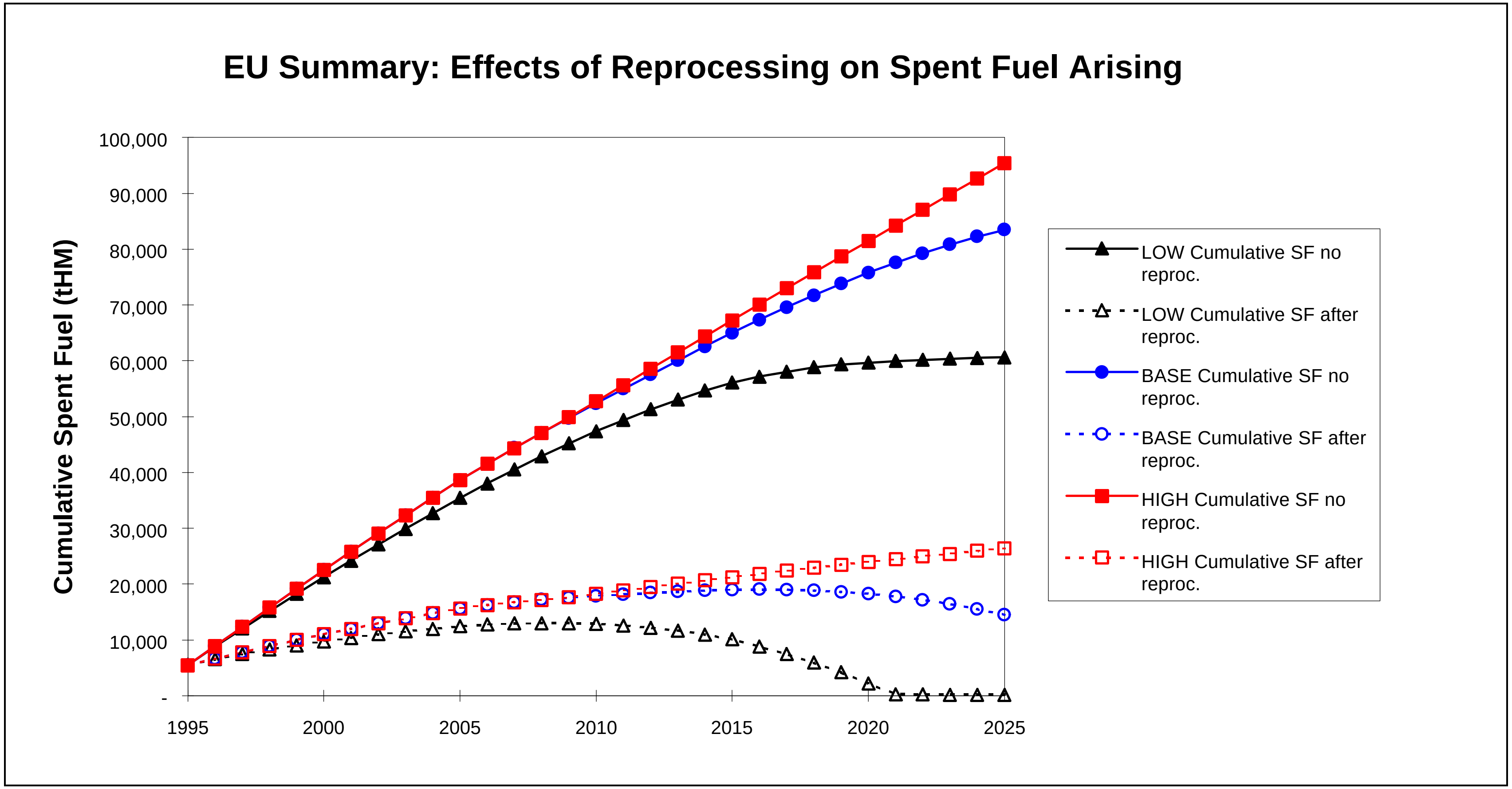
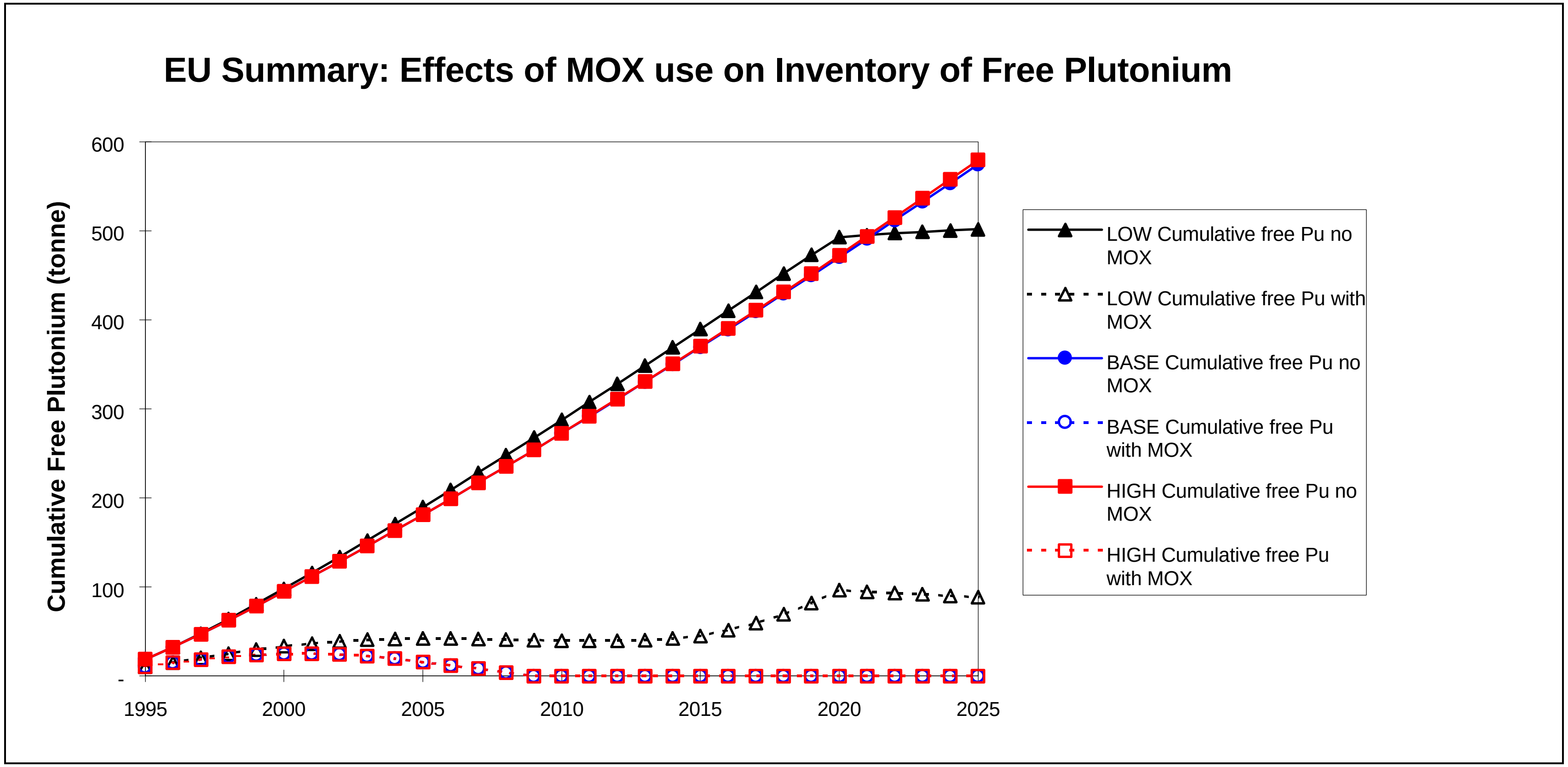


Figure 15.2 Effects of MOX use on Inventory of Free Plutonium



16 *EUROPEAN SYNTHESIS*

16.1 *CALIBRATION OF MODEL AND CHOICE OF SCENARIOS*

The scenarios are designed to be broadly consistent with the Conventional Wisdom scenario of DGXVII's *"Energy in Europe to 2020" ('EE2020')*. The energy demand forecasts are taken from that study as is the composition of existing generating plant and the timing of its retirement. The 'Conventional Wisdom' scenario denotes the 'business as usual' world, representing a conventional wisdom view of events. Economic growth gradually weakens as demographic changes mean slower growth in the labour force. Although some progress is made, many of the world's structural social and economic problems remain.

For the 8 countries with nuclear generation, the model has been calibrated against the actual performance of the individual countries' power systems in 1995. No modelling has been conducted for the other 7 countries in the EU which do not have nuclear capacity. It has been assumed that none of them will build nuclear capacity in the period to 2025. Results for the 7 non-nuclear countries have been taken directly from EE2020 (Conventional Wisdom scenario) and added the modelled results from the 8 nuclear countries in order to give results for the EU as a whole. Further scenario details are described in *Section 3.2.4.*

No major distortions were discovered between the 1995 outcome and the EE2020 study; calibration was achieved by adjustment of the demand to the actual 1995 figure. The split between hydro, nuclear and thermal has been reproduced to within a few percent. The estimated carbon dioxide emissions in 1995 are 893 million tonnes, which compares with the estimate in the *"1998 Annual Energy Review"* of 931 million tonnes. The discrepancy is largely due to the model projecting higher electricity generation from nuclear plant. Forcing the model to exactly reproduce 1995 figures would not lead to better projections of the future.

Verification has been made with DGXVII's Study *"The European Renewable Energy Study: Prospects for Renewable Energy in the EC and Eastern Europe up to 2010"* to ensure that the resource base exists to support such an expansion of renewables. UNIPEDE's *"Eurprog 1998"* Study has been used to validate capacity expansion plans.

Details of the Scenarios differ for individual countries. Generalised descriptions of the Scenarios are shown in *Table 16.1.*

Table 16.1 Description of Scenarios

Scenario	Description	Composition
N0R0G0	Base	40 year nuclear plant lifetime, two thirds of new fossil fuel build is gas. Base renewable generation.
N+R0G0	High Nuclear	40 year nuclear plant lifetime, new build of nuclear plant is undertaken to maintain nuclear at 1995 share of capacity, other factors as Base Scenario.
N-R0G0	Low Nuclear	30 year nuclear plant lifetime, no new build of nuclear plant, other factors as Base Scenario.
N0R+G0	High RETs	Renewable generation optimistic, other factors as Base Scenario.
N0R-G0	Low RETs	Renewable generation pessimistic, other factors as Base Scenario.
N0R0G+	High gas	All new fossil-fuel generation is gas fired CCGT, other factors as Base Scenario.
N0R0G-	Low Gas	One third of new fossil-fuel generation is gas fired CCGT, other factors as in Base Scenario.

16.2 RESULTS

Nuclear Capacity in the EU

Figure 16.1 shows total nuclear capacity in the EU by year. In 1995, the 125 GWE of nuclear capacity accounted for 23% of the EU's capacity of 554 GWe. In 2025, the three scenarios project that this share will be:-

- High Nuclear (N+R0G0): 164 GWe (23%)
- Base Scenario (N0R0G0): 66 GWe (9%)
- Low Nuclear (N-R0G0): 7 GWe (1%)

This is clearly a very wide range. Retaining nuclear's share of capacity would require the building of an extra 100 GWe of capacity by 2025. This must be considered highly unlikely in the current climate.

The Base scenario sees nuclear plant retired after a life-time of 40 years. By 2025, half of the EU's existing capacity will have been retired. The majority of nuclear plant was completed in the period 1970-1990. Thus it can be expected that nuclear's share of capacity will decline strongly from its 2025 value of 9% in the period 2025-2035; it will be no more than 1% by 2035.

The possibilities of such low nuclear capacity clearly has important implications on CO_2 emissions from the EU.

Emissions of Carbon Dioxide

Figure 16.2 summarises the emissions of carbon dioxide from the EU power system up to 2025 as forecast by this model.

EU CO_2 emission in 1990 were 3164 Mtonne. The most important emitters were Germany (30%), UK (18%) and Italy (12%). CO_2 emissions from the power generation sector were 964 Mtonne and represented 30% of the total EU emissions. *Table 16.2* shows 1990 emissions by country, and identifies which countries are nuclear generators.

Table 16.2 1990 CO_2 Emissions (Mtonne)

Country	**Nuclear Generator**	CO_2, All Sectors (Mtonne)	CO_2, Power Gen. (Mtonne)
Austria		56	12
Belgium	✓	111	22
Denmark		52	23
Finland	✓	52	16
France	✓	368	40
Germany	✓	978	344
Greece		72	34
Ireland		30	10
Italy		402	119
Luxembourg		10	1
Netherlands	✓	157	43
Portugal		40	15
Spain	✓	208	63
Sweden	✓	50	4
UK	✓	579	216
TOTAL	8 from 15	3164	964

CO_2 emissions from power generation fell 7% between 1990 and 1995. The model then projects that emissions will rise steadily to 2005 to reach 1100 Mtonnes. Post 2005, the effects of new plant replacing retired plant and the switch to gas reduce emissions again.

In the main Kyoto target year of 2010, the Base scenario (N0R0G0) emissions are projected to be 1000 Mtonnes, 4% above the 1990 value. The Kyoto target for all sectors is a reduction of 8%. Emissions from the High Nuclear (N+R0G0) scenario are projected to be 952 Mtonne (roughly equal to the 1990 level). Under the Low Nuclear scenario (N-R0G0), emissions are projected to be 1078 Mtonne (12% above the 1990 level).

After 2010, emissions in the Base scenario (N0R0G0) continue to decline to 2015 but then increase as electricity demand increases and nuclear plant is retired. By 2025, emissions are projected to be 1175 Mtonne, 22% above the 1990 level.

Nuclear policy has a significant impact on 2025 emissions. Supporting Nuclear power by retaining its share of capacity in those countries with nuclear generation (N+R0G0) leads to CO_2 emissions in 2025 of 926 Mtonnes (4% below the base scenario). Retiring nuclear plant early (N-R0G0) gives emissions of 1349 Mtonnes, 15% above the Base scenario and 40% above the 1990 level.

Carbon Dioxide Emissions and the Kyoto Targets

By signing the Kyoto Protocol, EU agreed to reduce emissions from 1990 levels by 8% in the year 2010. Total emissions in 1990 from all sectors were 3164 Mtonne CO_2, of which 964 Mtonne (30%) came from the power generation sector.

Assuming that 1990 levels must be met not only in 2010 but also in subsequent years, *Figure 16.3* shows the difference between projected values and the Kyoto target. Meeting the Kyoto target will require emissions reduction of 546 Mtonne (based on 2020 projections from the Conventional Wisdom scenario). Required reductions then increase to 600 Mtonne in 2015, 700 Mtonne in 2020 and 800 Mtonne in 2025. There is no clear indication of what CO_2 targets post-Kyoto will be: however, assuming that targets post-2010 will be equal to those in 2010 is useful to illustrate the challenges to be faced in the future.

Countries have the freedom to set policies to reduce carbon dioxide emissions. Assuming that each sector of the economy will have an equal responsibility towards meeting the targets, it has been assumed that the target for power generation will be to reduce emissions by 8% from the 1990 level to 885 Mtonne. Again this assumption is indicative: there are presently no specific targets for the power generation sector either for the EU as a whole or for any individual Member State.

Figure 16.4 shows how successful the EU will be in meeting this target under each of the Base (N0R0G0) and the two nuclear scenarios (N+R0G0, N-R0G0). Under the Base scenario, the EU will exceed its Kyoto target for the power sector by over 100 Mtonne in 2010, and by almost 300 Mtonne in 2025. Supporting Nuclear generators (N+R0G0) reduces excess CO_2 emissions to 70 Mtonne in 2010, then targets are very nearly met in 2015, 2020, and 2025. Supporting nuclear plant is projected to lead to emissions being 250 Mtonne less than Base scenario in 2025.

Excess emissions from retiring nuclear plant early (N-R0G0) are almost 200 Mtonne in 2010 and rise to over 450 Mtonne by 2025. In 2025, Low Nuclear scenario emissions are 170 Mtonne more than the base scenario and 420 Mtonne more than the High Nuclear scenario.

It should also be noted that targets by sector may vary widely from the national target and that all greenhouse gases are included, not only carbon dioxide.

Spent Fuel from Nuclear Plants

Figure 16.5 shows the discharge of spent fuel from nuclear plant over the period. Spent fuel arising in 1995 was 3500 tHM. Spent fuel declines in the Base Scenario to 2600 tHM in 2010 and 1250 tHM in 2025 (65% below 1995 level). In the High Nuclear scenario (N+R0G0) spent fuel arising stabilises at 2800 tHM, 20% below 1995 levels.

The Low Nuclear scenario (N-, Ro, Go) shows that effects of the retirement of nuclear plant, with steady retirement to 2010 then large amounts of retirement between 2010 and 2020. Spent fuel falls to less than 200 tHM in 2025.

Low and Intermediate Level Waste from Nuclear Plant

The discharges of LLW/ILW show a similar pattern to the discharges of spent fuel, (see *Figure 16.6*). This is because in both scenarios there are discharges that are associated with operation and discharges that are associated with decommissioning. The decommissioning discharges are spread over the life-time of the plant in both scenarios and therefore bring about higher notional discharges in the case of the low nuclear scenario, where life-times are postulated to be shorter. Similarly, in both scenarios there is assumed to be an improvement in performance; in the case of spent fuel through higher burn-ups and in the case of LLW/ILW through improved operation and maintenance practices.

The decommissioning wastes arising are proportionally larger, compared to operation, than is the case for spent fuel. Consequently, the divergence between the low nuclear scenario and the others in the earlier years is much larger. Because the LLW/ILW generated in decommissioning dominates that which arise in operation, the rather strong assumptions made about waste reduction in O&M do not pass through into an equally strong decline in annual waste production.

The divergence at the end of the period between the three scenarios parallels closely the behaviour for spent fuel. The discharges in 2025 in the high, base and low scenarios are approximately 105%, 43% and 5% of the values in 1995.

Plutonium Production

Typically 1% of spent fuel is Plutonium (before any reprocessing). *Figure 16.7* shows that Plutonium production in 1995 was 29 tonne. It remains at this level until nuclear plant is retired (from 2006 in the Low Nuclear scenario and 2016 in the Base scenario). By 2025, Plutonium production is just 2 tonne in the Low Nuclear scenario (N-R0G0) and 15 tonne in the Base scenario (N0R0G0).

Plutonium production rises from 2009 in the High Nuclear scenario (N+R0G0), corresponding to the assumed earliest date for the building of new nuclear plant. It then stabilises at 35 tonne from 2015.

The build up of plutonium raises concern over weapons production. Over the period 1995-2025 (31 years), total plutonium production is as follows:-

- Low Nuclear (N-R0G0)   594 tonne

- Base Scenario (N0R0G0) 824 tonne
- High Nuclear (N+R0G0) 975 tonne

Trade-Offs

It is evident that the environmental consequences of high and low nuclear scenarios can be represented as a trade-off between climate change, as represented by carbon dioxide emissions, and various impacts of nuclear power. These trade-offs for 2005, 2010 and 2025 can be summarised as in *Figure 16.8*, which shows each scenario as a point in a space defined by emissions of carbon dioxide along the abscissa and spent fuel along the ordinate.

The figure clearly illustrates the decision the EU can make concerning CO_2 emissions and spent fuel arising. In 2005, significant reductions in spent fuel can be made without increasing carbon dioxide emissions significantly: fuel switching to natural gas and closing inefficient older plant means nuclear generation can be replaced without significant carbon dioxide increases. In 2010, reducing spent fuel has a higher cost in terms of increased carbon dioxide.

By 2025, taking a straight line between the High Nuclear (N+R0G0) and Low Nuclear (N-R0G0) scenarios, there are differences of 423 Mtonne CO_2 emissions and 2650 tHm spent fuel. Reducing CO_2 emissions by 1 Mtonne will lead to an increase of 6.2 tHm of spent fuel. *Table 16.3* shows the differences between the two Nuclear scenarios and the Base scenario in 2025.

Table 16.3 Relative Differences between Scenarios, 2025

Scenario	**Emission / Waste Type**	**Low Nuclear**	**Base Scenario**	**High Nuclear**
Low Nuclear (N-R0G0)	CO_2 (Mtonne)	-	+174	+423
	Spent Fuel (tHM)	-	-1108	-2655
	LLW/ILW (k. m^3)	-	-27	-74
	Plutonium (tonne)	-	-13.2	-33.6
Base Scenario (N0R0G0)	CO_2 (Mtonne)	-174	-	+249
	Spent Fuel (tHM)	+1108	-	-1548
	LLW/ILW (k. m^3)	+27	-	-47
	Plutonium (tonne)	+13.2	-	-20.4
High Nuclear (N+R0G0)	CO_2 (Mtonne)	-423	-249	-
	Spent Fuel (tHM)	+2655	+1548	-
	LLW/ILW (k. m^3)	+74	+47	-
	Plutonium (tonne)	+33.6	+20.4	-

Figure 16.1 EU Nuclear Generation Capacity 1995-2025

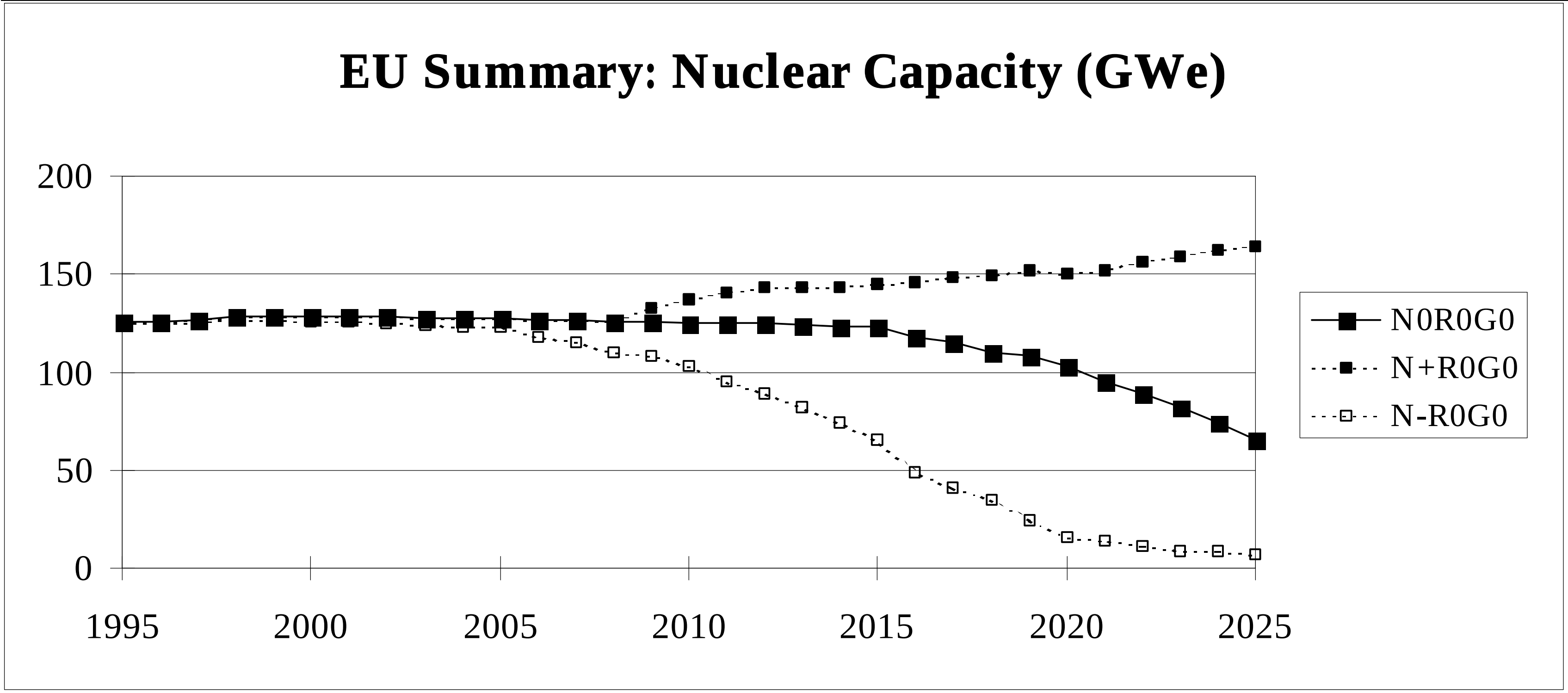


Figure 16.2 Carbon Dioxide Emissions from Power Generation

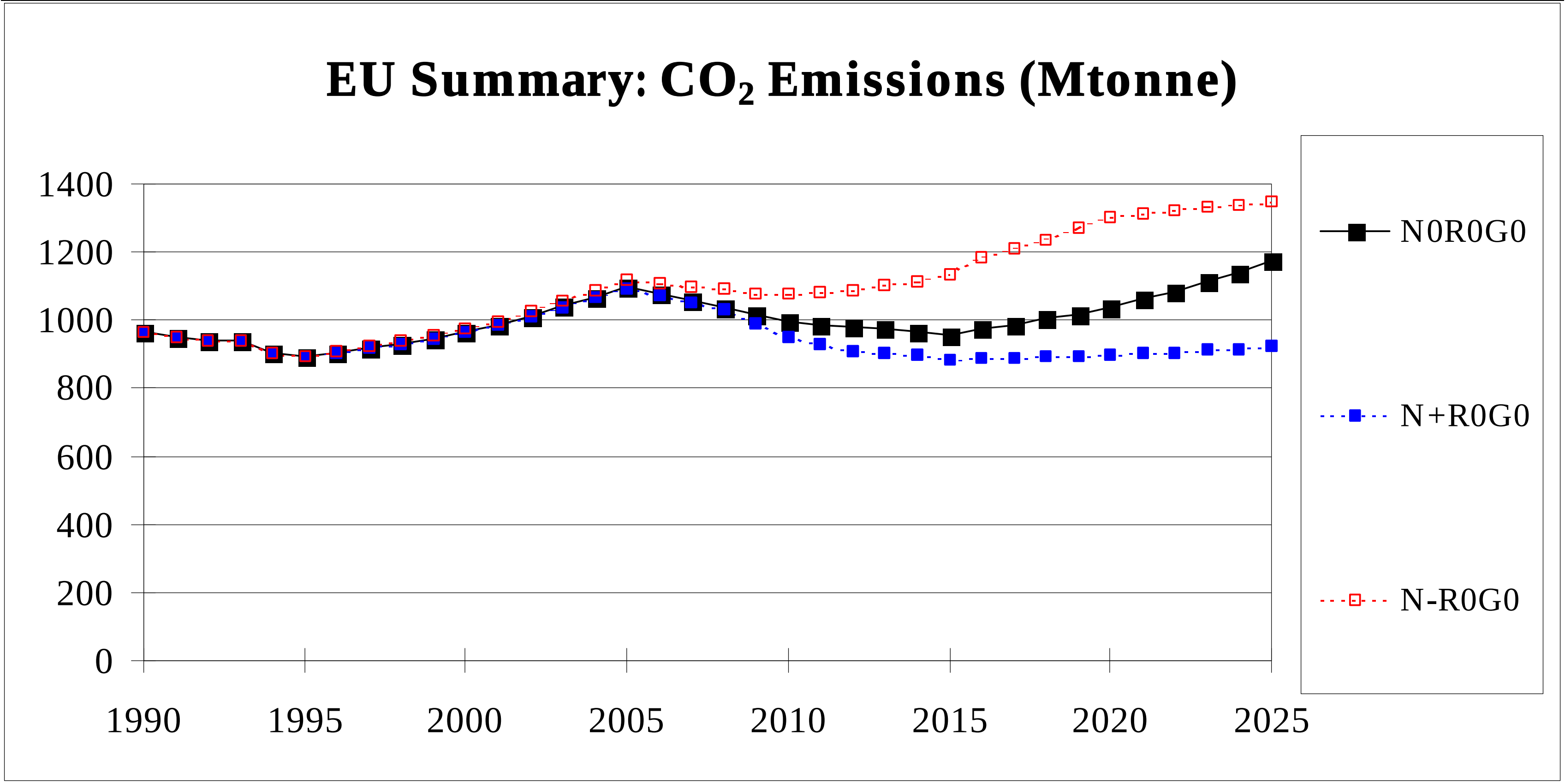


Figure 16.3 Notional Kyoto Target Reductions - All Sectors (Assuming target in years post-2010 = target in 2010)*

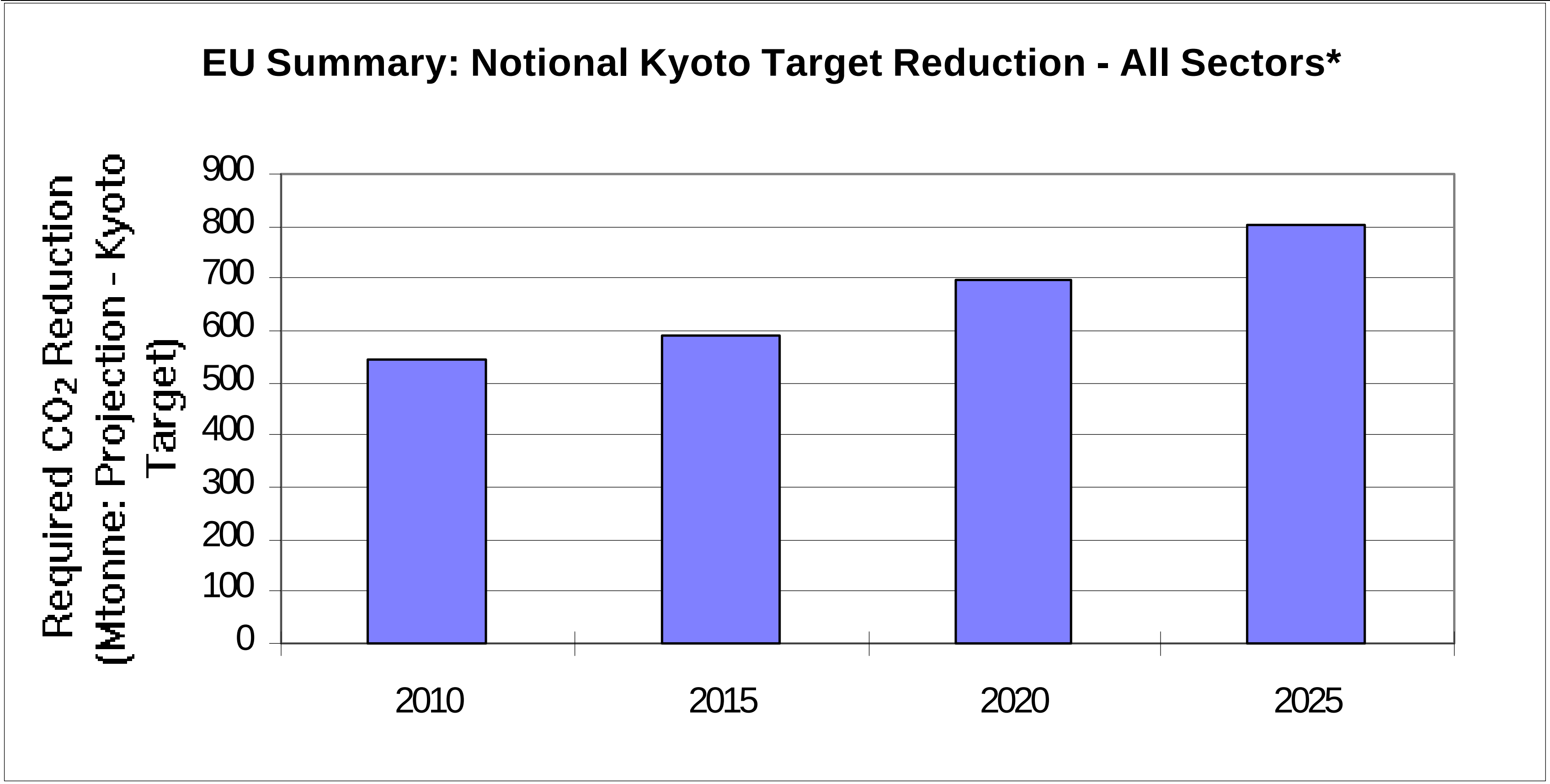


Figure 16.4 Carbon Dioxide Emissions from Power Generation in excess of Notional Kyoto Target (Assuming equal burdens on power generation sector and non-power generation sectors)*

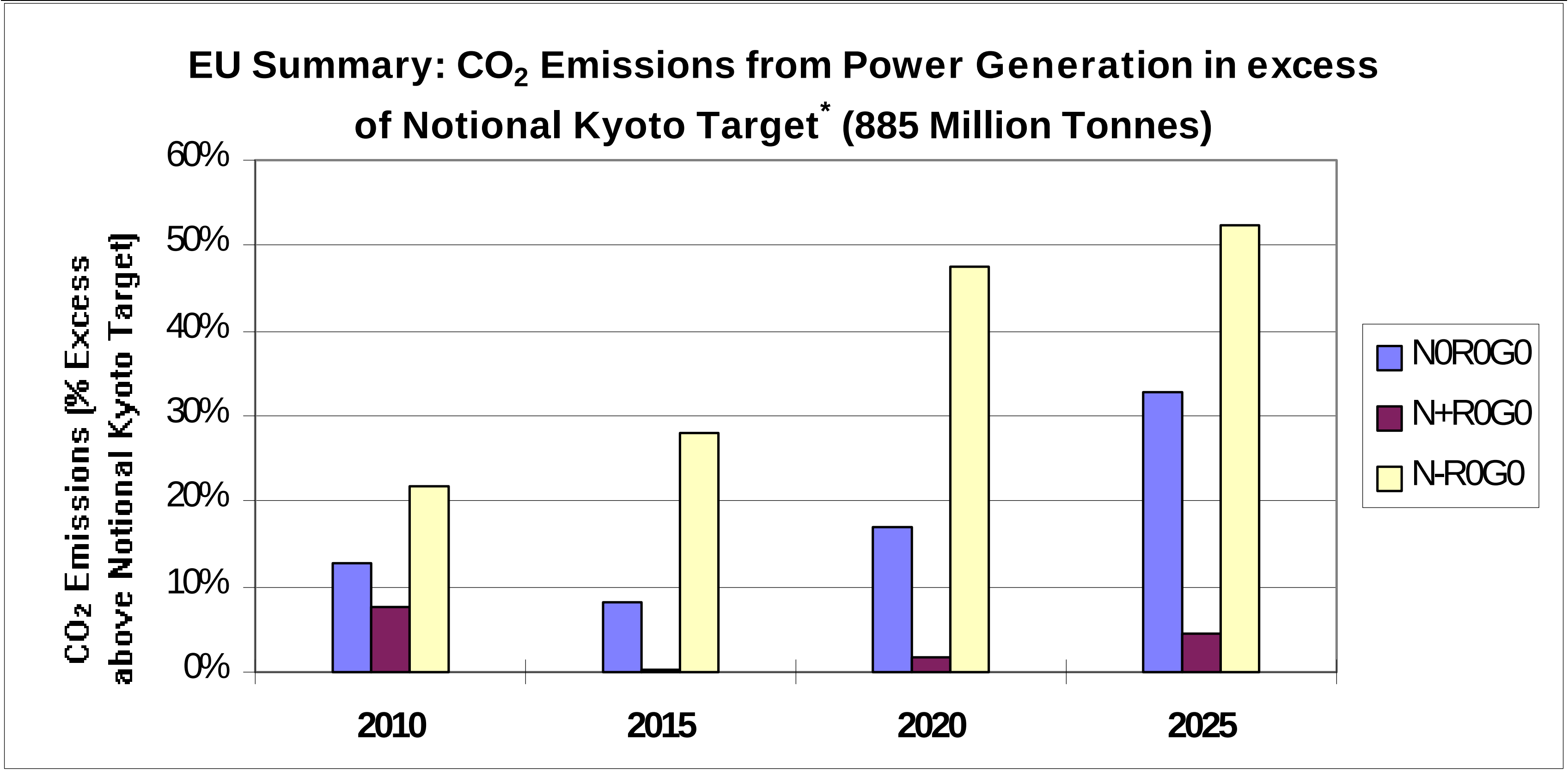


Figure 16.5 Spent Fuel Discharged

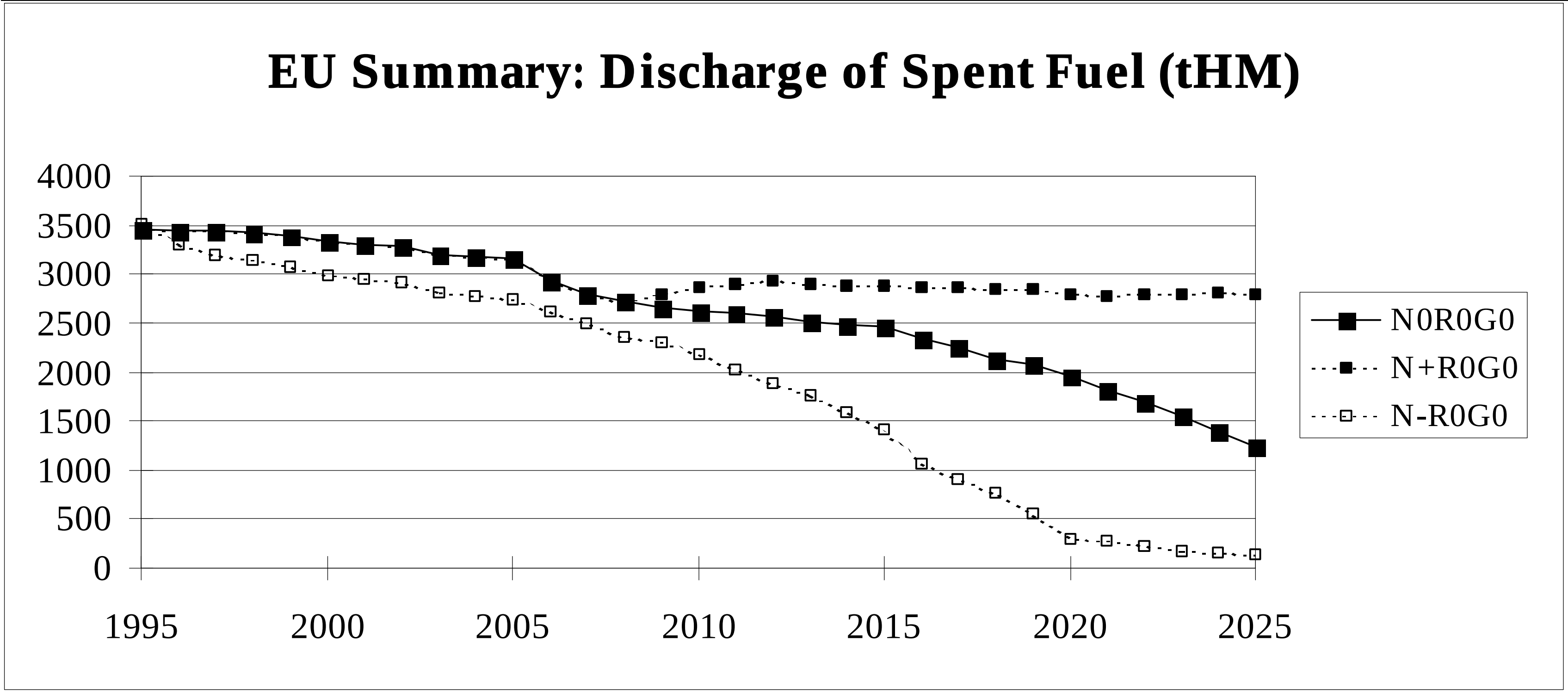


Figure 16.6 Low Level Waste (LLW/ILW)

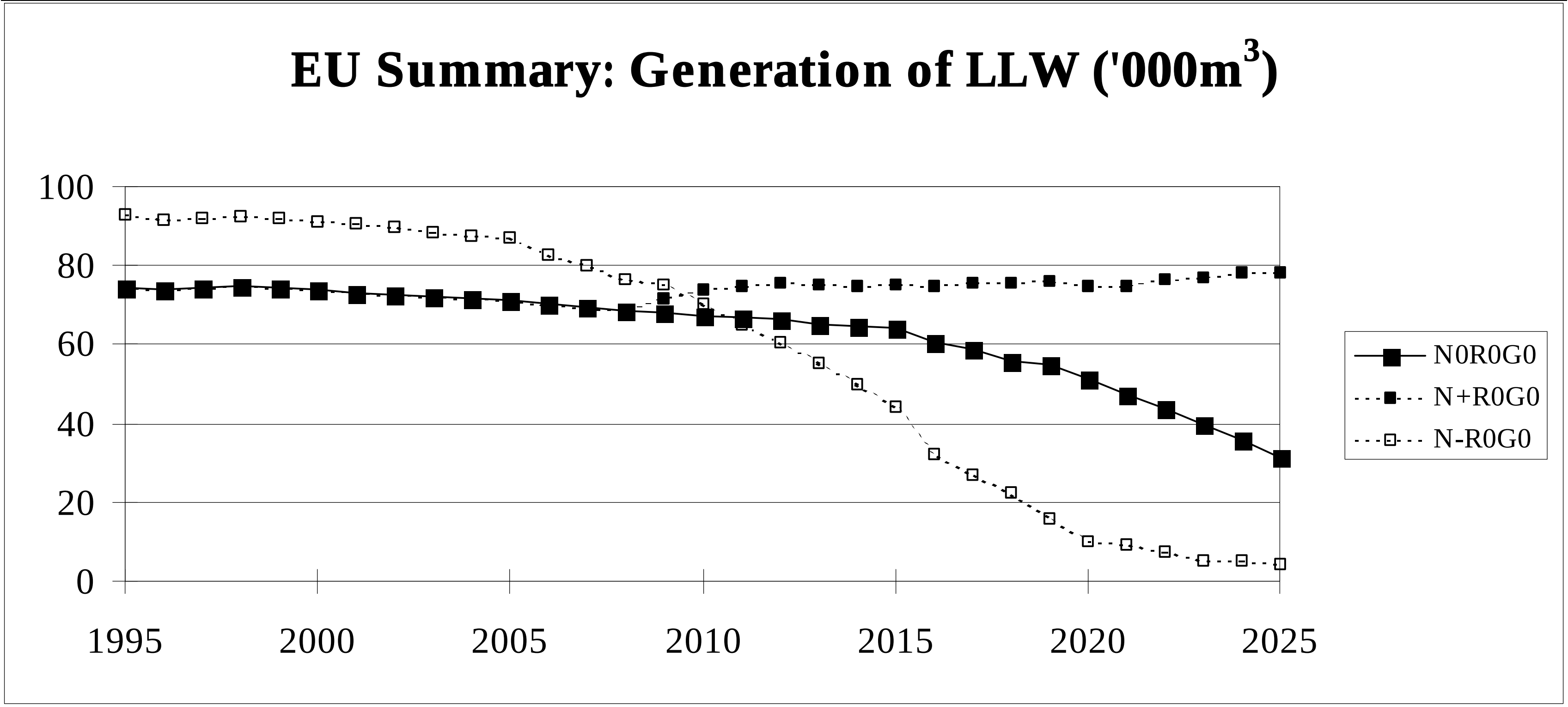


Figure 16.7 Plutonium Arising (tonne)

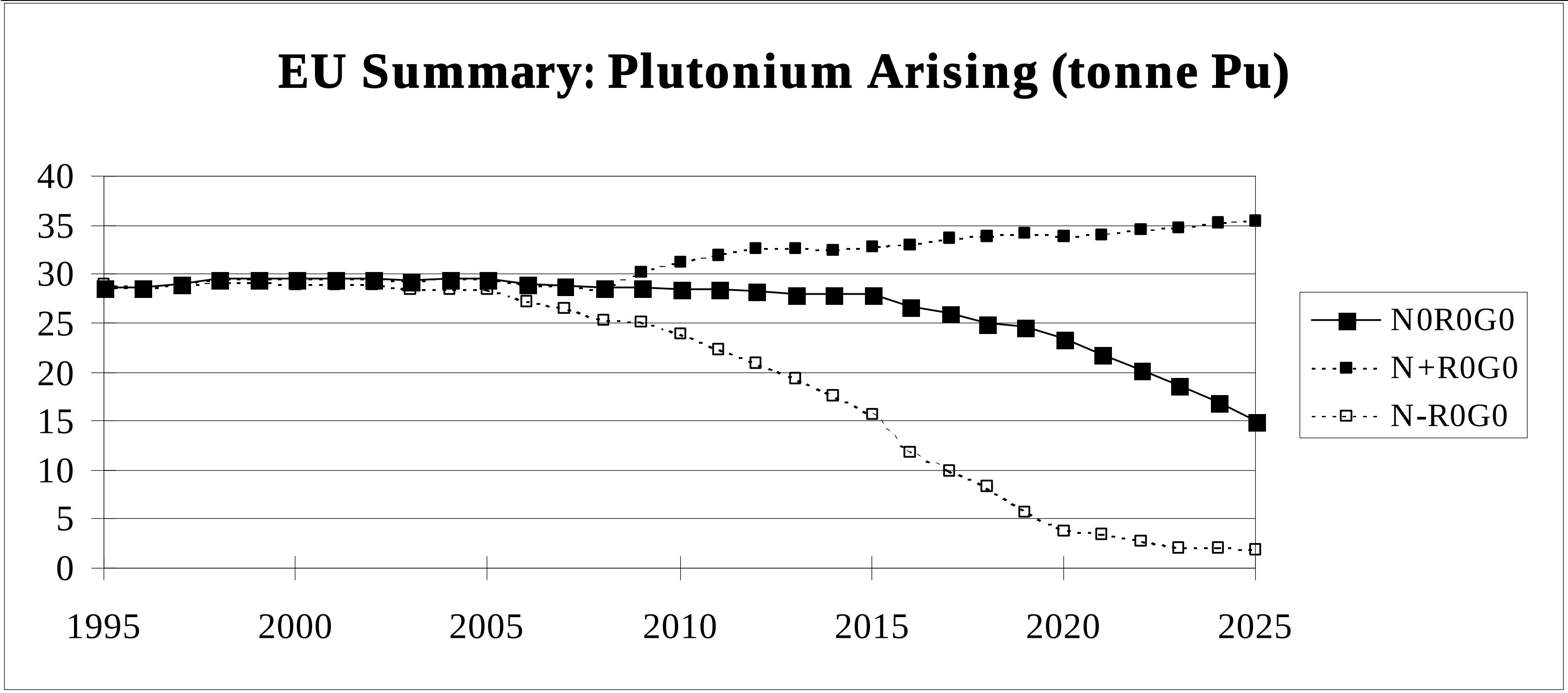
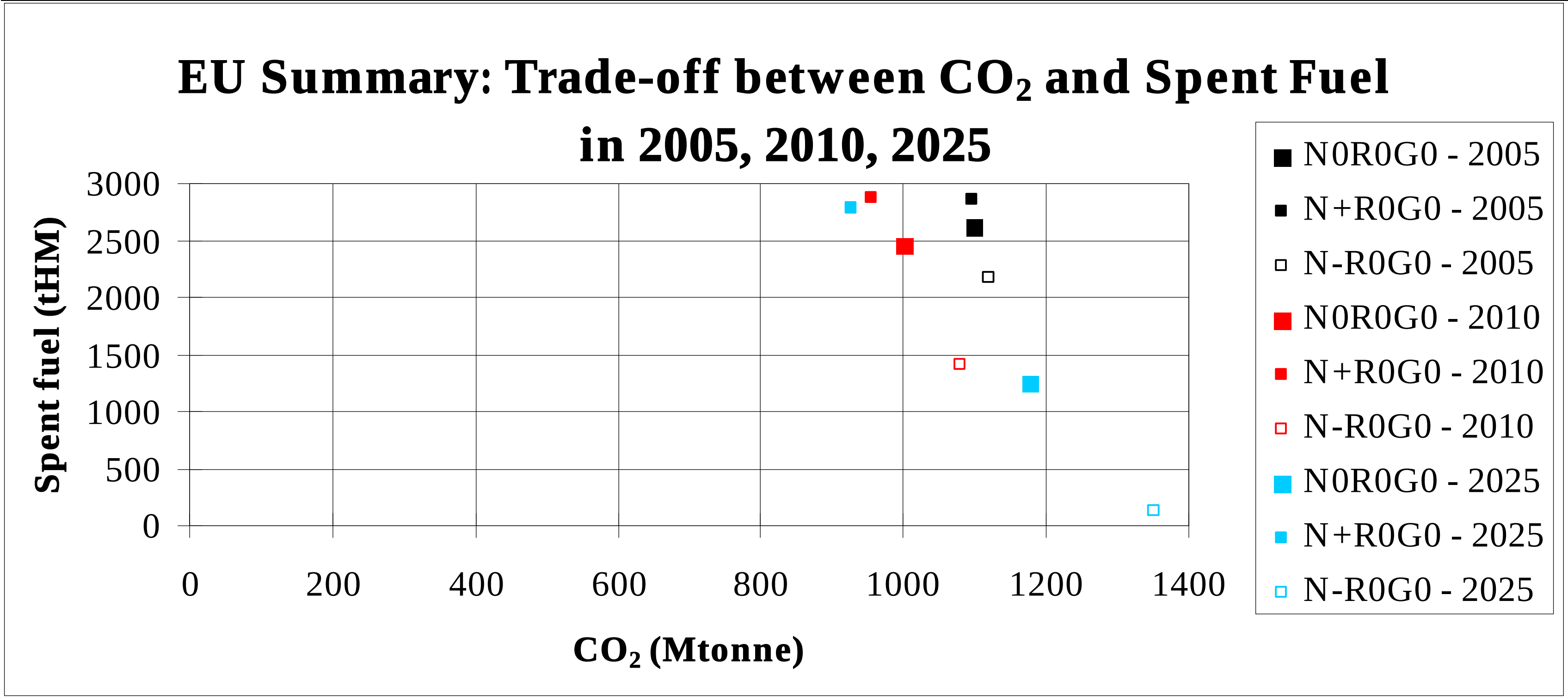


Figure 16.8 Trade-Off Between Carbon Dioxide Emissions and Spent Fuel



17 CONCLUSIONS

The major conclusions are as follows:

1. In 1995, the 125 GWe of nuclear capacity accounted for 23% of the EU's capacity of 554 GWe.

2. In 2025, the three scenarios project that this share will be:-

- High Nuclear (N+R0G0): 164 GWe (23%)
- Base Scenario (N0R0G0): 66 GWe (9%)
- Low Nuclear (N-R0G0): 7 GWe (1%)

3. This is clearly a very wide range. Retaining nuclear's share of capacity would require the building of an extra 100 GWe of capacity by 2025. This must be considered highly unlikely in the current climate.

4. The Base scenario sees nuclear plant retired after a life-time of 40 years. By 2025, half of the EU's existing capacity will have been retired. The majority of nuclear plant was completed in the period 1970-1990. Thus it can be expected that nuclear's share of capacity will decline strongly from its 2025 value of 9% in the period 2025-2035; it will be no more than 1% by 2035.

5. EU CO_2 emission in 1990 were 3164 Mtonne. The most important emitters were Germany (30%), UK (18%) and Italy (12%).

6. CO_2 emissions from the power generation sector were 964 Mtonne and represented 30% of the total EU emissions.

7. In the main Kyoto target year of 2010, the Base scenario (N0R0G0) emissions are projected to be 1000 Mtonnes, 4% above the 1990 value. The Kyoto target for all sectors is a reduction of 8%. Emissions from the High Nuclear (N+R0G0) scenario are projected to be 952 Mtonne (roughly equal to the 1990 level). Under the Low Nuclear scenario (N-R0G0), emissions are projected to be 1078 Mtonne (12% above the 1990 level).

8. After 2010, emissions in the Base scenario (N0R0G0) continue to decline to 2015 but then increase as electricity demand increases and nuclear plant is retired. By 2025, emissions are projected to be 1175 Mtonne, 22% above the 1990 level.

9. Nuclear policy has a significant impact on 2025 emissions. Supporting Nuclear power by retaining its share of capacity in those countries with nuclear generation (N+R0G0) leads to CO_2 emissions in 2025 of 926 Mtonnes (4% below the 1990 value). Retiring nuclear plant early (N-R0G0) gives emissions of 1349 Mtonnes, 15% above the Base scenario and 40% above the 1990 level. This is a major conclusion: the problems of limiting carbon dioxide emissions in the EU and its Member States post-2010 increase in severity.

10. Meeting the Kyoto target for all sectors will require emissions reduction of 546 Mtonne in 2010 (16%) [based on EE2020 projections from the Conventional Wisdom scenario]. There are no targets for years post-2010 at present. Assuming, for indicative purposes, that targets post-2010 are set equal to those in 2010, required reductions increase to 600 Mtonne in 2015 (17%), 700 Mtonne in 2020 (19%) and 800 Mtonne in 2025 (22%).

11. There are no targets for carbon dioxide emissions from the power generation sector in the EU or in its Member States. Again assuming, for indicative purposes, that all sectors must contribute equally to emissions reductions and that targets for all sectors post-2010 equal those for 2010, the EU will exceed its notional targets for the power sector by over 100 Mtonne in 2010 (13%), and by almost 300 Mtonne in 2025 (33%). Supporting Nuclear generators (N+R0G0) reduces excess CO_2 emissions to 70 Mtonne in 2010 (8%), then targets are very nearly met in 2015, 2020, and 2025. Supporting nuclear plant is projected to lead to emissions being 250 Mtonne less than Base scenario in 2025. Excess emissions from retiring nuclear plant early (N-R0G0) are almost 200 Mtonne in 2010 (22%) and rise to over 450 Mtonne by 2025 (52%). In 2025, Low Nuclear scenario emissions are 170 Mtonne more than the base scenario and 420 Mtonne more than the High Nuclear scenario.

12. Spent fuel arising in 1995 was 3500 tHM. Spent fuel declines in the Base Scenario to 2600 tHM in 2010 and 1250 tHM in 2025 (65% below 1995 level). In the High Nuclear scenario (N+R0G0) spent fuel arising stabilises at 2800 tHM, 20% below 1995 levels.

13. LLW discharges in 2025 in the high, base and low scenarios are approximately 105%, 43% and 5% of the values in 1995 (74,000 m^3).

14. The increase in the inventory of plutonium, both that contained within spent fuel elements and that separated after reprocessing, raises concerns of proliferation. Over the period 1995-2025 (31 years), total plutonium production is as follows:-

- Low Nuclear (N-R0G0) 594 tonne
- Base Scenario (N0R0G0) 824 tonne
- High Nuclear (N+R0G0) 975 tonne

15. Relative differences between the three scenarios are shown in *Table 17.1*. Reducing CO_2 emissions by 1 Mtonne will lead to an increase of 6.2 tHm of spent fuel.

Table 17.1 Relative Differences between Scenarios, 2025

Scenario	Emission / Waste Type	Low Nuclear	Base Scenario	High Nuclear
Low Nuclear (N-R0G0)	CO_2 (Mtonne)	-	+174	+423
	Spent Fuel (tHM)	-	-1108	-2655
	LLW/ILW (k. m^3)	-	-27	-74
	Plutonium (tonne)	-	-13.2	-33.6
Base Scenario (N0R0G0)	CO_2 (Mtonne)	-174	-	+249
	Spent Fuel (tHM)	+1108	-	-1548
	LLW/ILW (k. m^3)	+27	-	-47
	Plutonium (tonne)	+13.2	-	-20.4
High Nuclear (N+R0G0)	CO_2 (Mtonne)	-423	-249	-
	Spent Fuel (tHM)	+2655	+1548	-
	LLW/ILW (k. m^3)	+74	+47	-
	Plutonium (tonne)	+33.6	+20.4	-

16. Reprocessing has a significant effect on the accumulated volumes of spent fuel, and reduces the total in 2025 from between 60,000-95,000 tHM to under 30,000 tHM even in the High scenario. In the Low Nuclear scenario the back-log of accumulated spent fuel is fully reprocessed by 2020.

17. The cumulative total of plutonium arising if MOx fuel is not used, ranges from 550 to 900 tonne in 2025 depending on the scenario. If MOX is used as a fuel source, starting at 5% of the total fuel requirement and moving progressively to 30% by 2025, then the inventory of free plutonium is drastically reduced to less than 100 tonnes in the low case and effectively to zero in the base and high cases. The proportional impact is greater in the latter cases because the utilisation of plutonium in MOx is growing faster than the output from reprocessing. This ignores the very large stocks of plutonium that will arise from the decommissioning of nuclear weapons.

GLOSSARY OF TERMS

Term	Definition
Base Load Plant	Plants that are despatched preferentially and therefore operate all the year round; the amount of such plant will depend on the extent to which load is present all the year round; this constitutes the base load; nuclear plant are base load plants
Burn-up	The amount of thermal energy produced by a fuel element in a nuclear reactor overt he life of the element, generally expressed in GW-days per tonne of heavy metal originally present, i.e. GWd/tHM
CCGT	Combined Cycle Gas Turbine - a gas turbine that rejects heat into a steam cycle; characterised by low unit capital costs and high operating efficiencies
CHP	Combined Heat and Power - the simultaneous production of heat and power
Despatch	The control of a set of generating plants to ensure that within certain system constraints, electricity is always generated at the lowest cost.
EE2020	The Energy in Europe 2020 study conducted by the European Commission
External Costs	The costs of an activity that do not represented by any financial transaction; the costs of damage to the environment by emissions of pollutants are generally external costs.
Fissile plutonium	These are the isotopes of plutonium that are fissile within a reactor and have therefore commercial value
Free Plutonium	This term is used in the report to indicate plutonium that has been separated from the spent fuel, but not recycled; only plutonium from the civil programme is included in this inventory
Generation Curve	The generation curve shows the operating hours all generating plant over a period stacked in order of operating costs; the envelope approximates to a stretched version of the LDC on a narrower base
High Level Waste (HLW)	High Level Waste is waste that exceeds specified levels of radio-activity; the main sources are reprocessing of spent fuel; spent fuel if it is not reprocessed and some waste from decommissioning
Intermediate Level Waste (ILW)	ILW is all radioactive waste that is not included in LLW and HLW
Kyoto Protocol (targets)	The Kyoto protocol commits the signatories to actions to reduce emissions of carbon dioxide; the most restrictive requirements are those on developed countries that require reductions in 2020 with respect to emission levels in 1990
LILW	LLW and ILW are stored in the same or similar disposal sites; they are therefore for the purposes of

	this study combined Low and Intermediate Level Waste (LILW)
Load Duration Curve (LDC)	The LDC is a representation of the variation in a load over a specified period; a point on the curve indicates the proportion of the period for which load exceeds a specified value
Load Factor	The total load over a period divided by the peak load in the period multiplied by the number of hours in the period; it provides a measure of the overall variation of the load within a period and therefore the likely utilisation of generating plant installed to match the load
Low Level Waste (LLW)	Low Level Waste is radioactive waste that does not require additional shielding for handling and transportation, because of its low radionuclide content
Merit Order	The ranking of generating plants by unit operating costs - a high merit plant has low operating cost; generally plants are despatched in order of operating cost so that load is served at lowest overall cost
Mid Merit Plant	Plant that is situated in the middle of the merit order and operates part of the year and / or day; often this is fossil-fuel fired plant that was installed earlier as base-load plant, but has since been displaced in the merit order by new base load plant
MOx (Mixed Oxide Fuel)	Plutonium can be separated from spent fuel and reused as the oxide in new fuel elements generally also containing uranium; these are mixed oxide fuel elements
Peak Load	The maximum value of a load in a given period; often used loosely to indicate the maximum load on the combined power system over the year
Power (System) Planning Model	A numerical representation of load and capacity on a power system, with an algorithm for calculating the production cost from a variety of plant configurations and possibly a mechanism for selecting a least cost expansion plan
Scenario	A self-consistent set of assumptions defining a possible future state
Spent Fuel	Nuclear fuel elements at the end of their useful life are taken out of the reactor and constitute spent fuel; spent fuel contains isotopes of uranium, plutonium and higher actinides along with fission products and structural components

18 MODELLING METHODOLOGY

18.1 POWER SYSTEM PLANNING

The Generation Curve

Power system planning requires a model of load, a model of capacity and a basis for combining the two to calculate the production cost of serving that load with that capacity. A suitable expansion plan over a future period is then selected to minimise the total future costs. Often, but not necessarily this selection is made by an optimisation algorithm.

It is important in making this selection to ensure that the expansion trajectories that are considered have similar reliability. Otherwise an expansion plan that has low cost and poor reliability will be unjustifiably preferred to a plan that has higher costs and higher reliability.

The usual model of load in power system planning is the load duration curve (LDC). This has convenient mathematical properties and is a good choice for fully fledged power system studies. With the methods of probabilistic simulation that are normally used for production costing it is possible also to generate reliability levels for the system and to ensure that alternative expansion plans have similar levels of reliability. Dynamic programming is normally used as the optimisation algorithm.

Such exercises are complex and expensive to perform and lack transparency. For the purposes of this study a simpler simulation method with heuristic optimisation was used based upon the concept of a generation curve. Load duration curves have several disadvantages in simpler power system simulation because it is hard to deal with reliability, as discussed above, and the impact of plant outages on the production cost. An alternative is adopt the generation curve as the load model. The generation curve shows the operating hours of all generating plant over a period stacked in order of operating costs; the envelope approximates to a stretched version of the LDC on a narrower base. The production from a given plant can then be obtained by integrating under the generation curve between the capacity limits corresponding to the upper and lower bounds marking the position of the plant in the stack. The production cost can then be obtained by multiplying the output by the operating cost and summing over all plant.

The disadvantage of this approach is that the generation curves are normally an output of power system planning and not obtainable without considerable effort. In this case the generation curves in the base year and in the future were inferred from the results of the EE2020 model.

This procedure has some deficiencies but it should be remembered what purpose the power system planning serves in the present exercise. The intention is to calculate the savings in carbon dioxide that would be realised by different nuclear scenarios. This requires a detailed modelling of the nuclear stock, which is done in this methodology as described elsewhere. To a first approximation the savings in carbon dioxide could be estimated by subtracting the renewable component from the remaining non-nuclear generation and then assuming a fuel mix for the residual generation from fossil fuels. This procedure would give a reasonable first estimate.

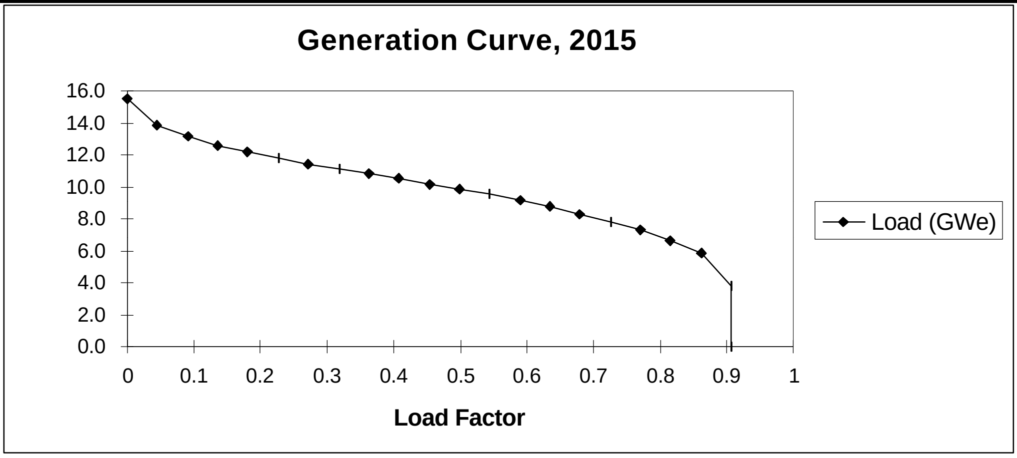
The power system planning is necessary mainly to improve upon the calculation of the fossil-fuel burn by allowing for the second order effects that arise from the timing of the despatch, principally of the fossil-fuel units themselves, but also of renewable units that can have a knock-on effect on the thermal plant. These calculations will be necessarily performed in the context of great uncertainty regarding the future fossil-fuel mix (among other things). There is therefore no point in adopting elaborate power system planning models that will refine the conclusions by orders of magnitude less than the major uncertainties that arise from matters quite beyond the powers of more refined methodologies to solve.

For these reasons we are confident that the transparent, simple methodology described here is to be preferred to more complex models that lack transparency and whose greater precision is of no value in this context.

An Example

Figure A1.1 shows the generation curve for Belgium in 2015 inferred from the detailed outputs of the EE2020 Study. There is a peak system capacity of almost 16 GW. At the other end of the curve, there is a load of almost 4 GW at the maximum load factor of 0.91 (this represents the nuclear plant). The area under the curve represents the total electricity generated in Belgium in 2015.

Figure A1.1 Generation Curve, 2015, Belgium



The model takes this generation curve and decides which plant should generate electricity. Firstly, the electricity generated from non-despatchable plant (renewables and CHP) is calculated and subtracted from the generation curve. Despatchable plant (thermal and nuclear) is then despatched in order to meet the remainder of the generation. This competitive plant is despatched in merit order. The merit order ranking is set in the database and is determined by a specified ranking of expected operating costs explicit costs of operation are not made. From *Figure A1.1*, it can be seen that the first plant despatched (that with the lowest operating cost) will have a load factor of 91%; the final plants despatched (those from 12 - 16 GW) will have a load factor of approximately 10%. Using these load factors, electricity generated by plant type is readily calculated. Emissions factors can then be applied to the fuels consumed by the plant types to give CO_2 emissions and waste arising (see *Section 5* for details).

There are several advantages of using generation curves as the basis for the study. The most important advantage is, as described above, that all reserve, reliability and load curve shape characteristics are implicitly contained within the curve and thus do not need to be considered exogenously. Furthermore, import and export of electricity do not be considered and added / subtracted to a country's demand: they are already contained within the generation curve.

Generation of Results

In common with other power planning models, the model developed takes databases, scenarios and generation curves representing 5 year intervals and produces results at 5 year intervals. The model's base year is 1995, and it has been calibrated against results from *DGXVII's 1998 Annual Energy Review*. Results are then produced for the years 2000, 2005, 2010, 2015, 2020 and 2025.

The model is used to determine important characteristics of the power systems of the member states as they evolve, notably:

- the capacity factor of nuclear plant;

- the composition of the fossil-fuel burn and therefore the carbon intensity of non-nuclear emissions.

These determinations are taken from the five yearly results and interpolated for the intervening years. This procedure is sufficient, because these are relatively slowly changing characteristics of the system.

An example is now given based on this method. *Table A1.1* illustrates the results.

1. Total Generation is known for the years 1995, 2000, ...2025 from the EE2020 data. Projections for intervening years are made by assuming that the annual rate of increase between 5 year points (1995 and 2000, 2000 and 2005, etc) is constant. Thus the annual increase between 1995 and 2000 is +0.5%/year. This assumption models reality well, and will not lead to any significant error in the results.

2. Available nuclear capacity can be calculated on the basis of plant age, lifetime extension, new build, etc. Since this is the most important factor in the calculation of the final result this calculation is made on an ANNUAL basis. It is of course subject to uncertainty - knowing with certainty whether a particular plant will operate for 38, 39 or 40 years is not possible.

3. Multiplying nuclear capacity by nuclear load factor gives electricity generated by nuclear plant, again on an annual basis.

4. Subtracting nuclear generated electricity from total generation gives electricity generated by fossil fuel and renewable plant. These plants are responsible for CO_2 emissions.

5. The CO_2 emissions factor for non-nuclear plant is calculated using the equation:-

   non-nuclear emissions factor = CO_2 *emissions / non-nuclear generation*

   This factor can be calculated explicitly from the power planning model for the years 1995, 2000, ... 2025. We then make the assumption that this factor can be interpolated for the intervening years (1996, 1997, etc). This is of course an assumption, and is based on the premise that changes in electricity generation from each fuel type (gas, coal, etc) and technology (CCGT, conventional, etc) will follow smooth paths.

6. Total CO_2 emissions can then be calculated by multiplying the emissions factor by the electricity generated by non-nuclear sources (see *Section 5* for a presentation of the emissions factors used). Results are calculated for each year, as shown in the attached Table A1.1. The most important factor in the calculation is the amount of nuclear generation (which is based on annual capacity values). It can be seen that the change in total CO_2

emissions varies greatly on a year-by-year basis when nuclear plant is retired. Thus annual CO_2 changes are 2.9%, 11.5%, 6.4%, 8.7%, 1.4% for the years 2013-2017 inclusive, when nuclear capacity falls from 6.73 GW to 1.97 GW.

There are alternatives to this method:-

- The simplest one (Method 2, illustrated in *Table A11*) assumes that total CO_2 results can be interpolated for intervening years directly. This method misses the effects of the step changes in nuclear capacity which occur on an annual basis. It can be seen that there are differences of up to 4.9Mtonnes CO_2 (in 2016) between the method we are recommending and method 2.

- A more complicated version could be produced by running the power planning model on an annual basis. This would not affect the total generation (which is an input into the power planning model) nor the nuclear capacity. However we would get a better estimate of which fossil fuel and renewables plants were generating electricity, and hence a better estimate of the CO_2 emissions factor. The attached Table shows that this extra accuracy is not necessary; between 2000 and 2025, the CO_2 emissions factor varies slowly between 517 g/kWh and 484 g/kWh. There are no significant step changes in non-nuclear generation which would lead to large annual differences in this factor. Thus this factor is thus adequately predicted by the method of interpolating between 5 year results. The most important factor is the amount of electricity generated by non-nuclear electricity; this can be derived by subtracting annual estimates of nuclear generated electricity from total generation.

A18.4 Calculation of Annual Factors

Year	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Generation (TWh)	**159.30**	160.05	160.80	161.56	162.31	**163.08**	166.26	169.50	172.81	176.18	**179.61**	184.25	189.00	193.88	198.89	**204.02**
(annual increase, %)		*0.5%*	*0.5%*	*0.5%*	*0.5%*	*0.5%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.6%*	*2.6%*	*2.6%*	*2.6%*	*2.6%*
Nuclear Capacity (GW)	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.32**	**7.17**	**7.17**	**6.73**	**6.73**	**6.73**	**6.73**
Nuclear Load Factor (%)	**88%**	88%	88%	88%	88%	**88%**	87%	87%	87%	87%	**87%**	87%	87%	86%	86%	**86%**
Nuclear Generation (TWh)	56.57	56.48	56.39	56.30	56.21	56.12	56.10	56.08	56.06	56.04	54.84	54.64	51.10	50.91	50.72	50.54
Fossil Fuel Generation (TWh)	102.73	103.57	104.41	105.26	106.11	106.96	110.16	113.42	116.75	120.14	124.77	129.60	137.90	142.97	148.16	153.48
CO2 emissions (g/kWh non-nuclear)	**621**	599	577	557	537	**517**	516	515	513	512	**510**	505	499	493	488	**482**
Total CO2 emissions (Mtonnes)	63,814	62,026	60,285	58,592	56,944	55,340	56,840	58,364	59,911	61,482	63,675	65,394	68,793	70,512	72,244	73,990
(annual increase, %)		*-2.8%*	*-2.8%*	*-2.8%*	*-2.8%*	*-2.8%*	*2.7%*	*2.7%*	*2.7%*	*2.6%*	*3.6%*	*2.7%*	*5.2%*	*2.5%*	*2.5%*	*2.4%*
Method 2: Total CO2 emissions	**63,814**	62,022	60,279	58,586	56,940	55,340	56,915	58,535	60,200	61,913	63,675	65,616	67,616	69,677	71,801	73,990
(method 2: annual increase, %)		-2.8%	-2.8%	-2.8%	-2.8%	-2.8%	2.8%	2.8%	2.8%	2.8%	2.8%	3.0%	3.0%	3.0%	3.0%	3.0%
Method 1 - Method 2	-	4	6	6	4	-	- 75	- 171	- 289	- 431	-	- 222	1,177	835	443	-

Year	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Generation (TWh)	207.54	211.11	214.74	218.44	**222.20**	225.39	228.62	231.89	235.21	**238.58**	242.05	245.56	249.12	252.73	**256.40**
(annual increase, %)	*1.7%*	*1.7%*	*1.7%*	*1.7%*	*1.7%*	*1.4%*	*1.4%*	*1.4%*	*1.4%*	*1.4%*	*1.5%*	*1.5%*	*1.5%*	*1.5%*	*1.5%*
Nuclear Capacity (GW)	**6.73**	**6.73**	**6.73**	**4.80**	**3.86**	**1.97**	**1.97**	**1.97**	**1.97**	**0.97**	**-**	**-**	**-**	**-**	**-**
Nuclear Load Factor (%)	85%	85%	84%	84%	**83%**	83%	82%	82%	81%	**81%**	0%	0%	0%	0%	0%
Nuclear Generation (TWh)	50.26	49.99	49.71	35.28	28.19	14.28	14.19	14.10	14.01	6.84	-	-	-	-	-
Fossil Fuel Generation (TWh)	157.27	161.12	165.03	183.16	194.01	211.11	214.43	217.80	221.21	231.75	242.05	245.56	249.12	252.73	256.40
CO2 emissions (g/kWh non-nuclear)	484	487	489	491	**494**	493	492	492	491	**490**	492	493	494	495	**497**
Total CO2 emissions (Mtonnes)	76,174	78,405	80,685	89,971	95,748	104,054	105,556	107,076	108,614	113,643	118,992	121,022	123,086	125,185	127,320
(annual increase, %)	*3.0%*	*2.9%*	*2.9%*	*11.5%*	*6.4%*	*8.7%*	*1.4%*	*1.4%*	*1.4%*	*4.6%*	*4.7%*	*1.7%*	*1.7%*	*1.7%*	*1.7%*
Method 2: Total CO2 emissions	77,905	82,027	86,367	90,937	95,748	99,086	102,541	106,116	109,815	113,643	116,256	118,928	121,662	124,459	127,320
(method 2: annual increase, %)	5.3%	5.3%	5.3%	5.3%	5.3%	3.5%	3.5%	3.5%	3.5%	3.5%	2.3%	2.3%	2.3%	2.3%	2.3%
Method 1 - Method 2	- 1,731	- 3,622	- 5,683	- 965	-	4,967	3,015	960	- 1,201	-	2,736	2,093	1,423	726	-

Future Technologies and their effects on CO_2 Emissions

In many ways the model will produce a conservative estimate of future CO_2 emissions since it is based on presently available technologies only. It is assumed that the performance of presently available technologies will improve with time, but not by step changes. *Table A1.2* shows the default values of efficiencies for the two new fossil fuel types with time. The increase in efficiency takes account of performance improving with time.

Table A1.2 Efficiency of New Fossil Fuel Plant with Time

Plant Type	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**
Natural Gas	49%	50%	51%	52%	53%	54%	55%
Hard Coal	39%	40%	41%	42%	43%	44%	45%

There are several reasons why emissions forecasts will be conservative (i.e. actual emissions may be lower, particularly towards the end of the projection period):-

- as discussed above, efficiencies of existing technologies are not assumed to improve by step changes;
- there is a real prospect that externality adders will be added to fuel prices in the future, be this through CO_2/energy taxes, trading, etc. Increasing the prices of fuel will lead to reduced fuel demand;
- the only technology assumed for new nuclear plant is PWR without significant performance improvements from today's values. Improvements will occur in burn-up and in lowering waste arising per unit of electricity produced: however the efficiency of nuclear generation s fundamentally limited by the efficiency of the steam cycle.
- it is not assumed that CHP will be taken up any faster than the scenarios proposed in EE2020. CHP could produce significant emissions savings at low cost, and many commentators have criticised the EE2020 study for being too pessimistic in its assessment of the economic potential of CHP to 2025. Additionally, CHP would benefit greatly from any externality adders on fuel prices.
- The biggest source of being conservative is probably treatment of new technologies. By 2025, it is possible that fuel cells, micro turbines, Stirling engines (of sizes down to 10KWe), heat pumps and wave energy technologies will be commercially available. Continuing improvements on wind and solar technologies could also lead to much higher penetration of renewables, particularly if the benefits of embedded generation are fully incorporated into power system planning.

Counteracting these factors which would lead to lower CO_2 emissions are the potentially considerable hurdles to overcome in closing certain coal mines and coal plants in favour of gas plant; public opinion could also close nuclear plant before its assumed technical lifetime of 40 years has been fulfilled, particularly in the countries of northern Europe.

On balance, it is felt that the CO_2 emissions projections made represent conservative estimates and are towards the higher end of the range of possibilities. These effects will not be as severe when considering the major output of the work, the differences in emissions between scenarios.

18.2 *NUCLEAR ENVIRONMENTAL ATTRIBUTES*

Deriving the nuclear environmental attributes is not straightforward and the values derived are the subject of some debate. A comprehensive literature review has been undertaken, and the following section describes this review, the values of the attributes chosen and the rationale for their choice.
Low and Intermediate Level Wastes have been combined into a single category for the Study, which is referred to simply as Low / Intermediate Level Waste (LLW / ILW). This is justified because LLW and ILW are disposed of in the same or similar facilities, generally above ground. They thus impose similar burdens in terms of waste management. The ILW is in any case a much smaller volume than LLW.

Waste from Normal Operation

An OECD / NEA study of volumes of waste from operation and decommissioning (1) gives the figures shown in *Table A1.3* for wastes arising from 25 years operation of different reactor designs (as of 1986):

Table A1.3 Volumes of LLW from Operation and Decommissioning

Plant	***k m³***	***m³/TWh****
4 x 515 MWe PHWR (Canada)	6.9 - 27.5	19 - 76
1200 MWe PWR (Germany)	6.1 - 11.0	29 - 52
800 MWe BWR (Germany)	6.0 - 20.0	42 - 142
900 MWe PWR (Sweden)	6.3	40
1000 BWR (Sweden)	7.5	43
1000 MWe PWR (US)	21.7	124
1000 MWe BWR (US)	40	228

*The m^3 / TWh figures have been derived from an assumption of an 80% load factor.

Since 1986 the volumes of wastes from operation have much reduced, partly as a consequence of rising costs of disposal.

The US DoE (2,3) says that in 1991, 92,000 m^3 of LLW were disposed of in the US. Of this the commercial nuclear power programme accounted for 30,590 m^3. The generation of power from nuclear facilities in this year was 577 TWh. The waste arising is therefore equivalent to 53 m^3/TWh, but this includes uranium mining, reprocessing etc.

The US Institute of Nuclear Power Operators (4) maintains statistics that distinguish between PWR and BWR reactors. On average in 1990 PWRs produced about 108 m^3 of solid waste and BWRs about 301 m^3 (down from x5 and x3 these figures in 1980). This is equivalent to 17 m^3/TWh and 54 m^3/TWh respectively.

ExternE (5) gives wastes from operation as numbers of packages and barrels - this is not very helpful as no measures are given for these units

A paper in NEI (6) says that the LILW generated by the three main producers in France is:

- EDF 7000 m^3/yr
- Cogema 8000 m^3/yr
- CEA 3000 m^3/yr

Volume has been reduced from 32 k m^3 to 17 k m^3 between 1988 and 1997. The waste from generation appears to be 7000/378 m^3/TWh = 18.5 m^3/TWh. (Note that this is close to the US figure for PWRs).

The objective for the production of LLW from Sizewell B (7) is 40 cubic metres per year. The gross electrical output is 1250 MW, at an availability of 80% that represents 4 m^3/TWh. As one of the most recently commissioned plants this may be taken as a reasonable target figure for other plant in service.

Unit volumes of LLW arising by technology type assumed for the Study are shown in *Table A1.4*. Values between 1998 and 2025 are obtained by linear interpolation.

Table A1.4 LLW from Normal Operation (m3/TWh)

Reactor Design	LLW 1998 (m^3/TWh)	LLW 2025 (m^3/TWh)
PWR	18	4
BWR	30	10
AGR	18	4
Others	18	4

Waste from Decommissioning

In 1992 the NEA made an international review of nuclear decommissioning costs (8). The focus of the Working Group was cost, but there is a comparative table of wastes arising from decommissioning. The data is reproduced below as *Table A1.5*

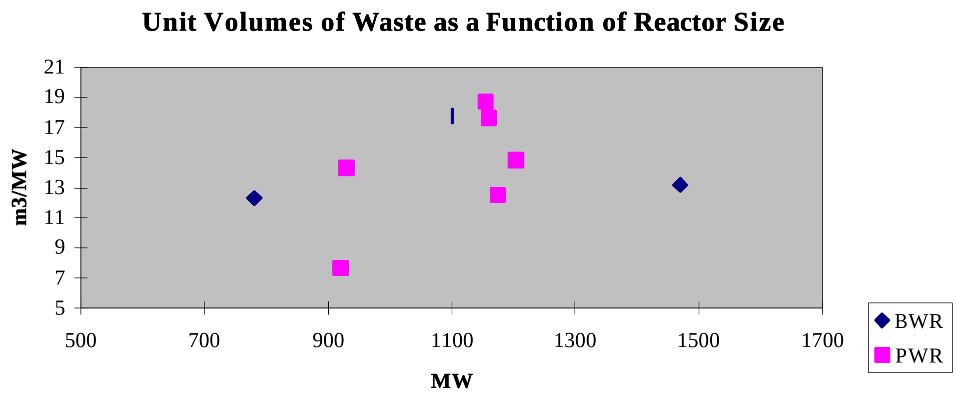
Table A1.5 LLW Arising from Decommissioning

Reactor Type	Country	Capacity	Mode of Decommissioning	Volume of waste (k m^3)	Waste per MW (m^3/MW)
PWR (VVER)	Finland	2x465	Stage 3	13.3	14.3
PWR	Germany	1204	Stage 3	17.8	14.8
PWR	Germany	1204	30 yrs +Stage 3	17.8	14.8
PWR	Japan	1160	Stage 1 +5-10yrs+ Stage 3	20.4	17.6
PWR	Sweden	920	Stage 3	7.0	7.6
PWR	UK	1155	Stage 3	21.6	18.7
PWR	US	1175	Stage 3	14.7	12.5
BWR	Finland	2x735	Stage 1 +30yrs+Stage 3	19.3	13.1
BWR	Japan	1100	Stage 1 +5-10yrs+ Stage 3	19.5	17.7
BWR	Sweden	780	Stage 3	9.5	12.3
GCR	Spain	500	Stage1+Stage2+25yrs+ Stage 3	24.6	49.3

Reactor Type	Country	Capacity (MW)	Mode of Decommissioning	Volume of waste (k m^3)	Waste per MW (m^3/MW)
GCR	UK	8x60	Stage1+Stage2+ 60-90yrs+Stage 3	140.9	293.5
GCR	UK	2x219	Stage1+Stage2+ 90yrs+Stage3	65.4	149.38
AGR	UK	2x660	Stage1+Stage2+ 90yrs+Stage3	41.2	62.4
HWR	Canada	600	Stage 1 +32 years + Stage 3	14.4	24.0

Figure A1.2 plots this data as unit volumes from LWRs as a function of size. There is no strong indication of much difference between BWRs and PWRs, nor is there any marked dependence on size.

Figure A1.2 LLW from Decommissioning as a Function of Reactor Size



The Working Group analysed some of the reasons for the wide range in estimates. The different reactor designs is an obvious source of divergence, especially for the gas-cooled reactors. The main structural difference is the large graphite moderator; since Magnox reactors use natural uranium the core is considerably larger than for a PWR or BWR. The Magnox reactors also have several primary coolant loops and some have large concrete structures encasing both the pressure vessel and the steam generators. The high values for HWR reactors also reflect the large core structure. There is still uncertainty in most countries about the regulatory rules and policies that will apply to decommissioning.

ExternE (5) uses the basic US references for decommissioning of PWRs (9). The study claims to adopt the figures for the deferred dismantling of a nuclear power plant after fifty years which it says correspond to the European situation. The figures given in ExternE are 17451 m^3 for a 1175 MWe PWR. The original US studies have been revised several times. The most recent figures for 50 yr deferment are: 1.83k m^3 for a 1100 MW Reference PWR and 1.78 k m^3 for a similar BWR. These figures are **very** different from those used by ExternE. The ExternE study appears to have taken the 30yr figures. There is a big difference (factor of 10) between 30 and 50 years, because much decay occurs in that period. See *Refs 10-12*. The fairly recent US OTA study (2) adopts the same figures. *Table A1.6* summarises these results.

Table A1.6 LLW Wastes from decommissioning (k m3)

	PWR	BWR
DECON	17.89	18.95
30 yr SAFSTOR	17.89	18.95
50 yr SAFSTOR	1.83	1.78
100 yr SAFSTOR	1.78	1.67
ENTOMB	3.06	8.04

DECON involves immediate dismantling of contaminated structures to a level allowing the return of the site to unrestricted use; SAFSTOR involves placing a plant into safe-storage followed after a time by enough decontamination and dismantling to allow the release of the site; ENTOMB involves partial dismantling followed by encasement and monitoring until the site can be released.

The estimate for Sizewell B is 18 m^3/MWe, putting it in with a cluster of similar plants in *Figure A1.5* On the basis of the above review we intend to adopt a figure of 18 m^3/MW for all LWRs. This is a conservative estimate; best practice might produce somewhat less. *Table A1.7* shows the waste factors assumed for each type of nuclear reactor. Note that waste from decommissioning has been allocated equally across all years of the plant's lifetime, e.g. if a plant has a 40 year lifetime, 2.5% of decommissioning waste arising is attributed to the plant each year.

Table A1.7   LLW from Decommissioning (m^3/MW)

Reactor design	LLW (m^3/MW)
PWR	18
BWR	18
AGR	60
VVER	18
Magnox	150

Waste from Reprocessing

ExternE (5) cites *Ref 13* as saying that the volumes of conditioned radioactive waste produced by the reprocessing of spent fuel from one year of operation of a 900 MWe PWR are approximately:

- fission products   2.7 m^3 vitrified
- structural wastes   14 m^3 solidified with concrete
- low and medium level wastes   95 m^3 conditioned

These are equal respectively to 0.4, 2.2 and 15 m^3/TWh at 80% capacity factor.

Conditioned waste is waste that has been prepared and packaged ready for transport and disposal; the values therefore include the volumes of grouting and packaging that are required. It is not clear if the figure of 95 m^3 of conditioned waste includes the structural wastes. The figure seems extremely high; the reference is from 1983 when burn-ups were lower and presumably the figures should be adjusted for this.

In 1986, the NEA (1) proposed that a reprocessing plant supporting 50 GW of nuclear plant would produce 54,000 tonnes of LLW over its lifetime. This corresponds to about 6 m^3/TWh.

Later papers describe recent experience at the UP3 plant (14,15). From the design basis of 3.1 m^3 waste per tonne fuel processed the operators have succeeded in reducing waste to 1.0 m^3/tonne. By the year 2000 the authors expected to reduce waste to one half of that figure. At a burn-up of 50GWd/t 1 m^3/tonne corresponds to 0.83 m^3/TWh. The target for 2000 is about 0.4 m^3/TWh.

Table A1.8 resumes the sources reviewed here.

Table A1.8 Summary of sources for LLW produced in reprocessing

Source	Date	LLW in m3/TWh
ExterneE (citing Ricaud and Patarin)	1983	15
Nuclear Energy Agency	1986	6
UP3 (actual)	1994	0.8
UP3 (f0recast)	2000?	0.4

We have assumed that 0.4 m^3/TWh in our calculations. It should be noted that this is very much lower than the ExternE figures.

Reference 1 also gives data for U enrichment and decommissioning of reprocessing plant. These are small compared to other sources (less than the uncertainties) and will be ignored in the study.

References for Radioactive Waste Arisings

1 Projections of Facilities to be Decommissioned and Resulting Waste Volumes, in Decommissioning of Nuclear Facilities, NEA/OECD, Paris 1986

2 Ageing Nuclear Power Plants: Managing Plant Life and Decommissioning, US Congress, Office of Technology Assessment, Sept 1993

3 US Department of Energy, Integrated Data Base for 1992, US Spent Fuel and Radioactive Waste Inventories, Projections and Characteristics, DOE/RW-0006, Washington, 1992.

4 Institute of Nuclear Power Operations, 1990 Performance Indicators for the US Nuclear Utility Industry, March 1991.

5 ExternE: Externalities of Energy, Vol.5, Nuclear, European Commission, DGXII, Luxembourg, 1995

6 WIPPing up Enthusiasm at WM'98, Nuclear Engineering International, 1998

7 Sizewell B Environmental Management Statement, British Energy, 1995/96.

8 International Comparisons of Decommissioning Cost Estimates: in Decommissioning Policies for Nuclear Facilities, NEA/OECD, Paris, October, 1992.

9 NUREG/CR-0130, "Technology, Safety and Costs of Decommissioning for the Reference Pressurised Water Reactor Power Station, (1978)

10 NUREG/CR-0672, "Technology, Safety and Costs of Decommissioning for the Reference Boiling Water Reactor Power Station, (1978)

11 NUREG/CR-5884, "Revised Analysis of Decommissioning for the Reference Pressurised Water Reactor Power Station, November 1995

12 NUREG/CR-6174, "Revised Analysis of Decommissioning for the Reference Boiling Water Reactor Power Station, July 1996

13 Ricaud, J.L., Patarin, L. (1983) Le retraitement des combustibles irradiés provenant des réacteurs à eau légères, Annales des Mines, France.

14 Masson, Waste Management Issue: Reprocessing or Direct Disposal, Fourth International Conference on Nuclear Fuel Reprocessing and Waste management, RECOD94, April, 1994

15 Ledermann, P., Miquel, P., and Boullis, M., Optimisation of Active Liquid and Solid Waste Management at the la Hague plant, Fourth International Conference on Nuclear Fuel Reprocessing and Waste management, RECOD94, April, 1994

Spent Fuel from Operation

Wherever possible, the achieved burn-ups are used for existing plant in the base year. Data is necessary for the burn-ups that will be achieved in existing plant and the design burn-ups of new plant. There is a wealth of literature on this subject and most of it is consistent.

Siemens (7) describe the factors limiting extended burn-up. They claim that simulation for PWRs and BWRs has indicated that equilibrium discharge burn-ups above 70 GWd/t can be expected using fuel assemblies with designs available today. Corrosion, H_2 pick-up and growth of cladding tubes and structural material are the main limitations. Another constraint is the enrichment limit of 5 % enrichment of ^{235}U for fabrication, transport and handling of fuel assemblies. This limits batch average burn-up in PWRs to about 65 GWd / t and in BWRs to about 60 GWd / t.

A paper to an IAEA conference (8) also analyses the economics of enhanced burn up; they are affected by both “front” and “back-end” consequences. At the front-end, the economics improve with burn-up to about 55-60 GWd / t, beyond this level the SWU rises steeply. At the back-end, both reprocessing and direct disposal costs increase with burn-up. The view of the author was that the economic optimum was around 60 GWd / t.

The US DoE (9) has based its own analysis of the need for uranium services on the assumptions for burn-up shown in *Table A1.9*

Table A1.9 US DOE Burn-up Assumptions (GWd/t)

	US		**Europe**	
	PWR	***BWR***	***PWR***	***BWR***
1993/1994	42000	36000	42000	
1995				36000
1996/1997	46000	40000		
1998			46000	39000
2000/2001	50000	43000		
2002			50000	
2004				43000
2007			55000	
2009/2010	55000	46000		46000

A Working Group of the Uranium Institute has analysed the issues in detail (10). The report lists historic design burn-ups for most countries and expected future burn-ups by country and reactor type to 2010. As the Working Group comprised members from all the large EU nuclear countries it is the most reliable source for the present modelling. The figures listed there have been adopted and extrapolated to 2025, taking into account the technical and economic constraints identified (7,8).

Burn-up for each nuclear plant is linearly interpolated from values at 1998 and 2025. These are country specific, and have been estimated as shown in *Table A1.10*.

Table A1.10 Burn-up in Nuclear Plant

Country	Reactor design	Burn-up 1998 (GWDth/t)	Burn-up 2020 (GWDth/t)
Belgium	PWR	48	50
Finland	VVER	35	50
	PWR	40	50
France	PWR	42	50
Germany	PWR	42	50
	BWR	45	50
Netherlands	PWR	33	33
	BWR	27	27
Spain	PWR	41	50
	BWR	38	50
Sweden	PWR	43	50
	BWR	42	50
UK	AGR	21	30
	Magnox	5	5
	PWR	33	50

If the burn-up is B GWd/tonne and the thermal efficiency is n then:

*Heavy Metal Used = 1/(24*n*B) tonne/GWh electricity generated.*

Spent Fuel from Decommissioning

If F is the fraction of fuel replaced annually, then N = 1/F represents a full load of fuel. Typically N-1 years worth of fuel will be left in a reactor when it is shut down. It has been assumed that N=4 for BWR and N=3 for all other reactor types.

Assuming a load factor of 80%, then the annual requirement for heat per MW of capacity is *0.8*8760/n* where n is the thermal efficiency of the plant. A tonne of heavy metal produces B GW-days of heat = 24 B GWh of heat, where B is the burn-up. Therefore the annual requirement in fuel is 0.8*8760/(nB*24*1000). The decommissioning spent fuel per MW can therefore be calculated using:

*Spent Fuel at Decommissioning = (N-1) * 0.8 * 0.365 / (n*B) tonne/MW.*

Note that waste from decommissioning has been allocated equally across all years of the plant's lifetime, e.g. if a plant has a 40 year lifetime, 2.5% of decommissioning waste arising is attributed to the plant each year.

Plutonium Production

Plutonium Production as a Function of Burn-Up

An EPRI study from 1996 (1) quotes average elemental Pu in spent fuel from 40GWd/t burn-up at 1.1%; and from 50GWd/t at 1.25%.

An OECD review of 1989 (2) provides figures on the net Pu production for BWR, LWGR, PWR, WWER, AGR, GCR and PHWR as functions of burn-up from 0 to 55 GWd/t. From 40 to 50 GWd/t they are broadly consistent with the EPRI data. These relationships have been employed in a recent SCK-CEN study (3). The relationships are non-linear. Over the range of commercial interest the curves can be approximated as linear relations. This data and such a relationship has been used as the basis for our modelling. Net Pu in kg/tHM is approximated as:

- PWR 10 + 4*(B-40)/15 where B is Burn-up (GWD/tonne)
- BWR 9.5 + 2.2*(B-40)/15
- AGR 4.5 + 1.5*(B-20)/10
- PHWR 2.2*B/5

Recent figures from the standard ORIGEN2 code were published by authors from the Institute for Transuranium elements (4). They give the detailed composition of spent PWR fuel at burn-ups of 33 GWD/t and 50 GWD/t. The Pu content is estimated at 9.1 g/kg and 12.74 g/kg respectively. This is consistent with the figures adopted for the study.

Replacement of Fissile Uranium by Fissile Plutonium

Technical papers such as a recent paper by authors from Siemens (5) indicate that fissile Pu has a significantly different neutron economy and therefore behaves differently from ^{235}U in the reactor. It may replace slightly more or slightly less ^{235}U depending upon where the element is situated.

The review by the OECD in 1989 (2) suggested a value of 1.3 and this is the value adopted in the EPRI study (1).

The SCK-CEN study (3) assumes a 5%Pu content of which about 70% is fissile (Pu-239; Pu-241). This results in 3.5% Pu239,241, only slightly higher than 3.3% U-235.

The OECD value appears high compared to current practice. A figure of 1.0 is adopted in the study, meaning that 1 gramme of fissile Pu will replace 1 gramme of U-235.

Isotopic Fissile Fraction of Plutonium in Spent Fuel

The isotopic fissile fraction of Plutonium in spent fuel depends on the history of the fuel. *Ref 5* gives a summary of the isotopic composition of fuels from various sources based on Siemens' experience in the fabrication of MOX fuel assemblies. The variation is shown in *Table A1.11*

Table A1.11 Isotopic Fissile Fraction of Plutonium in Spent Fuel

	Pu-238 (%)	Pu-239 (%)	Pu-240 (%)	Pu-241 (%)	Pu-242 (%)	Fissile (%)
Weapons Grade Pu (example)	0	94	5	1	0	95
Civil Pu						
Magnox	0.3	76.1	18.4	4.4	0.8	80.5
PWR (normal burn-up)	1.5	60.1	24.5	8.8	5.1	68.9
PWR (increased burn-up)	2.6	54.0	24.2	11.8	7.4	65.8

The EPRI study adopts a value for the fissile fraction of 0.8, based on rather old theoretical sources (6). The SCK-CEN study (3) assumes 0.7.

We have preferred the initial value of 0.7, corresponding to LWR commercial experience and have assumed it falls to 0.66 by 2025 as a consequence of higher burn-ups. Substantially different values could be achieved by mixing spent fuel with weapons-grade Pu, but this consideration lies outside the study and is ignored.

Equivalent Enrichment Fraction of Spent MOX Fuel

Because new MOX fuel is enriched with Pu instead of ^{235}U, the fissile Pu content of spent MOX is higher than in spent Uranium Oxide fuel. Reprocessing therefore gives more Pu than when reprocessing spent uranium oxide fuel. The Siemens' results suggest that 1.2 - 1.3 % of the spent fuel comprises fissile plutonium. 1.3% has been used in the analysis.

Eventually, as MOX fuel is reprocessed, this will impinge on the Pu production in reprocessing and further work through to Pu content and isotopic composition of spent fuel. The effect has been ignored at this stage.

Existing use of MOX and its Likely Development

MOX reprocessing capacity has been developed in several countries. The proportion of the core that can be loaded with MOX is generally restricted to 30% under current licences, although technically 100% MOX cores are feasible. Some German plant has been licensed up to 37 and 50%. Detailed information is available on the likely market development for MOX fuel in a report of the Uranium Institute (11). This was compiled by a working group with members from all the large EU nuclear countries and gives historic and forecast use of MOX by country up to 2015. This data has been adopted for the study and extrapolated to 30% MOX use by 2025 in countries where MOX use is permitted.

Enrichment Assay for Extended Burn-Up

Rather a detailed study of this topic was published by the US DoE after discussion with US nuclear fuel vendors (9). No other material of similar depth has been found in the literature so the regression equations cited there have been adopted, i.e:

- BWR $E = 0.765 + 0.0000526\,B\,(1 + F)$
- PWR $E = 1.015 + 0.0000457\,B\,(1 + F)$

where E is the enrichment assay of the enriched uranium required to produce fuel elements with a burn-up of B, if the fraction of the core replaced each year is F.

These figures are only of peripheral relevance, but they do have a bearing on the Pu requirements for MOX fuel and therefore on some environmental attributes. They are given here for completeness.

References for Spent Fuel and Plutonium Production

1. A Review of the Economic Potential of Pu in Spent Nuclear Fuel, EPRI, TR-106072, February 1996
2. Plutonium Fuel - an Assessment, OECD/NEA, 1989
3. Civil Plutonium in the World: an estimate by the Code REACTOR, Braet, J., Carchon, R., van der Meer, K., SCK-CEN, Nuclear Research Centre Mol, Belgium, November 1966
4. Closing the Fuel Cycle with ADS, Magill. J,, Peerani, P., and van Geel, J., International Workshop on the Physics of Accelerator-Drive Systems for Nuclear Transmutation and Clean Energy production, Trent, Italy, Oct. 1997
5. Use of Weapons Grade Plutonium in Existing PWRs - Supported by German MOX Recycling Experience, Burtak, F., and Schlosser, G.J., Nuclear Technology, 123, pp 268-277, Sep 1998
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