Cost-effectiveness analysis: The key for the identification of efficient response strategies to the climate issue Conceptual approach and modelling tools

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Abstract

Any reduction of greenhouse gases, particularly of carbon dioxide, to climatologically acceptable levels implies fundamental structural changes within the energy system. In the wake of drastic environment driven changes the need for effective and economically viable control strategies is evident. The paper argues that 'cost-effectiveness analysis' is the appropriate point of departure for the identification of efficient response strategies. The approach and available analytical tools are outlined and the limitations are discussed. Preliminary results of a case study for the F.R.G. are presented.

The climate problem and the need for cost-effective response strategies

During the past decade scientific monitoring of climate indicators, experimental efforts in climate research and the results of climate models have lead to a growing consensus in the scientific community that the anthropogenic production of several gazeous compounds may cause a severe climate warming causing rising sea-levels, altered precipitation patterns, changing frequency of climatic extremes and shifts of major climatological zones. The gases which have been identified to contribute to the greenhouse effect are called 'greenhouse gases'. They include carbon dioxide, contributing to about 50% to this effect, Methane (19%), chlorofluorocarbons (17%), ozone (8%), nitrous oxides (4%) and others. Although a large range of uncertainty (e.g. regional impacts, range of concentrations, possible warmings and sea-levels, contribution of greenhouse gases to natural catastrophes) still remains, many scientists have concluded that:

> 'Understanding of the greenhouse question is sufficiently developed that policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments'.[1]

They claim that delaying any counter measures while waiting for a final proof will be irresponsible with respect to future generations. In the light of this challenge many actions have been proposed addressing the climate issue. Generally, they fall into two categories:

- adaptive strategies (e.g. restructuring of agriculture, building of dams)
- preventive strategies (e.g. emission reduction)

It is most likely that climate response strategies reducing greenhouse gas emissions to acceptable levels will have a severe impact on the energy system and hence on national economies. Adaptive as well as preventive strategies appear to be extremely costly and will require additional quantities of scarce economic resources with considerable opportunity costs.

At stake is the well-being of billions of people as well as costs of billions of dollars. Consequently, climate response strategies must be identified on a rational basis. For this reason it is not sufficient to identify courses of action reaching certain emission targets without investigating their economic and social implications.

The real and important issue confronting the policy makers concern the design of an effective response strategy, both in terms of controlling greenhouse gas emissions with minimum costs as well as in terms of the temporal scope of the achievable levels. Inspite of the long time horizon involved, it is an important task to explore the robustness of the policy measures based on information available today.

Ideally, policy measures should be based on a detailed cost-benefit analysis implying a weighing of the positive and negative effects of any course of action. As a decision criterion the following rule should be applied: The greenhouse gas emissions should be reduced to the level where marginal costs of reduction equals the marginal costs of damages.

The potentially detrimentral or beneficial effects of climatic changes on human welfare (e.g. crop yields and hence food supplies, fisheries and population settlements) can not be evaluated with current knowledge. Therefore, there is no solid basis for an assessment of the benefit of climate response measures. Consequently, the design and evaluation of adaptive policies is not possible on a solid and rational basis (the need for regional differentiation of actions and the uncertainty of regional impacts).

The presently existing information gap for cost-benefit-analysis is obvious. Instead, a cost-effectiveness approach for identifying the most rational course of action appears to be the appropriate tool. The basis of this approach is the careful analysis of the costs and impacts of various greenhouse gas control measures. Further, the most efficient combination can be chosen from a variety of possibilities aiming at the same target. In other words: Reaching a greenhouse gas emission objective at minimal costs or achieving a maximum emission target given a fixed budget.

The subsequent illustration of the cost-effectiveness approach (CEA) is based on the underlying assumption that carbon dioxide and other greenhouse gases released by human activity might result in a climatic change which should be avoided. Furthermore, as an example, this analysis will focus on the most important energy related greenhouse gas CO_2. Nevertheless, CEA should also be applied to other greenhouse gases.

Energy systems and the CO_2-problem

The combustion of fossil fuels is a cornerstone of the global energy system. The thermal energy that is released by this process originates from the oxidation of the carbon atom to carbon dioxide. For most of the countries in the world this reaction dominates all kind of energy applications. But for most of these applications substitution by non-fossil or less carbon containing fuels are possible but often very expensive. The adaptation of the current energy system to a CO_2-benign energy system requires big efforts in the field of energy planning. In the light of the new challenge current national policies are to be checked and possible conflicts to national supply security are to be identified. The general strategy must be reviewed and in case of discrepancy with the CO_2-objective revised.

The two oil crises in 1972/73 and 1979 lead in many countries to a shift away from oil. But the necessary response to the new CO_2 issue seems to be even more severe. The management of the CO_2-problem might require not only a shift away from oil, but even may so from coal, a fuel able to cover the future energy demand for several centuries. Moreover, the oil crises demonstrated the sensitivity of industrialized as well as developing countries' economy to drastical energy price increases. Many economists agree that these oil price shocks were an important factor for the depression in the late seventies and early eighties. Therefore, any interference with the energy systems causing severe price increases has to be carefully analyzed.

The dependence of many countries on domestic fossil resources points to the problematic nature of the implementation of effective CO_2-reduction strategy. This is associated by the fact that the full benefit of such a strategy will become effective in the distant future investing in preventive reduction measures today. The dimension of this problem can be easily illustrated:

- CO_2-emission level today: about 20 Billion t CO_2/a
- Climatologically acceptable level: 10 Billion t CO_2/a ??
- with a global population of 10 Billion (second half of the next century): 1 t CO_2 per year and capita
- Present per capita emissions FRG 12t China 2.5t

Consequently, the need for a drastic restructuring of present energy system may be requested. However, it is important to avoid to rush into premature decisions. Instead, it is imanent to identify robust actions with the help of systems analysis procedure.

Because of the variety of final energy products, the large number of different conversion technologies and consumption categories, many possibilities exist in reducing energy related CO_2-emissions. Nevertheless, all these measures fall into one of the following classification categories:

- Interfuel substitution between fossil fuels (e.g. from coal to gas)
- Interfuel substitution between fossil and non-fossil fuels
- Energy conservation (substitution by capital or labour)
- Cut of energy services and useful energy demand reducing individual benefit
- CO_2-separation from combustion gases and deposition far from the atmosphere.

All these measures may contribute to national and global emission objectives. But, it is important to know about their costs and reduction potentials so as to determine their effectiveness.

Cost-effectiveness analysis (CEA): The approach

The approach of cost-effectiveness analysis starts from the fact that future damages are difficult to quantify. Therefore, CEA approach uses emission trajectories as a point of departure. For each trajectory a set of actions associated with minimum costs can be determined. But, CEA must be seen as a part of a more comprehensive approach, which also includes the interactions with the economy, the society and other area as well as the question of implementation and enforcement of efficient strategies.

A first step in a cost-effectiveness analysis is a detailed compilation of all possible measures which provides the basis for technology assessment and impact evaluations. Questions which are to be addressed during this compilation are:

- Which possibilities exist that agree with the objective?
- What are their potentials, restrictions and drawbacks?
- How could this potential be realized?
- What are the implications for the existing energy system?
- Do they interact with each other?
- What are their technical and economic characteristics?

This compilation of technologies and measures finally leads to a separate cost-effectiveness analysis for each measure.

Cost-effectiveness analyses deal mainly with the identification of efficient measures. The way how these measures could be enforced and implemented into the legal framework is not part of the approach. Nevertheless, institutional, legislative and contractual restrictions contribute to the overall evaluation of measures. CEA consists of 8 main steps:

- Compilation and characterisation of all possible measures
- Assessment of technologies and measures by there specific reduction costs [in terms of monetary unit per mass unit of CO_2 not emitted]
- Quantification of their potentials with respect to the current and future energy system
- Consideration of institutional, legislative and contractual restrictions
- Interaction of different measures
- Ranking and assessment of measures
- Efficient control strategies to reach a given reduction target
- Robustness of measures

The potential of single measures are closely connected to the specific reduction costs. Generally, these differ for various reduction levels. This relationship can be expressed in a so-called potential curve.

In summary, the generation of potential and specific reduction cost curve provides useful information for the decision maker. The schematic representation of such a cost curve is displayed in Figure 1. The gradients for different reduction levels correspond to the specific reduction costs associated with the measure in question.

For a more detailed analysis this curve could be generated for each measure separately and aggregated thereafter. But this procedure is very complicated and the interaction between measures can hardly be integrated.

Furthermore, the interaction of different measures may influence both specific reduction costs and the potentials of a single measure. For example: The insulation of buildings affects the effectiveness of a

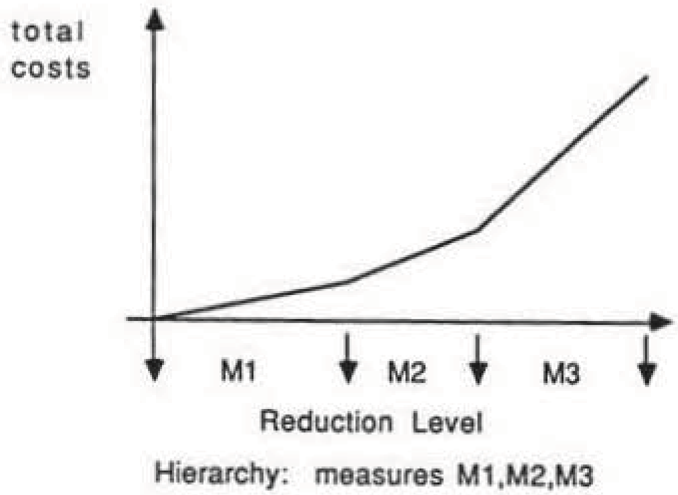

Figure 1: Total costs versus CO_2-reduction level

conversion of the heating system from oil to night storage heating. Moreover, the effectiveness of any switch to electricity on the end-use level depends directly on the structure of the power generation sector.

This analysis establishes a ranking order of measures and their contribution to the objective. Now it is possible to provide a set of measures for each trajectory as requested by the decision maker. Some examples for specific CO_2-reduction costs in [DM_{85}/kg CO_2] is depicted in Table 1.

To handle all steps of CEA in a common framework systems analysts use energy system models. These models support a straight forward approach to CEA and the handling of uncertainties associated with future developments of important economic factors.

Energy Models a Tool for Cost-effectiveness analysis

Models are the principal tools of such systems analytical concepts. The use of a model forces the planner to define a common terminology and helps make the decision process more transparent. Additionally, energy models make it easier to change assumptions or to create new scenarios if it seems to be necessary during different steps of the process [5] [3].

A number of energy models have been developed in the past, applying different methods, setting different system frontiers and spanning different time horizons.

This leads to the question: What is the appropriate model for a cost-effectiveness analysis of CO_2-reduction measures? As already mentioned, CO_2 is an inevitable by-product of the conversion and use of carbon containing fuels. Reduction measures therefore mainly focus on all aspects of energy sup-

Table 1: Specific emission reduction costs for selected CO_2-reduction measures in [DM_{85}/kg CO_2]

Measure	Today	After 2000
Heat Market		
Solar heating of swimming pools	±0	?
Warm water supply incl. 25% solar	0.25	0.5
Switch to gas	±0	?
Insulation of buildings	0.035 - 0.35	-0.12 - 0.19
Power Generation		
Switch from domestic coal to nuclear	-0.094	?
Switch from imported coal to nuclear power	0 - 0.02	?
Photovoltaik	1.4	0.4

ply,conversion, use and demand reduction. Reductions of CO_2 can be achieved (as already mentioned) by fuel substitution, energy conservation and CO_2-removal from the exhaust gas. An energy systems model representing all types of conversion and end-use processes on an appropriate aggregation level appears to be the best modeling tool for cost-effectiveness analyses.

Energy models usually represent a complete national energy system ranging from primary energy extraction and imports, conversion processes and transportation to end-use devices at the level of the consumer. Examplarily, the basic structure of the dynamic energy system model EFOM-ENV (a dynamic linear programming model developed by the Commission of the European Community) is displayed in Figure 2.

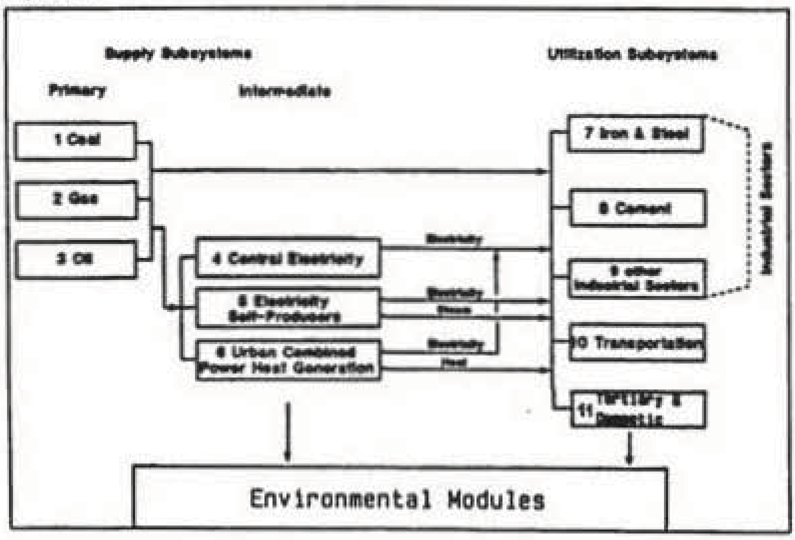

Figure 2: Basic structure of EFOM-ENV

In such models energy conversion and transport technologies are modeled by technical and economic data. These are:

- input and output fuels
- conversion efficiency, technical availability
- existing capacity stock and investment needs for additional capacity
- fixed and variable operating costs
- ancillaries, by-products and other side-effects (e.g. emission factors)

Generally, existing energy models are subdivided into optimisation and simulation models. The main difference is the determination of the activities of energy conversion and transport technologies. While these activities are determined exogenously in simulation, they are a result of the optimisation approach. As far as CO_2 is concerned, the choice of the fuel and technology mix under different emission trajectories is a fundamental task of CEA. This is why optimisation models are discussed in the subsequent paragraphs.

The determination of market shares of fuels and the technological structure is result of the objective function. Existing models use the total discounted costs, but different approaches are possible. Another (optional) element of optimisation models is the use of bounds to define a range of possible activities per fuel and technology. Bounds may represent structural, technical or contractual restrictions. Examples for the implementation of bounds are upper limits for gas contracts, ranges for market shares or emission constraints.

Energy models provide a variety of useful information about the system concerned:

- Primary energy demand
- Capacity requirements
- Average and marginal costs,
- Emission projections
- Various energy related data and balances

Furthermore, optimisation models include some additional features:

- Optimal allocation of fuels, not pre-determined
- Optimal structure of conversion technologies
- Explicit modelling of technology competitiveness
- Straight forward approach to cost-effectiveness analysis
- Shadow prices (e.g. costs to reduce CO_2 by one more unit)
- Optimal combination of interfuel substitution, energy conservation and CO_2-extraction
- Consideration of demand elasticities

Moreover, energy models are able to handle a high degree of detail (technology information).But the adaptation of an energy model to the CO_2-issue requires a detailed analysis of the existing energy systems and the structural elements of a CO_2-benign energy system. Reliable and consistent technical, cost and emission data on different greenhouse gas emissions reducing options are an inevitable prerequisite for the model application. More research is required in the following areas:

- future non-fossil supply options
- energy conservation and technological progress
- CO_2-extraction and transport
- cost curves of domestic primary energy supply
- demand elasticities (price responses)

Technology oriented energy systems models (e.g. EFOM,MARKAL or MESSAGE) have been applied in a number of countries. This work has been carried out on national basis and has covered energy supply planning as well as cost-efficient emission control strategies. Further, policy impacts on the energy sector have been analyzed. This research work has clearly demonstrated the usefulness of energy system models as a tool for CEA.

An example for the successive application of an optimisation model to CEA is the EC-study 'Energy and Environment - Strategy for Acid Pollutant Reduction'. Their objectives were the identification of cost-efficient SO_2- and NO_x-control strategies, the calculation of national cost curves (see Figure 3) and the cost-effectiveness analysis of environment legislation. A sequence of measures was identified reflecting also national specialties of the energy sector (see Figure 4). This analysis was carried out for each member country of the EC using the common framework of the extended EFOM-ENV model. Comparisons of the national results from a European viewpoint yielded useful information for European wide legislation.

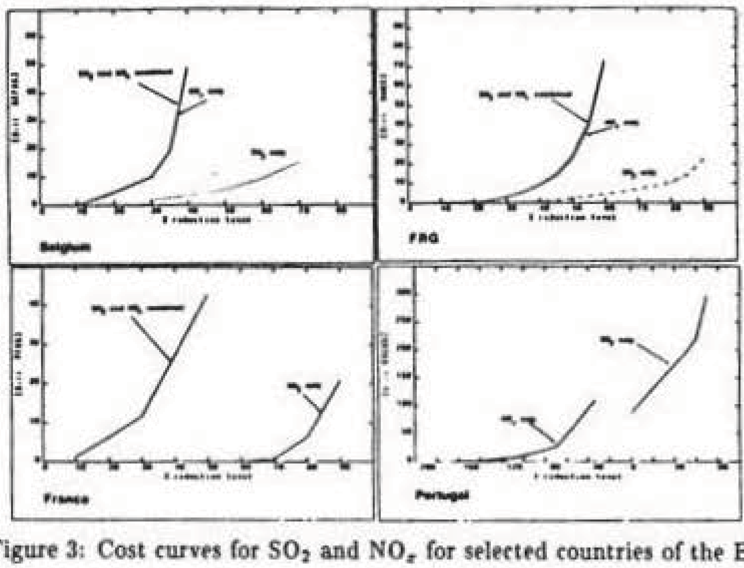

Figure 3: Cost curves for SO_2 and NO_x for selected countries of the EC

To summarize, energy system analyses proved most helpful in identifying least-cost measures leading to pre-specified emission reductions. Additionally, it is a valuable instrument for examining the implications of alternative energy demand scenarios and control technology scenarios on the development of future pollutant emission.

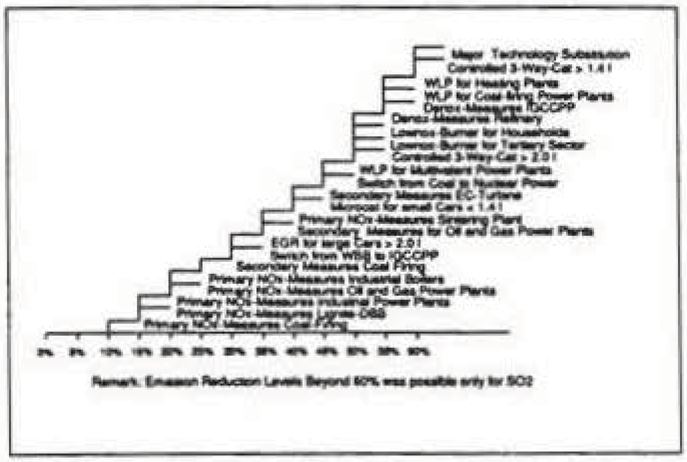

Figure 4: Ranking order for combined SO_2- and NO_x-emission reduction

Uncertainties and Limitations

As already pointed, cost-effectiveness analysis does not only mean the isolated generation of specific reduction costs, but includes a variety of questions linked to the economic assessment of technologies and measures. Moreover, a comprehensive CEA integrates the uncertainty and risk associated with the future developments of important energy-economy factors, such as GDP growth rates, energy price developments and technical progress.

Many of the issues are in close connection with future energy demand and price development. In the case of CO_2, the important influence of fuel prices on the specific reduction costs is obvious, since the cost-effectiveness of fuel switching measures depends mainly on the fuel price differentials. Past decades have shown that the development of energy prices can hardly be forecasted, due to high uncertainties. Moreover, the interrelations between a global CO_2-target and energy prices in world markets are very difficult to identify.

To deal explicitly with the uncertainty associated with decisions in the field of future energy systems several tools have been created and implemented in a common framework called 'systematic analysis of the future' [4]. This approach starts from the call that today's decisions should be based on a scientific evidence. The main target is the identification of imminent actions for the near term future and the consideration of the uncertainties linked to these actions. The following tools can be deployed for this purpose.

- Sensitivity analysis for one or several exogeneous factors which significantly influence the model results (e.g. energy price variation to identify the ranges of specific reduction costs of measures and their ranking order)
- Scenario construction: These are defined 'as self-consistent and interacting socio-political and economic developments, describing a feasible course of events leading into the future'. They should span the whole range of uncertainty [6].
- 'Robust decisions': Decisions which are necessary and correct for a large area of uncertainty.
- 'Tolerated decisions': Actions which do not foreclose any future developments.

This concept is based on the fact that future uncertainties cannot be removed and that policy makers should be aware of this. The evaluation of the risks associated with different decision alternatives enables the policy makers to include a risk preference into the decision making process.

All the aspects of CEA described above can be treated endogenously in a techno-economic optimisation model. But there are several aspects which cannot be handled by such a model. These can be taken into account within the definition of scenarios or evaluated in other models and are summarised as:

- feedbacks between global CO_2-constraint and the world market for primary energy carriers.
- impacts on the economy and feedbacks to the energy system
- socio-political implications

To summarize, existing energy models are a useful tool for the assessment of cost-effective CO_2-reduction measures. Implemented in a well-defined set of scenarios and a systematic analysis of the future, such a model provides useful information.

A Case Study for FRG: Preliminary Results

To demonstrate the usefulness of an optimisation model in a framework of systematic cost-effectiveness analyses a case study was performed addressing the following questions:

- Is the 'Toronto' Conference target of a 20%-CO_2-reduction by the year 2005 feasible for the FRG?
- What are the cost-effective fuel and technology substitution measures reducing CO_2-emissions to the desirable level?
- Do national policies, e.g. domestic coal policies, agree with the control of greenhouse gases?

Therefore, the following scenarios were defined:

1. Base Case: Continuation of the present energy policy, succesive reduction of the obliged coal take-off for utilities and industry ("Jahrhundertvertrag").
2. Toronto Case: Cost-efficient analysis to reach a 20%-CO_2-reduction in 2005 with respect to 1988.
3. Contract Case: Impact on the Toronto Case of a prolonguation of the coal contract between coal mining industries and utilities.
4. Cost-efficient Case: Identification of efficient measures to achieve certain CO_2-reduction levels: 10%, 20%, 25% by the year 2005.

The present model version does not allow a detailed investigation of end-use energy conservation and the removal and disposal of CO_2. But a variety of future supply options and improved technologies are included. The model results indicate the feasibility of meeting the Toronto target, even if the coal contract is extended. Nevertheless, a cost-effective CO_2-abatement strategy implies fundamental structural changes at primary energy level as displayed by Figure 5.

The main structural change concerns the switch from hardcoal and lignite to nuclear power implying a further construction of light water reactors (see Table 2). A 20%-reduction can be achieved by changes

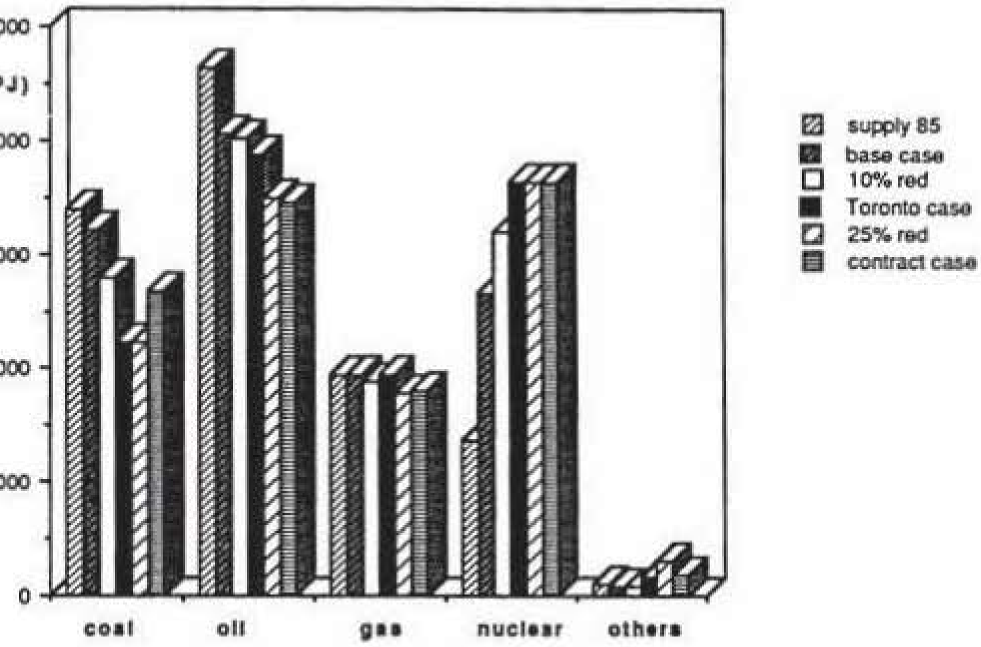

Figure 5: Primary Energy Development by Scenarios and Fuels

in the central conversion sector alone. The extension of the coal contract pushes the introduction of advanced integrated gasification combined cycle power plants due to their higher conversion efficiency (less carbon input).

The economic implications of the different scenarios are displayed in Figure 6. Severe cost increases were identified for the 25%-Case and the Contract case, both implying also restructuring on the energy end-use side also.
The Toronto target can be achieved at the expense of an additional total discounted cost of 10 Billion DM_{85}, that refers to a 0.4% increase of the total energy system costs over the whole time horizon.

The first results of the case study also indicated that further model extensions are required including an improved representation of energy conservation measures in different end-use sectors, a disaggregation of the demand side and inclusion of CO_2-removal and disposal options. This will contribute to a more realistic cost function for the CO_2-reduction in the FRG. The preliminary cost function is given in Figure 7.

Pleading for an international project

Indeed, the greenhouse effect problem can only be solved by an international cooperation. Since individual countries will be affected in different ways, any control strategy can only be effective if national energy policies do not conflict with a globally set CO_2-limit. But this does not necessarily mean that all the countries have to reduce their emissions in the same way. Any reduction strategy must account for the characteristics of national energy systems and the economy like:

- climate

Table 2: Technology Substitution in the Central Conversion Sector

Technology	Base Case	Toronto	Contract
New Technologies			
Combined cycle power plant	-43	-45	-58
Integrated gasification ccpp	-	-	+66
Pressurized fluidized bed combustion	-	-	-
Renewables	-	+1	+1
Existing Technologies			
Dry bottom boiler (steam coal/lignite)	-66	-161	-171
Wet bottom boiler (steam coal)	±0	±0	±0
Nuclear light water reactor	+420	+750	+750
Hydroelectric	+8	+8	+9
Trivalent coal/oil gas	-14	-14	-14
Oil and gas power plants	+69	-22	-30

These figures refer to the difference in annual power generation level in 1985 and in 2005, given in [PJ]

- per capita energy consumption
- energy intensity of the economy
- welfare of the nation, general economic situation
- dependency on domestic fossil fuels
- social acceptance of different supply options

Taking into account these factors the cost-effectiveness analysis must be performed for selected (if not for all) countries representing a group of countries with similar characteristics with respect to the factors mentioned above. For reasons of comparison, it is necassary to accept a common methodology and a consistent data framework. Such an international project should be able to answer these questions:

- How can national energy system be adjusted to different emission levels and what are the related costs (cost-efficient strategies and obstacles)
- How can the burden of a global CO_2-target be distributed across countries of different economic power?
- What are the price effects on world energy markets for different strategies?
- What are the aspects of global supply security and how can they be taken into account?

The national strategies and potentials are to be evaluated from a global perspective. Furthermore, it is necessary to incorporate the assessment of positive side-effects of a CO_2-benign energy system such as technical progress, primary energy conservation, reduction of all kind of pollutants and the reduction of fossil fuels import dependence. Most of these issues can only be evaluated satisfactorily

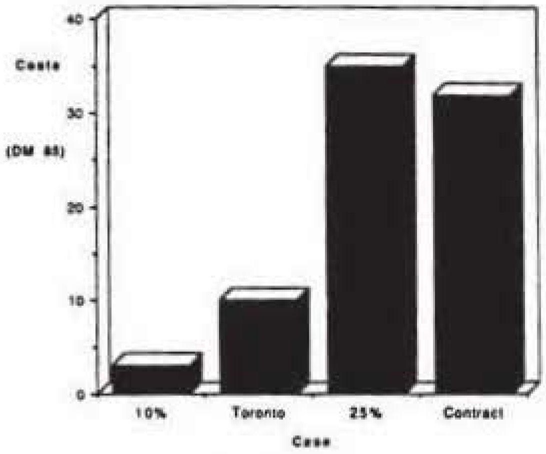

Figure 6: Discounted Additional Costs with respect to the Base Case

on a global level since the interdependences of resources and world markets are very import for this issue.

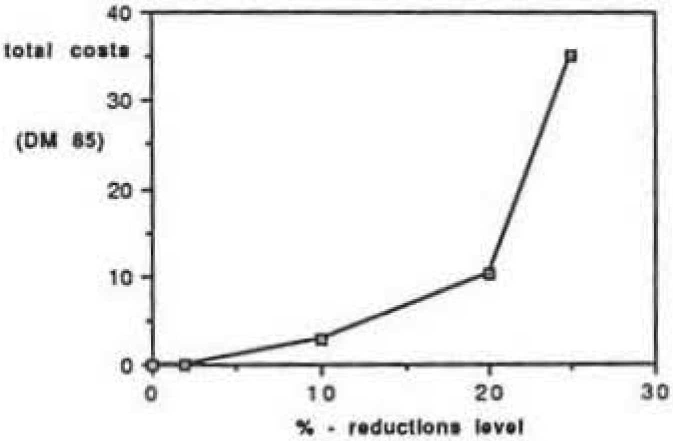

Figure 7: Cost Curve for Emission Reduction of CO_2

References

[1] Mintzer, I.M.:A Matter of Degrees: The potential of controlling the Greenhouse Effect, World Resources Institute, 1987

[2] Kahn,H. and Wiener,A.:The year 2000. A framework for speculation on the next thirty three years, Hudson-Institute, New York, 1967

[3] Voß,A.:Nutzen und Grenzen von Energiemodellen - einige Grundsaetzliche Ueberlegungen, Angewandte Systemanalyse 3(3) 111-117,1982

[4] Voß,A.:Moeglichkeiten und Grenzen von Energieprognosen, in: A.Voß, Existenzfrage Energie, Econ, Duesseldorf - Vienna, 1980

[5] Kübler,K. Einsatzmöglichkeiten von Energiemodellen fuer die Energiepolitik - Grundlagen, Entwicklungsstand und Perspektiven, Angewandte Systemanalyse Band 4, Heft 4, 1983

[6] Stümke W. and Löw A.: Angewandte Systemanalyse in der Praxis eines Energieversorgungsunternehmens; Angewandte Systemanalyse Band 1/Heft 4(1980)

[7] Voß,A. et. al: Energy and Environment - Optimal Control Strategies for Reducing Emissions from Energy Production and Energy Use, Schlussbericht fuer das Bundesministerium fuer Forschung und Technologie, 1988