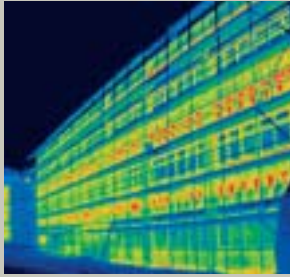




Forschungszentrum Jülich  
*in der Helmholtz-Gemeinschaft*



# Energy Systems Analysis for Political Decision-Making

J.-Fr. Hake, W. Kuckshinrichs, R. Eich (Ed.)



**Energietechnik**  
**Energy Technology**







Forschungszentrum Jülich GmbH  
Programmgruppe Systemforschung und  
Technologische Entwicklung

# Energy Systems Analysis for Political Decision-Making

Jürgen-Friedrich Hake, Wilhelm Kuckshinrichs, Regina Eich (Ed.)

Schriften des Forschungszentrums Jülich  
Reihe Energietechnik / Energy Technology

Band / Volume 32

---

ISSN 1433-5522      ISBN 3-89336-365-3

Bibliographic Information published by Die Deutsche Bibliothek.  
Die Deutsche Bibliothek lists this publication in the Deutsche  
Nationalbibliografie, detailed bibliographic data are available in the  
Internet at <<http://dnb.ddb.de>>.

Publisher and  
Distributor: Forschungszentrum Jülich GmbH  
Zentralbibliothek  
52425 Jülich  
Phone +49 (0)2461 61-5368 · Fax +49 (0)2461 61-6103  
e-mail: [zb-publikation@fz-juelich.de](mailto:zb-publikation@fz-juelich.de)  
Internet: <http://www.fz-juelich.de/zb>

Cover Design: Grafische Betriebe, Forschungszentrum Jülich GmbH

Printer: Grafische Betriebe, Forschungszentrum Jülich GmbH

Copyright: Forschungszentrum Jülich 2004

Schriften des Forschungszentrums Jülich  
Reihe Energietechnik/Energy Technology Band/Volume 32

ISSN 1433-5522  
ISBN 3-89336-365-3

Neither this book nor any part of it may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.

**ENERGY SYSTEMS ANALYSIS FOR  
POLITICAL DECISION-MAKING**



## Content

PREFACE .....	5
INTRODUCTION.....	7
SUSTAINABLE DEVELOPMENT AND ENERGY – PRESENTING CONNECTIONS BETWEEN THESE TWO CONCEPTS .....	15
<i>R. Eich, J.-Fr. Hake</i>	
COMPARISON OF GERMAN AND EUROPEAN ENERGY SCENARIOS.....	33
<i>P. Markewitz, G. Kolb, S. Vögele</i>	
MEASURES FOR CO <sub>2</sub> REDUCTION IN GERMANY.....	61
<i>D. Martinsen, P. Markewitz, S. Vögele</i>	
THE ROLE OF MODERN FOSSIL POWER PLANT CONCEPTS IN EUROPE.....	75
<i>P. Markewitz, S. Vögele</i>	
CO <sub>2</sub> CAPTURE AND STORAGE .....	89
<i>G. Kolb</i>	
THE RESIDENTIAL BUILDING SECTOR – POTENTIALS AND CONSTRAINTS OF CO <sub>2</sub> MITIGATION.....	115
<i>M. Kleemann</i>	
SCENARIO STUDY: DEVELOPMENT OF EMISSIONS IN THE GERMAN TRANSPORT SECTOR .....	133
<i>J. Linssen, M. Walbeck</i>	
STRATEGY WITH REGARD TO FUEL-CELL SYSTEMS FOR MOBILE AND STATIONARY APPLICATIONS .....	151
<i>B. Höhle, Th. Grube</i>	
LCA AND ENERGY TECHNOLOGIES.....	161
<i>P. Zapp</i>	



## Preface

Sound political decision making requires input from various sources. Science represents one important source. Among the scientific disciplines systems analysis particularly provides the means for knowledge transfer between science and political decision making because systems analysis incorporates a multidisciplinary approach covering the spectrum from engineering and the natural sciences to economics and the political sciences.

For instance, the development of an efficient, environmentally friendly and safe energy supply system may be regarded as one of the great challenges a country continuously has to face. In industrialized countries like Germany, the results from systems analysis have been used very fruitfully for this task since the early 70s. For this purpose energy models have been developed to provide the analyst with an appropriate tool. Over the years the number of energy models has increased significantly and the models have become more sophisticated. However, one can identify a few lighthouse projects representing the state of art. The IKARUS Project on behalf of the German Government may serve as such an example where a large number of institutions from science and industry have been involved to establish a solid platform for the debate on the future German energy system under the boundary conditions of climate protection. This effort led to a large database containing the relevant data and a family of models covering the various aspects of the energy system. After successful completion of these tools they have served to formulate the official German strategy to achieve reductions in the emissions of energy related greenhouse gases according to the Kyoto process. But even such a big effort cannot cover all aspects of technology evaluation and as political decision making proceeds to new or modified targets the tools of energy systems analysis have to be updated.

This volume provides an overview of methods and corresponding results in the field of energy systems analysis at Forschungszentrum Jülich. The papers have been prepared on the occasion of a visit of an Iranian delegation of experts from the Iranian Energy Ministry and have served as our input for the intensive bilateral discussions. Encouraged by the feedback of our Iranian guests and colleagues we have decided to provide the material to a broader public.

Jülich, August 2004

Jürgen-Friedrich Hake Dr. Wilhelm Kuckshinrichs Dr. Regina Eich



## Introduction

### *Change and Sustainable Development*

Change represents an intrinsic property of human and societal development. For the past decades, the impact of technology on these processes can hardly be overestimated. Science and research do not only accelerate developments but also lead to changes in perspectives based on technological progress. Telecommunication technologies now support individual and institutional global communication. Transportation of goods and passengers is no longer restricted to countries or continents and has been significantly accelerated. Global markets have been established for economic transactions and for the production and consumption of agricultural and industrial goods.

These impressive developments have also led to a global view on the environmental and social conditions of life. Differing environmental standards will lead to the export of emissions from countries with higher standards and specific production costs to developing countries with less advanced environmental regulation. For instance in the case of greenhouse gas emissions leading to climate change the export of emissions will not provide a solution. In any case the result will be an increase in global mean temperature in the lower atmosphere. Severe damages to the natural life support system have to be expected [Intergovernmental Panel on Climate Change 2001].

Global markets provide new business opportunities, but have also enlarged the number of players and increased competition among them. In many cases the position of production units is now subject to international competition resulting in additional pressure on labour forces and creating social stress.

Sustainable Development represents the political response to these grand challenges. This guiding principle acknowledges the responsibility of the present generation

1. to reduce poverty in the present generation, but also
2. not to exhaust the resources for future generations [World Commission on Environment and Development 1987].

Over the past two decades, several institutions have worked out concepts to derive a more concrete vision of Sustainable Development. In this context, global development goals have been postulated for a few fields [United Nations 2000]:

- **Poverty and Hunger**

*„to halve, by 2015, the proportion of the world's people who suffer from hunger and whose income is less than one Dollar a day“*

- **Health**

*„by 2015, to reduce the rate of maternal mortality by  $\frac{3}{4}$ , the death rate for children under the age of 5 years by  $\frac{2}{3}$  and to have halted and begun to reverse the spread of AIDS and other major diseases“*

- **Environmental Sustainability**

*„to halve, by 2015, the proportion of people who are unable to reach or afford safe drinking water and to stop the unsustainable exploitation of natural resources“*

- **Universal Primary Education**

*„to ensure that, by 2015, children everywhere will be able to complete a full course of primary education“*

- **Gender Equality and Women´s Empowerment**

*“make progress towards empowerment of women by ensuring girls and boys have equal access to primary and secondary education”.*

As a further result of this process to make Sustainable Development operational certain key action areas have been defined: water, energy, health, agriculture and biodiversity [United Nations 2002].

From the beginning of the debate on Sustainable Development the energy system is particularly in the focus of concepts because of its cross-cutting function.

### *Energy and Sustainable Development*

The Brundtland Commission stated “energy is necessary for daily survival. Future development crucially depends on its long-term availability in increasing quantities from sources that are dependable, safe and environmentally sound. At present, no single source or mix of sources is at hand to meet this future need” [United Nations 2002]. This statement is still right. An additional important restriction for the energy system arises from climate change which is closely related to the consumption of fossil energy carriers. Hence, there is a need for an optimized energy system providing least cost energy services while obeying the prescribed environmental standards at the same time.

Topics of energy demand and supply have to be addressed at least at three levels: global, regional, national. At each level the abstract representation of the energy system as indicated by Fig. 1 remains the same, but for any concrete energy level the corresponding data and parameters have to be identified and give Sustainable Development a concrete meaning.

At the global level, most experts foresee an increasing energy demand for the next half century [International Energy Agency 2002]. The overarching problem consists in finding a concept that allows the rich countries to maintain their high level of welfare with less consumption of natural resources and to stimulate development in the poorer countries to reduce poverty. In both cases the decoupling of welfare from the use of natural resources has to be achieved. The challenge is twofold: Reducing the poverty gap within the individual countries and also globally. Economic poverty is closely related to energy poverty. So far, no solution has been found. For the World Summit on Sustainable Development (WSSD) held at Johannesburg in 2001 a list of key issues and corresponding action areas has been assembled for the energy sector. Access to energy services is placed on top of the list at Tab. 1. The next three

topics indicate how this should be achieved. The last topic addresses the energy demand of the transport sector directly.

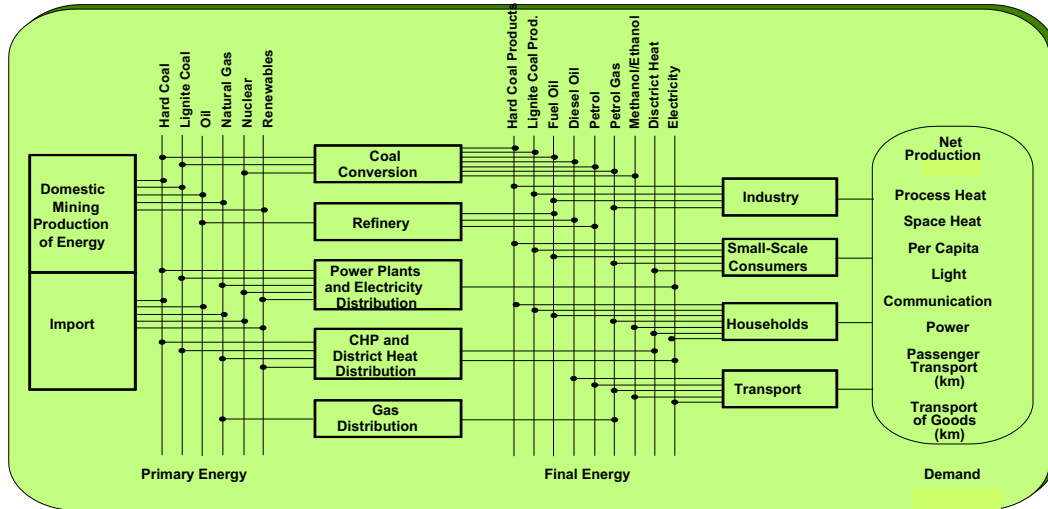


Fig. 1: Technical representation of the energy system

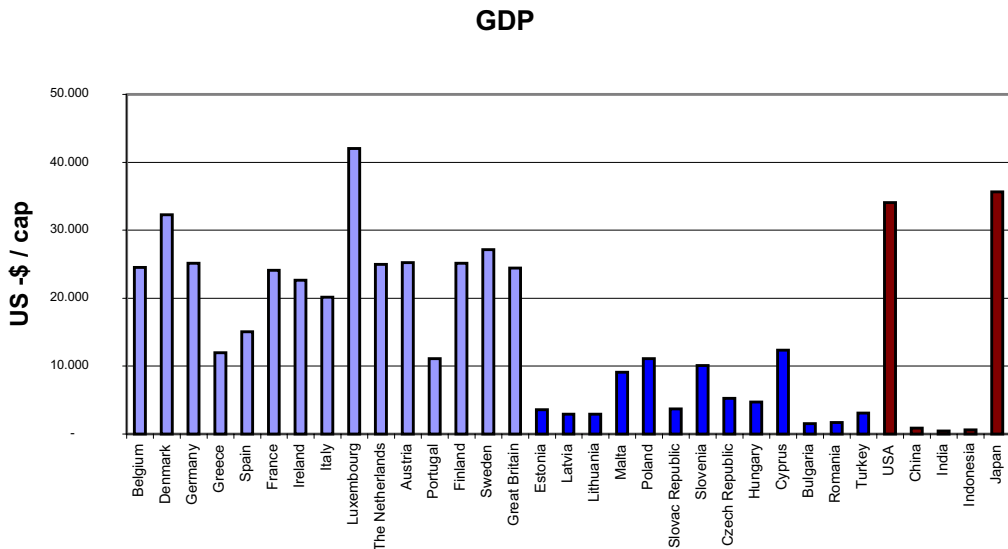
Key Issue	Action Areas
1. Access to energy and modern energy services	<ul style="list-style-type: none"> <li>- Reduce poverty by providing access to modern energy services in rural and peri-urban areas.</li> <li>- Improve health and reduce environmental impacts of traditional fuels and cooking devices.</li> <li>- <u>Improve access to affordable and diversified energy sources in Africa.</u></li> </ul>
2. Energy efficiency	<ul style="list-style-type: none"> <li>- Reduce poverty by providing access to modern energy services in rural and peri-urban areas.</li> <li>- Improve energy efficiency in all sectors using established practices on standards and labelling techniques.</li> <li>- <u>Improve efficiency in power generation.</u></li> </ul>
3. Renewable energy	<ul style="list-style-type: none"> <li>- Progressively increase contribution of renewable energy mix of all countries.</li> <li>- Improve access to basic health care and education for poor people through the provision of renewable energy systems in primary health care centres and schools.</li> <li>- Promote the use of renewable energy in vaccine and immunisation programmes.</li> <li>- Provide the use of renewable energy to facilitate access to safe drinking water.</li> </ul>
4. Advanced fossil-fuel technologies	<ul style="list-style-type: none"> <li>- Increase the use of advanced fossil fuel technologies for energy generation.</li> <li>- Promote the use of clean coal technologies in countries using coal.</li> <li>- Reduce atmospheric pollution from energy generating systems.</li> <li>- <u>Enhance productivity through advanced fossil fuel technologies.</u></li> </ul>
5. Energy and transport	<ul style="list-style-type: none"> <li>- Improve air quality and public health through the introduction of cleaner vehicular fuels.</li> <li>- Implement better transportation practices and systems in mega-cities.</li> <li>- <u>Promote new technologies for transport.</u></li> </ul>

Tab. 1: Key issues and action areas for the energy sector [United Nations 2002]

Several initiatives deal with the above mentioned key issues. For instance the Global Network on Energy for Sustainable Development (GNESD) represents a UNEP facilitated knowledge network of partners aiming for enhanced capacity of national institutions in developing countries for integrated solutions to energy, environment and development challenges [GNESD].

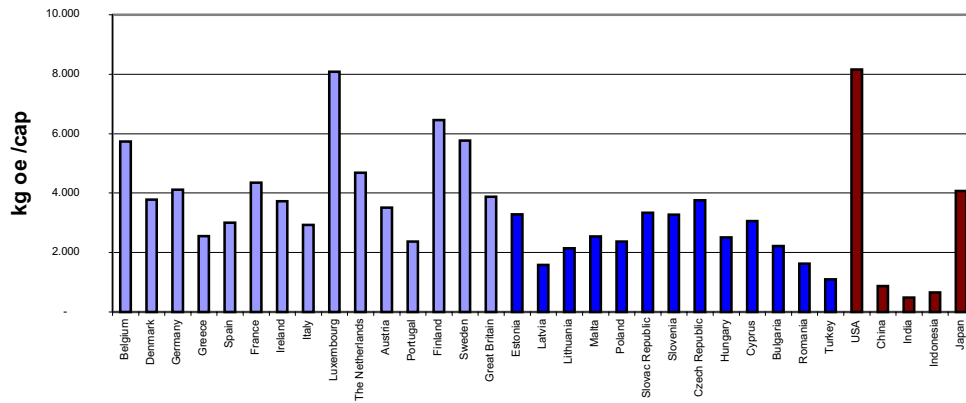
At the *regional level* multi-national organizations like the European Union have to interpret the meaning of Sustainable Development with respect to the requirements of the people belonging to their member states and to their energy sectors. Presently, the EU comprises 25 member states representing all together an economic power of comparable size like North America. A closer look shows the large variety of GDP and energy consumption per capita in the individual member states. In comparison to the “old” 15 member states the new EU member states belong to a category of less economic power (Fig. 2).

In contrast to the picture on GDP, the energy consumption per capita in the various “new” member states is quite high indicating a less efficient national energy system (Fig. 3). Hence, setting the framework for modernization of the energy system represents a major task for a European energy policy. The Commission of the EU structures the European energy market by issuing directives prescribing the directions for Sustainable Development in the corresponding sector. National policies have to implement appropriate laws and measures. Their implementation in the individual member states is regularly benchmarked [European Commission 2004].



**Fig. 2:** GDP of European member states [Wold Bank 2003]

## Energy

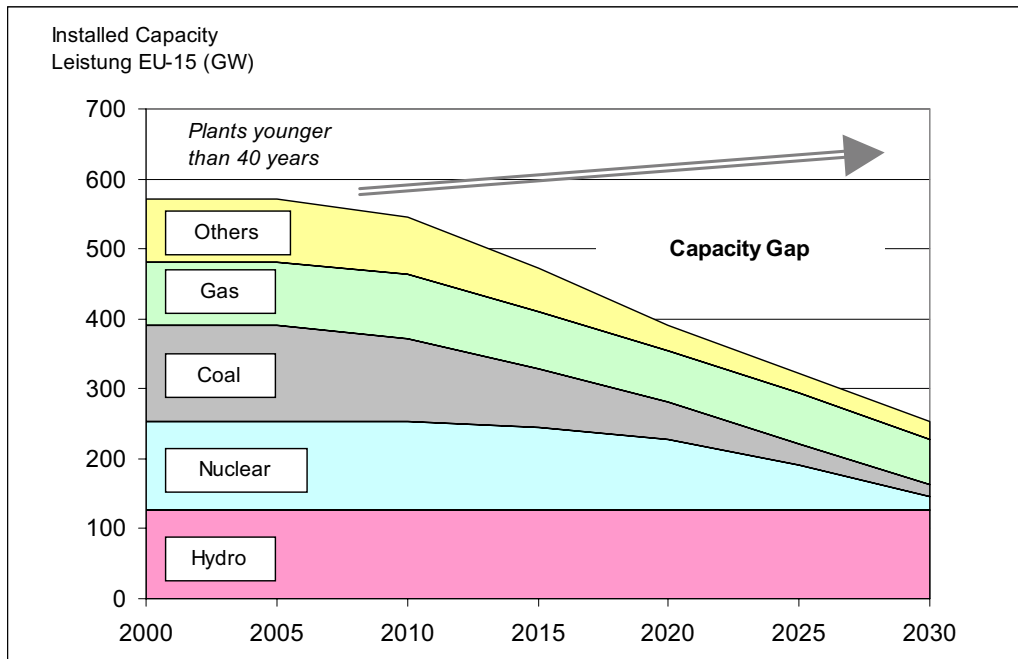


**Fig. 3:** Energy consumption per capita of European member states [European Commission 2004]

The energy sector of the EU-15 will face a severe capacity problem in the conversion sector very soon [European Commission 2004]. Assuming a moderate growth of electricity demand for the next 30 years and an expected life-time of power plants of approximately 40 years results in a growing capacity gap of 250 GW already in 2020 (Fig. 4). It is one of the main obligations of European energy policy to establish appropriate boundary conditions for investment.

At the *national level*, industrialized countries like Germany play an important role because they have been the drivers of global economic and political development in the past. Over the last decade Germany has been strongly committed to Sustainable Development and consequently a strong promoter of renewable energy technology and of an active policy for mitigation of climate change. The present situation of the German electricity sector is similar to the European situation. An increasing demand for new power plants has been identified. Estimates show that – similar to the EU – a capacity of 40 GW has to be replaced.

In contrast to the industrialized countries developing and less developed countries face a different category of problems. In most cases they miss a differentiated infrastructure for energy supply. Lack of capital hinders appropriate investment. Moreover, experts are concerned that simply copying a path of development from an industrialized country will only work for a very limited number of poor countries. If adopted by the majority of the poorer countries this model would lead to an exhaustion of natural resources for all countries.



**Fig. 4:** Capacity gap for electricity generation in the European Union [BMWA 2003]

### *Energy Research for Sustainable Development*

All concepts under consideration are strongly based on technology. Existing technology will not suffice to fulfil future global energy demand. Increased efficiency represents a major part of the solution. In addition, there exists a strong request for new technological options on both sides: production and demand. Experts point out that even an efficiency revolution would require measures to reduce demand.

These few examples show that permanent change is intrinsic to development and hence indicates an ongoing demand for analysis and research. Particularly, energy research has to be intensified. In the context of Sustainable Development the scope of energy R&D has to be reconsidered. An energy R&D programme has to generate a broad spectrum of different topics – ranging from materials research to Sustainable Development. For this purpose it has to cover a broad spectrum on different topics comprising at least five interrelated fields:

- Advances in materials research provide the basis for higher efficiencies of energy technologies. Most energy technologies require high temperature materials.
- Computer-based simulation represents another source of stimulation of energy research.

- Increases in the efficiency of energy technologies also originate from the optimization of subcomponents and their interaction.
- Energy R&D has also to cope with the manufacturing processes of technologies.
- Systems Analysis represents another pillar of energy research.

### *Energy Systems Analysis and Sustainable Development*

In general, systems analysis provides the means to analyse complex problems arising for instance in the context of societal guiding principles. The methodological challenge of Sustainable Development can be characterized by its high complexity and the requirement of a multi-disciplinary approach covering political, economic and natural sciences. Uncertainties and incomplete information represent additional characteristics. In most cases, multi-criteria decision support has to be provided for political decision-making. Energy systems analysis addresses these problems with respect to the overarching guiding principle of Sustainable Development. Regina Eich and Jürgen-Friedrich Hake give a survey on the present status of the discussion.

Scenarios represent an important approach to make guiding principles like Sustainable Development operational because they offer the possibility of a systematic analysis of energy system with respect to economic and ecological boundary conditions. The article by Peter Markewitz, Gerhard Kolb and Stefan Vögele focuses on energy outlooks for Europe and Germany.

Dag Martinsen and his colleagues discuss measures for CO<sub>2</sub> reduction in Germany. This topic has played a major role in the political debate of the past decade. The results of their study may be regarded as representative for the IKARUS project on behalf of the German government.

The conversion sector, particularly the electricity sector has to bear an increasing load for energy supply. Peter Markewitz and Stefan Vögele analyse the role of modern fossil power plant concepts in Europe. The results of this study provide useful insights for a strategy to overcome the already mentioned gap in European power plant capacity.

Mitigation of climate change represents the most important global challenge to the energy sector because it fundamentally questions the role of fossil fuels. Besides mitigation of greenhouse gas emissions the option of capturing GHG emissions and storing them in suitable reservoirs for a long period of time represents an explorable possibility. Gerhard Kolb examines the status of this new option.

Manfred Kleemann addresses the potentials and constraints of CO<sub>2</sub> mitigation in the residential sector for Germany. Over the past years, great attention has been paid to this topic but - as the author points out - action is still required.

In addition to the residential sector, the transport sector has to play a major role in mitigating climate change because in many countries this sector still leads to an in-

creasing demand for fuel and to increasing emissions of CO<sub>2</sub>. Jochen Linssen and Manfred Walbeck provide a scenario study for that problem.

Fuel cells in a hydrogen based energy economy represent an option for long-term perspectives of future energy supply. Bernd Höhle and Thomas Grube discuss corresponding technological aspects in their paper.

The evaluation of energy technologies according to guiding principles like Sustainable Development represents a major challenge to systems analysis. Petra Zapp outlines the potential of Life Cycle Assessment with respect to energy technology.

This list of papers shows to a great deal the various facets of energy systems analysis. However the systems analysts from other institutions could easily extend the list with other very interesting topics.

## References

### **[Altvater 2004]**

Altvater, Elmar, Birgit Mahnkopf: Grenzen der Globalisierung. Münster 2004.

### **[International Panel on Climate Change 2001]**

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2001. Cambridge University Press, Cambridge 2001.

### **[World Commission 1987]**

World Commission on Environment and Development (WCED): Our Common Future. Oxford, New York 1987. p. 43.

### **[United Nations 2002]**

United Nations – WEHAB Working Group: A Framework for Action on Energy. World Summit on Sustainable Development. Johannesburg 2002.

### **[IEA 2002]**

International Energy Agency (IEA): World Energy Outlook 2002. Paris 2002.

### **[GNESD]**

Global Network on Energy for Sustainable Development (GNESD). For further informations : [www.gnesd.org](http://www.gnesd.org).

### **[World Bank 2003]**

World Bank: World Development Report. New York 2003.

### **[European Commission 2004]**

European Commission: Third Benchmarking Report on the Implementation of the Internal Electricity and Gas Market. Brussels 2004.

### **[BMWA 2003]**

Bundesministerium für Wirtschaft und Arbeit: Research and Development Concept for Zero-Emission Fossil-Fuelled Power Plants - Summary of COORETEC. Berlin 2003.

# **Sustainable Development and energy – presenting connections between these two concepts**

R. Eich\*, J.-Fr. Hake\*

## **1 Introduction**

The term of "Sustainable Development" plays a major role in the debate on a future-oriented social development. It denotes a concept whose central element consists in the linkage of economic progress to the conservation of our natural environment and to maintaining social justice. The starting point is the observation that, although the development in the past has brought prosperity for many people, a much greater proportion of mankind still lives in poverty and in underdeveloped conditions. Closely related to this status description is the view that both the nature of present-day economic activities and the current patterns of behaviour and consumption in the industrialized countries are probably not suited as a model for future development, but may rather lead to serious disturbances in ecological, economic and social subsystems. The concept of Sustainable Development thus links the issue of conserving the natural basis of life for future generations to the claim for economic prosperity and social development of the people living at present.

Besides the demand for clean drinking water and food, the energy issue is among the problems to be primarily solved in the context of a steadily growing world population. The sufficient availability of useful energy is a basic prerequisite for economic and social development. The production, conversion and use of energy, however, also involve risks and consequential effects that should not be neglected or underestimated. The provision of useful energy for eight to twelve billion people in future, of whom a large percentage will probably live in conurbations with several million inhabitants each, has several geopolitical dimensions which should not be ignored.

The unequal geographical distribution of global energy reserves and the demand which strongly deviates from this distribution require a flexible and also robust system of international trade and supply relations. The commitments to active climate protection resulting from the United Nations Framework Convention on Climate Change and from the Kyoto process can also only be fulfilled in close international cooperation.

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

In this essay, considerations will be presented and discussed concerning the possibilities of implementing Sustainable Development in international context and concerning the effects this may have on the sector of energy policy and energy supply.

## **2 The concept of Sustainable Development - a short overview**

In 1972 an "Action Plan for the Human Environment" was adopted by the UN General Assembly. It contained measures and agreements in the following fields: the worldwide acquisition of environmental data, the sector of environmental research, the exchange of information, the careful handling of resources, the creation of global environmental administrations and the targeted education, training, and information of the population.

A first step was to establish an independent environment secretariat designated "UNEP" with headquarters in the Kenyan capital Nairobi. In this context, Maurice Strong, the first Executive Director of UNEP, coined the term of "ecodevelopment" for this new development strategy. The expression "ecodevelopment" was replaced in the early 80s by the term of "Sustainable Development". This term was used for the first time by the International Union for the Conservation of Nature (IUCN) in 1980. Its statements can be summarized, in essence, to the effect that without intact ecosystems any further economic development would lose its basis in the longer run and would ultimately not make sense anymore.

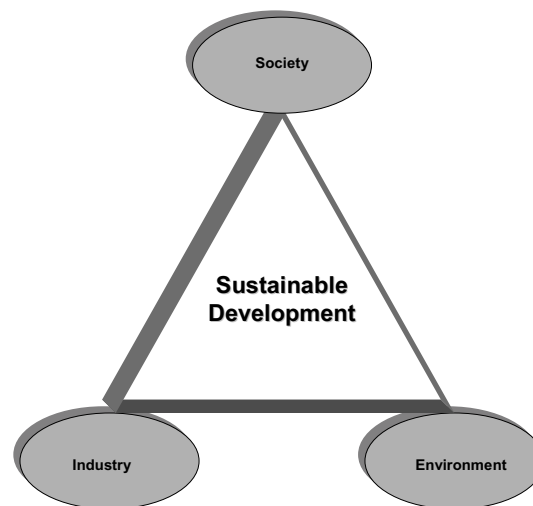
The aim of the programme established under the control of UNEP was to show up a middle course between the conflicts emerging in the early to mid-70s between the eco- and the technocentric positions concerning the value of the environmental protection concept. The concept of ecodevelopment, which in the beginning was mainly meant as a development approach towards supporting the efforts for the predominantly rural regions in Africa, Asia, and South and Latin America, due its theoretical basic assumptions opened up the possibility of establishing a new definition of development, growth and prosperity going beyond the original target groups in the Third World.

In the history of the origin and further development of the overall concept of Sustainable Development, the report "Our Common Future" presented in 1987 by the United Nations Commission on Environment and Development represents a milestone despite the work already performed by UNEP before. The commission is generally called "Brundtland Commission" after its chairwoman, the Norwegian politician Gro Harlem Brundtland. Starting out from the problem of finite resources, on the one hand, and unequally distributed prosperity and resource consumption, on the other, the Commission formulated the following definition of Sustainable Development: "Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [World Commission 1987]. Sustainable Development thus centres on a fiduciary use and at the same time also on the conservation of the basis for life available to humans for subsequent generations. In its report, the Commission also referred to the necessary limitation of anthropogenic material inputs into existing ecological cycles. Relative to

the greenhouse effect, a restriction of the energy-related emission of greenhouse gases against the background of global climate change was already claimed here.

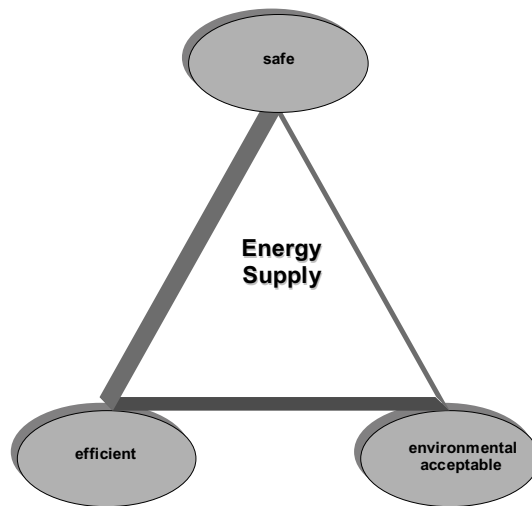
### 3 Sustainable Development and energy

Since the adoption of Agenda 21 the energy issue has been at the centre of the Rio process – either directly, if aspects of supply for humans are concerned, or indirectly, if the anthropogenic greenhouse effect is dealt with. At the special session of the United Nations General Assembly in 1997 ("Rio plus 5") the interdependence of Sustainable Development and the production, distribution and use of energy was emphasized once again. The General Assembly declared this topic to be a priority of work of the United Nations Commission on Sustainable Development (CSD-9) in 2001. In preparation of the debate the United Nations Development Programme (UNDP), the United Nations Department of Economic and Social Affairs (UNDESA) and the World Energy Council (WEC) had a "World Energy Assessment" carried out. The results have been available since the year 2000. The associated report constitutes a comprehensive review of the social, economic and ecological aspects of energy supply and its use and of issues of supply assurance but the report hardly addresses the structural change in the energy sector currently taking place at company level [UNDP 2000].



**Fig. 1:** Three dimensions of Sustainable Development

At the world summit on Sustainable Development in Johannesburg, the energy issue was on the agenda again in a prominent position under the heading "Access to Energy and Energy Efficiency".



**Fig. 2:** Three-pillar concept of energy supply

### 3.2 *Brundtland-Commission*

The adequate supply with useful energy, on the one hand, forms the basis for life in line with human dignity and an efficient society. On the other hand, the material flows associated with energy use dominate all the other material flows initiated by humans on the earth. The issue of future energy supply therefore occupies a prominent position in connection with the concept of Sustainable Development.

In the seventh chapter of its 1987 published final report "Our Common Future", the Brundtland Commission dealt at great length with the topic of energy. The introductory formulations there read as follows: "Energy is necessary for daily survival. Future development crucially depends on its long-term availability in increasing quantities from sources that are dependable, safe, and environmentally sound. At present, no single source or mix of sources is at hand to meet this future need" [World Commission 1987].

The central question is how to ensure a globally permanent and reliable energy supply in the future. The commission arrives at the following conclusions here: present-day energy supply is based to a major extent on fossil fuels such as oil, coal and natural gas. Abandoning the use of these energy carriers on a larger scale does not seem possible. At all levels, however, there are great potentials for a more efficient use than in the past. The Brundtland-Commission derives the following claims for a Sustainable Development in the energy sector:

- expansion of energy supply to meet the demand for energy services to a sufficient extent worldwide,
- measures to improve efficient energy use,
- reduction of health risks associated with energy use,
- measures for the protection of the biosphere and prevention of the increase of local environmental pollution.

The recommendations derived by the Brundtland-Commission can be subsumed under the following keywords:

- lowering specific per-capita energy consumption,
- expanding the investments for the development of technologies and mechanisms resulting in a reduction of energy consumption and
- reducing the provision of energy from non-renewable resources.

In order to achieve these goals also in practice, the Brundtland-Commission considers fundamental political and institutional adaptations in the energy sector to be necessary. At the same time, it underlines that a specific reduction in energy consumption can only be achieved by an optimum use of the currently available energy sources. Optimum use is understood by the commission to be the consumption of the least expensive environment-friendly energy source [World Commission 1987]. In its judgement, it is only possible within the framework of a national sustainability strategy to set the future course for a sustainable energy policy. The commission argues that its proposed goals should not be achieved by prohibitions and restrictions, but by a policy of incentives.

### 3.2 *UN-Summit in Rio de Janeiro*

The results of the Brundtland-Commission led in 1992 to the International United Nations Conference on Environment and Development in Rio de Janeiro. Its aim was to initiate a global - newly structured - cooperation in environmental and development policy focussing on the stepwise implementation of the "Sustainable Development" concept. Within the framework of the Rio Conference, in addition to the conventions on climate protection and biodiversity, a declaration on forests and Agenda 21 – an action plan for Sustainable Development – was also adopted. In the following time, the term of "Sustainable Development" developed into the central overall concept for further environmental discussions. However, it also became apparent very soon that Sustainable Development comprises problems and topics going far beyond environmental issues. This has been evidenced by the world conferences held since 1992 by the Commission on Sustainable Development (CSD) established at the conference in Rio de Janeiro. The CSD was instituted - without time restrictions - as a commission of the UN Economic and Social Council (ECOSOC). It is in its function an inter-state forum which provides advice on issues of Sustainable Development in general and on the establishment and enforcement of an overall concept of Sustainable Development.

Individual interests threaten to slow the process down or even bring it to a standstill as the political deliberation process progresses and technical aspects are given priority, at least temporarily, in the concrete formulation of individual agreements. Thus, for example, the "Rio plus 5" Conference in New York, at which in 1997 a balance of the Rio process progressed until then was to be struck, took place in a rather sceptical environment. In the meantime, the phase of disappointment seems to have been superseded by realism. The negotiating parties involved as well as the NGOs active in this context seem to have accepted that the complexity of the deliberation process demands its (justified) price in terms of speed. At the world summit on Sustainable Development ("Rio plus 10") in Johannesburg in 2002 – initiated by the United Na-

tions Secretary-General – the debate will continue to be characterized by the topic of "Implementing Agenda 21".

### 3.3 *UN-Summit in Johannesburg*

The focus in the energy sector during the Johannesburg-Summit was concentrated on four major topics: renewable energy, access to energy, energy markets and energy efficiency.

The Johannesburg Summit was terminated with the aim to diversify the energy supply by a substantial increase of the share of renewable energy to the total energy supply. The WSSD also pointed out the necessity to improve the access to reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources. This also includes the removal of market distortions including the restructuring of taxes and the phasing out of harmful subsidies and support efforts to improve the functioning, transparency and information about energy markets with respect to both supply and demand. The aim was to achieve greater stability and to ensure consumer access to energy services [United Nations 2002]. This includes efforts to improve the energy efficiency and the promotion of research and development.

## **4 The implementation of Sustainable Development in the energy sector**

Since the adoption of Agenda 21 the energy issue has been at the centre of the Rio process – either directly, if aspects of supply for humans are concerned, or indirectly, if the anthropogenic greenhouse effect is dealt with. At the special session of the United Nations General Assembly in 1997 ("Rio plus 5") the interdependence of Sustainable Development and the production, distribution and use of energy was emphasized once again. The General Assembly declared this topic to be a priority of work of the United Nations Commission on Sustainable Development (CSD-9) in 2001. In preparation of the debate the United Nations Development Programme (UNDP), the United Nations Department of Economic and Social Affairs (UNDESA) and the World Energy Council (WEC) had a "World Energy Assessment" carried out. The results have been available since the year 2000. The associated report constitutes a comprehensive review of the social, economic and ecological aspects of energy supply and its use and of issues of supply assurance [UNDP 2000], but the report hardly addressed the structural change in the energy sector currently taking place at company level (see Figure 1 and 2).

### 4.1 *Presentation of different indicator sets*

Indicators for Sustainable Development in the energy sector are components of a more complex higher-level system, where they play a central role, however, due to the significance of the energy sector. From the top-down perspective, a disaggrega-

tion of indicators can be involved in a change to the next lower level. At the end of this multistage process there are frequently measurable indicators for which it is then possible to fix barriers, limits etc. in the sense of specifications as required.

The starting point is the assumption that the indicator sets derived for the different dimensions are universally applicable, taking into account, however, the different initial requirements of the respective countries. In the field of energy supply and energy use, one of its major aims is to uncouple energy and resource consumption from economic growth. This includes the economic efficiency goal for producers and consumers, the conservation of the environment, climate and resources as well as the security of energy supply.

The aim of sustainable climate protection and energy policy is manifested in the elements of the target triangle, which should be in a consistent relation to each other (see Figure 1 and 2).

#### 4.1.1 *UN – CSD*

The indicator system of the CSD, which develops on the OECD indicator system, was adopted 1995 at the third meeting of the CSD. The CSD system was supported by intensive methodical-conceptual pre-working more differently international mechanisms, e.g. US ACT, UNEP, World Bank, OECD as well as the non-governmental organizations WWF International and New Economics Foundation (NEF).

The CSD system is tested at present in 22 countries (e.g. Germany) on practicability and completeness. In Germany an interministerial working group under the leadership of the Federal Ministry of Environment was formed. Additionally studies were assigned to compile the indicators for the ranges environmental awareness and environmental formation, sustainable consumption, sustainable traffic and international institutions [United Nations 2002]. The Federal Government published the indicator catalogue adapted on Germany in April 2000 [Bundesregierung 2002]. This catalogue served as basis for the new consultation of the general indicator catalogue on the 9th Conference of the CSD in April 2001.

The indicator set is divided like the agenda 21 into four sections (socially, economically, ecologically and institutionally) and 40 chapters. The headlines of the chapters serve as the categories of the OECD as topic rewritings, similarly. The indicators are - oriented at the structure suggestion of the OECD - divided in drive indicators (drivers), condition indicators (state) and measure indicators (response). In contrast to the beginning of the OECD the CSD does not put the drive indicators to affect however to value on the statement that between the individual indicators no causal connection exists, thus (directly) the condition indicators.

The CSD indicator system is in its structure not consistently updated, there the distinction between driving indicators, state indicators and response indicators represents only one classification. This does not correspond to the structural unanimity of the OECD catalogue. Hence it seems difficult to derive elements of a steering policy.

As further points of criticism are stated: The relative strong cut on developing countries, the given national aggregation level, the missing purchase to participant and

groups of concerning, and the different abstraction level of the indicators (e.g. eco national product vs. portion of the consumption of renewable energies).

#### 4.1.2 OECD

On the world economy summits of 1989 and 1990 the G7 states had informed itself to integrate economic and ecological questions in the future more strongly into the decision-making processes. The OECD was requested to develop for this purpose environmental indicators.

The environmental indicator set should serve to analyse the environmental achievement of individual countries. The use from environmental indicators to the analysis of the environmental efficiency of a country, a region or an economical sector implies that these indicators are connected with the measurement and used analysis reached of the already and, in order to identify the driving forces and the specific conditions. The indicators can be connected with quantitative goals and qualitative goals, e.g. efficiency of human activities, lastingness of the use of natural resources and development. Before this background the OECD 1991 presented a first indicator beginning, which placed environmental referred factors for the first time as far as possible into an economic connection. The indicators can be classified according to the facts, which are to seize them, as follows:

- Harming and waste material entries into the environment,
- Emissions per unit GDP,
- Emissions per capita of the population,
- Temporal trends of GDP,
- Consumption of fossil fuels and pollutant emissions,
- Use profile of selected natural resources,
- Environmental condition,
- Defensive efforts of environmental protection and
- Public perception of the environmental problems.

The "Group on the State of the Environment" of the OECD developed a conceptual framework, which defined first environmental indicators on the basis of this first beginning and whose function and whereupon constructing the Pressure State Response Model (PSR) described. The OECD concentrated on two central functions of indicators. They reduce the number of the measurements and parameters, which were normally needed, in order to describe the situation accurately. They simplify the communication processes for the representation of the results of measurement and can so the public more purposefully over the reached degrees of a lasting development inform. Criteria were set up, which permit it to select indicators and examine their effectiveness. All indicators were examined according to their politics relevance, their analytic founding and their measurability.

#### 4.1.3 *World Bank*

The set of indicators established by the World Bank is designated "World Development Indicators". It represents at present the most extensive set of indicators. Its advantage is to be seen in the fact that the World Bank has already acquired data for about 150 states for 40 years. The World Bank works with a total of 600 indicators, which can be assigned to the following six categories: economic scope/economic structure ("World View"), data on population, labour market, income and property, poverty, health and education ("People"), environment ("Environment"), GDP, production structures, imports, exports, balances of payment, indebtedness, demand, supply, investments, money and prices ("Economy"), tax policy, infrastructure, science, technology, the state as an entrepreneur, stock markets ("States and Markets") as well as the scope and structure of trade with goods and services, cash flows and number of foreign employees ("Global Links") [World Bank 2000].

#### 4.1.4 *World Resources Institute*

An aim of the World Resources Institute is to observe and evaluate global development trends within the framework of its continuous "World Resources" reporting scheme. This also includes roughly 20 economic and 80 social indicators for evaluation in addition to ecological indicators. The economic parameters are concerned e.g. with the scope and structure of the GDP, indebtedness, domestic and foreign investments, energy as well as price and goods indices. The social measurement quantities concentrate on the sectors of population, health, urban development, agriculture and nutrition [World Resources Institute 2001].

#### 4.1.5 *European Union*

Following the recommendations of the Commission for Sustainable Development (CSD) the statistic office of the European Union (Eurostat) developed a Sustainable Development indicator set. Eurostat extended and to the conditions of the countries of the European union adapted the present indicator catalogue of the CSD from 59 indicators to 63 indicators. It is differentiated thereby between economic, social, ecological and institutional indicators.

The selection of the indicators was determined by the following criteria:

- Data availability in the European Union and
- Availability of indicators, which supplement the present UNCSD indicator list and thereby refer to important European Union questions, which are not covered by the agenda 21.

Attention is paid to establish a indicator catalogue which is consistent with the CSD list.

### a. Social dimension

The social dimension of Sustainable Development was described in 2000 by the UN by the following indicators: Equality, health, training, living, security and population. The UN divided these main topics still into subregions.

EU modified and adapted the UN indicators in such a way partly that the living conditions of the people in the European Union are considered. Access to safe drinking water and contraception are not considered as relevant for the European Union.

Eurostat SD Indicators		
Social Dimension of SD		
UN Main-Dimension	Sub-Dimension	Eurostat Indicators
Equality	Poverty	SOC 1 Population below the poverty border
		SOC 2 Mass for the measurement of the income inequality
		SOC 3 Unemployment rate
		SOC 4 Youth unemployment
		SOC 5 Development of the social
Health	Sex equality Child welfare Food Disease Mortality rate	SOC 6 Relationship of the woman remuneration to the men
		SOC 7 Child welfare
		SOC 8 Food supply of the population
		SOC 9 Mortality due to certain diseases
		SOC 10 Child number of deaths
Training	Sanitarily Health Care	SOC 11 Life expectancy with the birth
		SOC 12 Population is attached to the sanitary system
		SOC 13 national expenditures for health
Dwelling	Level of education Reading and write talent	SOC 14 child protective inoculation
		SOC 15 highest level of education
Safety	Life circumstances	SOC 16 small level of education
		SOC 17 Number of areas per head
Population	Criminality Change of the population	SOC 18 Composition of the household
		SOC 19 Criminality rate
		SOC 20 Population growth rate
		SOC 21 Population density
		SOC 22 Net migration rate

**Tab. 1:** Social dimension of SD in the EU indicator system [Eurostat 2001]

### b. Ecological dimension

The EU act assumes many human activities a threat for the environmental media air, country, water and diversity of species to represent. Eurostat took up UN indicators also in the range of the ecological indicators not with, since these are not relevantly judged the European Union as: Desertification; development of the coastal ranges and key ecological system areas. Four new environmental indicators (industrial waste, waste treatment and refuse disposal, expenditures for environmental protection and goods traffic) were added, but inserted according to the UN systematic into the range of economic indicators.

Eurostat SD-Indicators			
Ecological Dimension of SD			
UN		Eurostat Indicators	
Main Dimension	Sub-Dimension		
Atmosphere	Climate Change	ENV 1	Per head missions of GHG
	Ozone layer	ENV 2	Consumption of the ozone layer damaging substances
	Air quality	ENV 3	Air pollution in cities
Land	Agriculture	ENV 4	Agriculture surfaces
		ENV 5	Nitrate pollution
	Forest	ENV 6	Use of pesticides
		ENV 7	entire forest surface
		ENV 8	Wood impact relationship
Sea	Urbanization	ENV 9	Utilization of land
	Territorial waters	ENV 10	Acidification of territorial waters and sea
	Fishery	ENV 11	Fishing of threatened kinds
Fresh water	Water quantity	ENV 12	Intensity of the water use
	Water Quality	ENV 13	BOD concentration of selected rivers
Biodiversity	Ecosystem	ENV 14	Quality of the bath water
		ENV 15	Protected surfaces in % at total area
	Kinds	ENV 16	Number of threatened kinds

**Tab. 2:** Ecological dimension of SD in the EU indicator system [Eurostat 2001]

### c. Economic indicators

The economic indicators were selected, in order to receive the goal of Sustainable Development the safety device and preservation of the standard of living of humans over the time. The conversion of this goal means the implementation of lasting production procedures and consumer habits. Sustainable Development means an efficient use of energy resources and material resources, an effective waste management and a sustainable traffic.

The EU follows with the selection of the indicators to a large extent the UN defaults. However still some indicators were added, which are to consider the special conditions of the European Union national economies.

Eurostat SD-Indicators			
Economic Dimension of SD			
UN Main Dimension	Sub-Dimension	Eurostat Indicators	
Economic Structures	Economic efficiency	ECON 1	GDP per head
		ECON 2	Portion of the investments of GDP
	Trade	ECON 3	Portion of the individual sectors to GDP
		ECON 4	Inflation rate
		ECON 5	Deficit on the balance of payments on current account
		ECON 6	European Union and international markets
		ECON 7	public debts
		ECON 8	Development assistance
Consumption and Production	Material consumption	ECON 9	Materials consumption
	Energy consumption	ECON 10	Per head energy consumption
		ECON 11	REN
	Waste	ECON 12	Energy intensity of the individual sectors
		ECON 13	Public waste arising
		ECON 14	Industrial waste arising
		ECON 15	Special refuse arising and special refuse disposal
		ECON 16	Radioactive waste
		ECON 17	Recycling of paper and glass
		ECON 18	Waste treatment and Refuse disposal mechanisms
		ECON 19	Passenger traffic-arise after mode of transport
	Transport	ECON 20	Goods traffic-arise after mode of transport
		ECON 21	Expenditures for environmental protection
	Environmental protection		

**Tab. 3:** Economic dimension of SD in the EU indicator system [Eurostat 2001]

d. Institutional indicators

Sustainable Development cannot be achieved from the view of Eurostat, if the institutional basic conditions do not make full participation for the society possible in a national Sustainable Development strategy to convert also international conventions.

Eurostat SD -Indicators			
Institutionelle Dimension of SD			
UN Main Dimension	Sub-Dimension	Eurostat Indicators	
institutional frameworks		International Co-operation	
institutional Capacities	Information entrance	INST 1	Internet entrance
	Communication infrastructure	INST 2	Communication infrastructure
	Research and Technology	INST 3	R+D Expenditures
	Disaster control	INST 4	Risks for humancapital and nature capital

**Tab. 4:** Institutional dimension of SD in the EU indicator system [Eurostat 2001]

#### 4.1.6 *National approaches and considerations*

Apart from these supranational efforts, individual nation-states are developing their own indicator systems in response to the resolutions passed in Rio de Janeiro. Thus, in 1996, the US President's Council on Sustainable Development instituted by Bill Clinton presented a first set of roughly 50 indicators [SDI 1996], which referred to ecological, social and economic matters. As indicators for the social dimension, for example, the school-leaving quality, internet access rate, income distribution or poverty rate were specified; economic measurement quantities included the GNP, the unemployment rate, per-capita savings, per-capita productivity or also energy efficiency.

Furthermore, many European countries have meanwhile also adopted sustainability strategies with associated indicator systems. Among these are Sweden, the United Kingdom and the Netherlands.

The concept of Sustainable Development has also met with approval in Germany, especially in the debate on the country's further internal development.

The first steps towards institutionalising the overall concept of Sustainable Development were initiated in Germany in the mid-90s. Under the title "Steps towards sustainable, environmentally appropriate development" a discussion forum under the leadership of the German Federal Ministry for the Environment (BMU) was instituted in 1996 at the federal level. The following subject areas have been treated by the forum and its working groups: climate protection, protection of the ecosystem, conservation of resources, protection of human health, environmentally acceptable mobility and environmental ethics.

Like many other states - roughly 180 in total - by signing the Rio declaration the Federal Republic of Germany committed itself to developing a national sustainability strategy in connection with the Agenda 21 process. The signatory states furthermore agreed in Rio de Janeiro to present their national strategies at the 2002 Conference in Johannesburg at the latest. Within the framework of negotiations on the formation of a coalition between the Social Democratic Party of Germany and The Greens, this commitment was taken up and included in the coalition agreement signed in autumn 1998. In line with this, in summer 2000 the Federal Cabinet adopted a bill according to which a Council for Sustainable Development was to be instituted by the Federal Government at the beginning of the following year. Its task should be to participate in the development and formulation of a sustainability strategy for the Federal Republic of Germany. For this purpose, high-ranking representatives of different social groups in the Federal Republic of Germany – such as representatives of the two Christian churches, the consumer associations, the local authorities as well as industry and science – were appointed to this panel by the Federal Chancellor.

It was selected a form of presentation comprising for target levels with associated lower-level indicators. These four target levels comprise the topics of generation justice, quality of life, social bonds and international responsibility. The target indicators and objectives developed by the State Secretary Committee will be presented in the former survey. The Committee furthermore states that it considers a design of Sustainable Development only feasible as a joint task in the international context.

<b>Generation Justice</b>	<b>Quality of Life</b>	<b>Social Bonds</b>	<b>International Responsibility</b>
conservation of resources	economic prosperity	employment	development cooperation
climate protection	mobility	prospects for families	opening markets
renewable energies	nutrition	equal rights	
land use	air quality	integration of foreign citizens	
biodiversity	health		
national indebtedness	crime		
economic precautions for the future			
innovation			
education			

**Tab. 5:** German SD Indicator Catalogue [Bundesregierung 2002]

## **5 Goals, indicators and measures for the implementation of the concept of Sustainable Development in the energy sector**

With the comparative analysis of different indicator systems on international and national level it showed up that to the range a strong priority grants of the lasting development and power supply.

The allocation of the group of topics "Energy" is however not clear in this connection. This appears both under the aspect of the economics and in the environmental and social sector. It is remarkable that the majority of the industrialized countries assigns the range of the power supply in the context of Sustainable Development in all rule to the economic aspects. In contrast to this in the global context also the environmental and distribution-political dimension into the considerations are included.

All kinds of the energy supply and energy use in the Sustainable Development dimension are generally considered. But the focus is naturally in the context of the Sustainable Development debate strengthened on an establishment of the use of renewable energies.

Thus an intensified promotion of the establishment and use of renewable energies is the centre of attention apart from the goal of the efficiency increase with conventional energy engineerings. Important measured variables are thereby the range of the research funds, which are made available both by national side and by the industry for this sector. In this framework it is besides necessarily to measure the output from greenhouse gases to. These are an important indicator in the reference to a successful conversion of the measures specified before.

It is from great importance that the selected single indicators of the different indicator models are as well as possible quantifiable. This increases first the comparability between the different indicator sets. It is also much more simple at the same time in this context to derive on the basis clearly comparable defaults recommendations for action as well as action measures.

## **6 Conversion on national and international level (by the example of the European Union as well as selected member states)**

In order to be able to meet interpretable statements, a multiplicity of possible observations and information must be systematized and consolidated to key characteristics. The aggregation level is determined by the specific problem definition of the respective analysis (internationally, national or regionally). A high degree of aggregation is necessary, if an indicator system has to fulfill its major tasks within the range of the information and communication on national and international level. Regional aspects of Sustainable Development can be analyzed also with not aggregated indicator systems.

All beginnings for the implementation of the principle of Sustainable Development it is common that the range appears meaningful to SD principles to the energy supply and energy use only regarding a total adjustment of the individual nations as well as the world community.

Therefore a detached view of the indicators for the energy sector is only very conditionally meaningful. A last-finite evaluation of the different compiled concepts is to be realized only in the total context of the respective indicator conception.

In the case of an investigation of the different indicator sets of the European Union as well as some of its member states it becomes clear that both on supranational level and in the selected national states the range is attached to a power supply great importance arranged into the future. The examined indicator sets as far as possible consider to the specific requirements, which are characteristic for the respective society and national economy. Before this background it is not amazingly that no outstanding position is granted to the question of supply security. Rather aspects of an efficient and safe supply of energy step into the foreground. Beyond this an emphasis of the indicator systems is on a sequential dismantling of the emissions of greenhouse gases. For this both the European Union and its member states developed concrete goal sizes and/or goal passages and action defaults.

Besides the European Union as well as its member states pay their attention to an increased development of the use renewable energies. For this reason it is of great importance, the techniques, to force the promotion and the use in this connection strengthened. In particular in this connection the focus on a close co-operation and co-operation with states are in the less developed world.

## 7 Conclusions

The approaches of Sustainable Development, discussed at present, have their seeds in a new concept of society. Taking into account local and global perspectives for the three dimensions economy, society and environment. The implementation of corresponding concepts requires a common view on individual goals, values and measures.

Closely related to the debate on these issues is the question how the processes can be observed, measured and evaluated. For this purpose various indicator sets have been developed. A review of already existing catalogues of indicators shows a great variety. Moreover the indicator sets are not uniform with respect to a specific dimension, i.e. each system reflects the position of its author(s) expressing the different political views.

The indicator sets discussed so far have been mainly compiled by institutions from the industrialised world. Assuming that the least developed countries and less developed countries contribute to the process of establishing goals for Sustainable Development it is also important to guarantee the applicability of the indicator sets in these countries, i.e. they have to build up their own capacities to measure the individual indicators.

Standards are required to assure the same level of quality in order to reduce country-specific artefacts. For instance the quality of drinking water should be measured by one set of indicators. The measurements should be based on the same procedure in all countries or regions. It is also necessary to publish the values of the indicators to keep the public informed about the status of Sustainable Development. Depending on the progress of scientific understanding and the values of indicators goals for Sustainable Development have to be revised or further actions have to be taken.

In many cases the energy sector can serve as a model for the implementation of strategies for Sustainable Development because the efficient, environmental friendly and safe supply of energy is fundamental for every economy.

## 8 References

### **[World Commission on Environment and Development 1987]**

World Commission on Environment and Development: Our Common Future. Oxford, New York 1987.

### **[UNDP 2000]**

[UNDP – UNDESA – WEC: World Energy Assessment – Energy and the Challenge of Sustainability. New York 2000.

### **[UN 2002]**

United Nations: Report of the World Summit on Sustainable Development, New York 2002.

**[SRU 2002]**

Sachverständigenrat für Umweltfragen - SRU: Umweltgutachten 2002. Wiesbaden 2002.

**[Bundesregierung 2002]**

Bundesregierung der Bundesrepublik Deutschland: Perspectives for Germany – Our Strategy for Sustainable Development, Berlin 2002.

**[World Bank 2000]**

World Bank: World Development Indicators. Washington, D.C. 2000.

**[World Resources Institute 2001]**

World Resources Institute: World Resources 2000/2001. Washington, D.C. 2001.

**[Eurostat 2001]**

Eurostat: Sustainable Development Indicators for the European Union. Brussels 2001.

**[SDI 1996]**

SDI Group (U.S. Interagency Working Group on Sustainable Development Indicators): Sustainable Development in the United States: An Experimental Set of Indicators. Washington, D.C. 1996.



# Comparison of German and European energy scenarios

P. Markewitz\*, G. Kolb\*, S. Voegelé\*

## 1 Introduction

Since the discussions about climate change and mitigation strategies started, the scenario technique has been increasingly used to show what could happen if current trends continue and what are the effects of changes in the political, economic, legal or technological conditions.

The subject of this study is the analysis and evaluation of current scenarios and prognoses regarding a sustainable energy system. Beside studies for Germany, outlooks for the European Union are considered. The aim of the analysis is a comparative view of scenario results on the basis of characteristic indicators.

Tab.1 shows a list of new studies focusing on the future development of energy use and supply in Germany and the EU. In some cases the studies contain a number of different scenarios, which differ in terms of the underlying restrictions and assumptions. However, both the assumptions used to create the scenarios and the results are often only presented verbally or by using graphs and not in the form of numerical values. Therefore a comparison of the different studies is only possible to a certain extent.

The figures presented in the next chapters are merely meant to give you an impression of the trends which different authors expect for Germany and the EU. Thereby uncertainties will be accepted.

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

Name of Scenario/Prognosis	Author	Year	Time horizon	Source
<b>Scenarios for Germany</b>				
BMWi-Energiegutachten	Prognos AG/EWI	1999	2020	[Prognos, EWI 1999]
Energiewende 2020	Öko-Institut	2000	2020	[Matthes, Cames 2000]
BMWi-CO <sub>2</sub> -Szenario	Prognos AG	2001	2020	[Prognos 2001]
Esso-Energieprognose 2000	Esso AG	2000	2020	[ESSO 2000]
Esso-Energieprognose 2001	Esso AG	2001	2020	[ESSO 2001]
Enquete-Szenarien	IER	2002	2050	[IER 2002]
HGF-Zukunftsfähiges Deutschland	DLR	2002	2050	[Nitsch 2002]
UBA-Langfristszenarien	Wuppertal-Inst. DLR	2002	2050	[Fischedick 2002]
UBA-Politikszzenarien	STE	2004	2030	[DIW, STE, ISI, Öko-Institut 2004]
<b>Scenarios for EU</b>				
Energy Outlook to 2020	Europäische Union	1999	2020	[EU 1999]

**Tab.1:** Current scenarios for Germany and the EU

## 2 Scenarios for Germany

In the following sections a selected number of energy scenarios for Germany published in last years will be presented. After a short description of the main characteristics and important assumptions the scenarios will be compared by key indicators.

### 2.1 Short Description of the scenarios

#### **PROGNOS, EWI 1999**

Title: „Längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt“ (“Long-term development of the energy markets against the background of competition and environment“)

Author: Prognos and Energiewirtschaftliches Institut Köln (EWI)

Source: [Prognos, EWI 1999]

The Energy Report III of Prognos/EWI focuses on a prognostic description of the development of energy demand and supply in Germany up to the year 2020. Among other things it is assumed that the greenhouse gas reduction measures, which are in the pipeline, will be implemented. Regarding the future of nuclear power in Germany Prognos/EWI (1999) assumed that the German nuclear power plant will be phase out after a service life of 35 years.

According to the agreement about phasing out the peaceful use of nuclear power reached by the Federal Government and the nuclear power station operators, phasing out will be completed after a quantity of 2.623 TWh have been produced, which corresponds to approx. 33 years for each power plant. The assumption used by Prognos/EWI for the use of nuclear power in Germany thus corresponds approximately to this agreement.

### **EU - Energy Outlook to 2020**

Title: „EU - Energy Outlook to 2020“

Author: EU - DG Energie

Source: [EU 1999]

The Energy Outlook shows a prognosis of the development of the energy use and supply in the countries of the EU (EU-15) up to the year 2020. It represents the official outlook of the EU.

Beside a baseline scenario, a lot of other scenarios are presented in this study. The baseline scenario is the only one, which is documented in detail. As for the other scenarios, many data about the developments in individual countries is missing. The scenarios were created by using the market-equilibrium model PRIMES. This model is calibrated for the year 1995. Correspondingly the main part of data used in PRIMES dates from 1995.

### **ÖKO-INSTITUT 2000**

Title: „Energiewende 2020: Der Weg in eine zukunftsfähige Energiewirtschaft“ (“Energy turnaround 2020: A path to a sustainable energy system“)

Author: Öko-Institut

Source: [Matthes, Cames 2000]

A few years ago the Öko-Institut provided energy scenarios for Germany on behalf of the Heinrich Boell-Stiftung. For their baseline scenario the Öko-Institut used the data of [Prognos/EWI 1999]. The Öko-Institut updated this data taking into account new developments in energy policies. Two alternative scenarios were compared with the baseline scenario. The alternative scenarios were provided on the basis of other studies (e.g. [Öko-Institut 1996]; [Hohmeyer 2000]; [Stein, Strobel 2000]; [WI, Öko-Institut 2000]; [DLR 1999]).

The alternative scenario “Policy” describes a more environmental friendly development which from today's point of view appears to be realizable. In the second alternative scenario (“Potentials”) a development regarding more ambitious climate protection targets was assumed, which seemed to be reachable by exploiting attainable potentials.

## PROGNOS 2001

Title: „Energiepolitische und gesamtwirtschaftliche Bewertung eines 40% Reduktionsszenarios“ („Energy-political and overall economic evaluation of a 40% reduction scenario“)

Author: Prognos AG (in cooperation with EWI and Bremer Energieinstitut)

Source: [Prognos 2001]

The study of Prognos (2001) focuses on the costs and consequences of a reduction in the carbon dioxide emissions of 40 % by 2020. For the scenarios the energy report of Prognos/EWI (1999) was used as basis. Reduction potentials and their cost were identified by using bottom-up models for individual sectors. With the help of the data from the bottom-up models a baseline scenario and the “40% Variant” scenario were derived which show the developments for the whole economy. For these scenarios no explicit overall economic optimization calculation was used. Instead the data for the national scenarios were derived by assuming the same marginal abatement cost for each of the sectors.

## ESSO Energy Prognosis

Title: ESSO Energie Prognose 2001 – Potenzial der Öl und Gasvorräte (“ESSO Energy Prognosis 2001 - Potentials of oil and gas resources“)

ESSO Energie Prognose 2000 – Zukunft sichern - Energiesparen (“ESSO Energy Prognosis 2000 - Safeguarding the future – energy conservation”)

Author: ESSO AG

Source: [ESSO 2000]; [ESSO 2001]

In certain intervals ESSO publishes energy prognoses for Germany, each with a special main focus. In the ESSO prognosis of 2001 the development of oil- and gas resources were highlighted. The focus of the study presented in 2000 was energy conservation. In its prognosis ESSO assume that main trends observed in the past will continue. A detailed description of how ESSO created its scenarios is not available.

## IER 2002

Title: Scenarios of the Enquete-Commission of the German Bundestag „Nachhaltige Energieversorgung“ (“Sustainable Energy Supply”)

Author: Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), University Stuttgart

Source: [Fahl, Remme, Blesl 2002]

In the year 2000 the Enquete-Commission „Nachhaltige Energieversorgung“ (Sustainable Energy Supply) of the German Bundestag commissioned the IER and the Wuppertal-Institute to create scenarios for the middle and long-term development of the German energy system. In the following we present some key figures of the IER-

scenarios because these scenarios are better documented than the scenarios of the Wuppertal-Institute. The IER-scenarios were generated by using the optimization tool TIMES. For the calibration of the model data of Prognos/EWI was used.

Beside the baseline scenario three main scenarios and a lot variants of them were presented: For the scenario „Umwandlungseffizienz“ (“Efficiency Conversion”) a high increase in energy efficiency was assumed. A large rise in the use of renewable energies was assumed for the scenario “REG/REN- Offensive”. In this scenario just like in the other scenario “Efficiency Conversion” and “Fossil-nuclear Energy Mix” a reduction path for the greenhouse gases was assumed. Contrary to the other scenarios in the scenario „Fossil-nuclear Energy Mix” an only small increase in the extension of the use of renewable energies was presumed. Additionally in this scenario further restrictions were relaxed. Thus, for example the extension of the use of nuclear power plants was admitted in this scenario.

### **HGF 2002**

Title: „Global zukunftsfähige Entwicklung – Perspektiven für Deutschland“ („Global Sustainable Development – Prospects for Germany”)

Author: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Forschungszentrum Karlsruhe, Institut für Technikfolgenabschätzung und Systemanalyse

Source: [Nitsch 2002]

In 2002 scenarios of the HGF regarding the future development of the energy system were published by [Nitsch 2002]. They were based on the energy report of [Prognos/EWI 1999]). The benchmark figures taken from the Prognos/EWI-report were extrapolated up to the year 2050. Taking new developments into account, the data was also updated and adjusted. Beside the baseline scenario the scenario “Orientation” was presented in the HGF-study. For this scenario a large extension of the use of renewable energies was assumed. [Nitsch 2002] does not include a detailed description methodology used for creating the scenarios.

### **Wuppertal-Institut, DLR 2002**

Title: „Langfristszenarien für eine nachhaltige Energienutzung in Deutschland“ („Long-term scenarios for a sustainable energy use in Germany“)

Author: Wuppertal Institut für Klima, Umwelt, Energie (WI), Deutsches Zentrum für Luft- und Raumfahrt (DLR)

Source: [Fischedick 2002]

Commissioned by the Federal Environment Agency, the Wuppertal Institute (WI) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) presented three long-term scenarios for the German energy system last year. In the first scenario business as usual was assumed. The second scenario focuses on the effects of a drastic increase in energy efficiency. For both scenarios no assumptions were made regarding the development of the CO<sub>2</sub> emissions. Unlike these scenarios the third one, called “Sustainability Scenario”, uses a reduction path for the CO<sub>2</sub> emissions of 80 % by 2050 as restriction.

**STE 2004**

Title: Politikszenerarien für den Klimaschutz (Politikszenerarien III)  
 ("Policy scenarios towards climate protection (Policy scenarios III)")

Author: STE

Source: [DIW, STE, ISI, Öko-Institut 2004]

Within the project "Policy scenarios towards climate protection (Policy scenarios III)" which was initiated by the German Federal Environment Agency, STE together with DIW, ISI and Öko-Institut provided different kinds of scenarios regarding the future development of the energy system in Germany. STE used the optimization tool IKA-RUS-MARKAL to create consistent scenarios.

In the baseline scenario called "Model-Basis-Scenario" a business as usual development was assumed taking into account climate mitigation measures, which are likely to be realized in the near future. Beside this scenario two CO<sub>2</sub>-reduction-scenarios were presented. In the first one a CO<sub>2</sub>-reduction of 40% by 2030 was used as target. In the second one a reduction target of 50% was set as political aim.

## 2.2 Key Factors

Regarding the population trends, the projections listed in Tab. 2 do not differ very much. This is not very surprising, because most of them use the study of [Prognos/EWI 1999] as a basis. In the long-term studies of IER and WI/DLR the same population trends are assumed: In both studies a significant reduction of the population is expected taking into account projections of the Federal Statistical Bureau.

Tab. 3 shows the development of the GDP assumed in the different scenarios. As mentioned above [Öko-Institut 2000], [Prognos 2002] and [Nitsch 2002] used [Prognos, EWi 1999] as a reference point. This leads to similar economic growth rates in the scenarios of these institutes. Differences in the figures listed in Tab. result mainly from using a different price basis. The EU, for example used EUR<sub>90</sub> as a price basis meanwhile in other studies economic values are presented in DM<sub>98</sub>.

Most of the studies for the GDP expect an average increase of 1.8 to 2 % for the next years. In the EU-study even a growth rate of 2.4% is assumed. ESSO expected that after 2010 the GDP will still increase by 2% per year. However in the other studies for the periods after 2010 a decrease of the growth rate is expected according to the development of the population.

	<b>Scenario</b>	<b>2010</b>	<b>2020</b>	<b>2030</b>	<b>2050</b>
Prognos, EWI 1999	- Baseline	82.6	80.8		
EU 1999	- Baseline	83.0	81.2		
Öko-Institut 2000	- Baseline	82.4	80.8		
	- Policy				
	- Potentials				
ESSO 2000	- Baseline	82.0	81.3		
Prognos 2001	- Baseline	see Prognos, EWI 1999			
	- 40% -Variant				
ESSO 2001	- Baseline	81.4	80.5		
IER 2002	- Baseline	82.1	80.8	77.9	67.8
	- Fossil-Nuclear Mix				
	- Con.-Efficiency				
	- REG-REN-Off.				
HGF 2002	- Orientation	see Prognos, EWI 1999		n.a.	n.a.
WI, DLR 2002	- Status Quo	82.6	80.8		
	- Sustainability	82.1	80.8	77.9	67.8
STE 2004	- Model-Basis	81.5	80.3	78.0	
	- 40%-Reduction				
	- 50%-Reduction				

**Tab. 2:** Population trends (in millions)

	Scenario	Unit	2010	2020	2030	2050
Prognos, EWI 1999	- Baseline	billion DM <sub>91</sub>	4,059	4,798		
EU 1999	- Baseline	billion EUR <sub>90</sub>	2,013	2,390		
Öko-Institut 2000	- Baseline - Policy - Potentials	billion DM <sub>91</sub>	see Prognos, EWI 1999			
ESSO 2000	- Baseline	billion DM <sub>95</sub>	4,797	5,868		
Prognos 2001	- Baseline - 40% -Variant	billion DM <sub>91</sub>	see Prognos, EWI 1999			
ESSO 2001	- Baseline	billion DM <sub>95</sub>	4,754	5,804		
IER 2002	- Baseline - Fossil-Nuclear Mix - Con.-Efficiency - REG-/REN-Off.	billion DM <sub>95</sub>	4,629	5,471	6,238	7,574
HGF 2002	- Orientation	billion DM <sub>91</sub>	see Prognos, EWI 1999		n.a.	n.a.
WI, DLR 2002	- Status Quo - Sustainability	billion DM <sub>91</sub> billion DM <sub>98</sub>	4,059 4,768	4,798 5,536	6,427	7,802
STE 2004	- Model-Basis - 40%- Reduction - 50%- Reduction	billion EUR <sub>95</sub>	2,367	2,798	3,190	

**Tab.3:** Economic Trends (GDP)

Fig. 1 illustrates the way the growth rate develops in the different scenarios. A comparison of the growth rates of alternative and the corresponding baseline scenarios shows that for all of the scenarios it is assumed that a CO<sub>2</sub> restriction has no influence on economic growth.

Beside assumptions about population development and economic growth the scenarios are based on a large number of other assumptions. There are only few studies that list the basic assumptions and the assumed development of key figures are listed; in most cases they are missing. Some key figures which are available for the different scenarios are presented in Tab. 4. This table shows again that most of the scenarios are based on the study of Prognos/EWI (1999). The long-term development of the passenger transport activity is remarkable: If you take the assumed population trends into account, a nearly constant passenger transport activity means an increase in the specific demand for energy service.

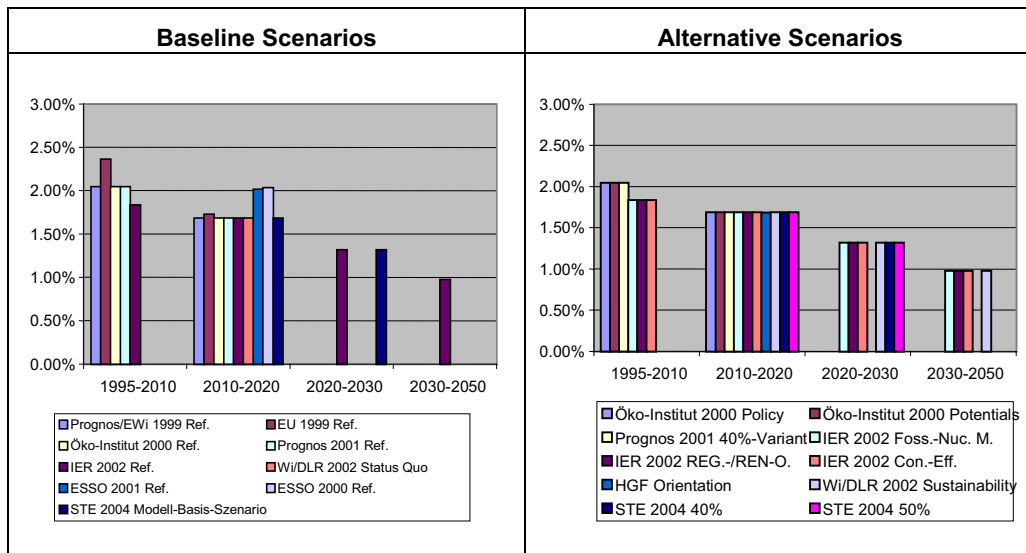


Fig. 1: Energy scenarios for Germany: Comparison of the GDP growth rates

	Scenario	Unit	2010	2020	2030	2050
<b>Transport</b>						
<i>Passenger transport activity</i>						
Prognos, EWI 1999	- Baseline	billion Pkm	1,091	1,138		
EU 1999	- Baseline	billion Pkm	1,133	1,355		
Öko-Institut 2000	- Baseline	billion Pkm	1,093	1,138		
	- Policy - Potentials					
ESSO 2000	- Baseline	billion Pkm	n.a.	n.a.		
Prognos 2001	- Baseline - 40% -Variant	billion Pkm	s. Prognos, EWI 1999			
ESSO 2001	- Baseline	billion Pkm	n.a.	n.a.		
	<b>Scenario</b>	<b>Unit</b>	<b>2010</b>	<b>2020</b>	<b>2030</b>	<b>2050</b>
IER 2002	- Baseline	billion Pkm	1,091	1,138	1,139	1,027
	- Fossil-Nuclear Mix - Con.-Efficiency					
	- REG-/REN-Off.					
HGF 2002	- Orientation	billion Pkm	s. Prognos, EWI 1999		n.a.	n.a.
WI, DLR 2002	- Status Quo - Sustainability	billion Pkm	see IER 2002			
STE 2004	- Mode-Basis	billion Pkm	see IER 2002			
	- 40%-Reduction					
	- 50%-Reduction					
<i>Freight transport activity</i>						
Prognos, EWI 1999	- Vaseline	billion tkm	584	669		

EU 1999	- Baseline	billion tkm	535	585		
Öko-Institut 2000	- Baseline - Policy - Potentials	billion tkm	585	670		
ESSO 2000	- Baseline	billion tkm	n.a.	n.a.		
Prognos 2001	- Baseline - 40% -Variant	billion tkm	s. Prognos, EWI 1999			
ESSO 2001	- Baseline	billion tkm	n.a.	n.a.		
IER 2002	- Baseline - Fossil-Nuclear Mix - Con.-Efficiency - REG-/REN-Off.	billion tkm	607	732	839	964
HGF 2002	- Orientation	billion tkm	s. Prognos, EWI 1999		n.a.	n.a.
WI, DLR 2002	- Status Quo - Sustainability	billion tkm	see IER 2002			
STE 2004	- Model-Basis - 40%-Reduction - 50%-Reduction	billion tkm	see IER 2002			
<i>Housing space</i>						
Prognos, EWI 1999	- Baseline	Million m <sup>2</sup>	3,733	4,142		
EU 1999	- Baseline	Million m <sup>2</sup>	n.a.	n.a.		
Öko-Institut 2000	- Baseline - Policy - Potentials	Million m <sup>2</sup>	3,733	4,142		
ESSO 2001	- Baseline	Million m <sup>2</sup>	3,393	3,645		
Prognos 2001	- Baseline - 40%-Variant	Million m <sup>2</sup>	s. Prognos, EWI 1999			
ESSO 2001	- Baseline	Million m <sup>2</sup>	n.a.	n.a.		
IER 2002	- Baseline - Fossil-Nuclear Mix - Con.-Efficiency - REG-/REN-Off.	Million m <sup>2</sup>	3,733	4,141	4,231	3,972
HGF 2002	- Orientation	Million m <sup>2</sup>	s. Prognos, EWI 1999		n.a.	n.a.
WI, DLR 2002	- Status Quo - Sustainability	Million m <sup>2</sup>	see IER 2002			
STE 2004	- Model-Basis - 40%-Reduction - 50%-Reduction	Million m <sup>2</sup>	3,409	3,637	3,839	

**Tab. 4:** Other key figures

### 2.3 Results

In the studies, the assumptions about technical, economic and demographic trends were used to calculate figures which represent the development of energy demand and supply. Some of the results are presented in the following paragraphs.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenario</b>						
Prognos, EWI 1999	Baseline	14,270	14,676	13,809		
EU 1999	Baseline	14,177	14,679	14,666		
Öko-Institut 2000	Baseline	14,270	14,545	13,708		
ESSO 2000	Baseline	n.a.	14,214	13,511		
Prognos 2001	Baseline	see Prognos, EWI 1999				
ESSO 2001	Baseline	n.a.	14,536	13,540		
IER 2002	Baseline	14,296	14,298	13,621	12,725	11,372
WI, DLR 2002	Status Quo	see Prognos, EWI 1999				
STE 2004	Model-Basis		13,487	12,661	11,817	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	14,270	13,116	11,506		
	Potentials	14,270	11,958	9,974		
Prognos 2001	40%-Variant		13,220	11,710		
IER 2002	Fossil-Nucl. E.	14,269	13,947	13,980	13,889	13,616
	Con.-Efficiency	14,269	13,881	12,759	11,402	10,474
	REG-/REN-Off.	14,269	13,869	12,650	10,920	8,810
HGF 2002	Orientation		12,626	11,144	9,874	7,966
WI, DLR 2002	Sustainability		12,072	9,942	8,624	6,644
STE 2004	40%-Reduction		13,303	12,047	10,760	
	50%-Reduction		12,949	11,077	10,010	

**Tab. 5:** Primary energy use (in PJ)

The development of the primary energy demand in the different scenarios is presented in Tab. 5. For the first periods an increase in the primary energy demand is expected. Later the primary energy demand declines more or least clearly. In most of the scenarios the primary energy demand drops after 2010 to below the level of 1995. The scenario of [EU 1999] is the only one that projects a high level of the primary energy demand for the long-term. In the alternative scenarios the primary energy demand declines continually. The largest decrease occurs in the "Sustainability" scenario of [WI, DLR 2002]. In contrast to this scenario the primary energy demand

in the scenario „Fossil-Nuclear Energy Mix (FNE)“ of IER seems to be more or less unchanged after 2010.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	174.7	177.6	170.9		
EU 1999	Baseline	173.5	176.9	180.6		
Öko-Institut 2000	Baseline	174.9	176.5	169.9		
ESSO 2000	Baseline	n.a.	173.3	165.8		
Prognos 2001	Baseline	174.7	177.6	170.9		
ESSO 2001	Baseline	n.a.	178.6	168.2		
IER 2002	Baseline	174.7	174.2	168.6	163.4	167.7
WI, DLR 2002	Status Quo		177.7	170.9		
STE 2004	Model-Basis		165.5	157.6	151.5	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	174.9	159.2	142.6		
	Potentials	174.9	145.1	123.6		
Prognos 2001	40%-Variant	174.7	159.9	144.7		
IER 2002	Fossil-Nucl. E.	174.7	169.9	173.0	178.3	200.8
	Con.-Efficiency	174.7	169.1	157.9	146.4	148.1
	REG-/REN-Off.	174.7	168.9	156.6	140.2	129.9
HGF	Orientation		152.8	137.9	128.2	117.5
WI, DLR 2002	Sustainability		147.0	123.0	112.0	98.0
STE 2004	40%-Reduction		163.2	150.0	138.0	
	50%-Reduction		158.9	137.9	128.4	

**Tab. 6:** Primary energy demand per cap (in GJ/cap)

Apart from the EU-scenario the primary energy demand per capita drops in the baseline scenarios to nearly 170 GJ/capita. For the long term IER expects no big changes in this ratio. Between the alternative scenarios the primary energy demand per capita varies widely. A decrease to 98 GJ/capita is projected in the “Sustainability”-scenario

of [WI, DLR 2002]. In the scenario „Fossil-Nuclear Energy Mix (FNE)“ of IER, however, the primary energy demand per capita increases to 200 GJ/capita.

Most of the baseline scenarios show the same trends in the primary energy/capita ratio. Again the study of [EU 1999] is an exception. In contrast to the other scenarios in this study an ongoing increase in the primary energy/capita ratio is expected for the periods after 2010.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	4.18	3.17	2.53		
EU 1999	Baseline	4.32	3.15	2.65		
Öko-Institut 2000	Baseline	4.18	3.15	2.51		
ESSO 2001	Baseline	n.a.	2.96	2.30		
Prognos 2001	Baseline	4.18	3.18	2.53		
ESSO 2001	Baseline	n.a.	3.06	2.33		
IER 2002	Baseline	4.05	3.09	2.49	2.04	1.50
WI, DLR 2002	Status Quo		3.12	2.49		
STE 2004	Model-Basis		2.91	2.31	1.89	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	4.18	2.84	2.11		
	Potentials	4.18	2.59	1.83		
Prognos 2001	40%-Variante	4.18	3.00	2.25		
IER 2002	Fossil-Nucl. E.	4.05	3.01	2.56	2.23	1.80
	Con.-Efficiency	4.05	3.00	2.33	1.83	1.33
	REG-/REN-Off.	4.05	3.00	2.31	1.75	1.16
HGF 2002	Orientation		2.86	2.14	n.a.	n.a.
WI, DLR 2002	Sustainability		2.74	1.91	1.23	0.78
STE 2004	40%-Reduction		2.87	2.20	1.72	
	50%-Reduction		2.79	2.02	1.60	

**Tab. 7:** Primary energy demand per unit GDP (in MJ/DM<sub>95</sub>)

Most of the baseline scenarios expect a decrease of the primary energy demand per GDP of 1.8 % for the period 1995 to 2010 and a drop of 2.2% for the period 2010-2020. In the alternative scenarios the primary energy demand/GDP ratio declines to 3.5 % per year. The biggest changes in the primary energy demand/GDP ratio are projected for the period 2010-2020. After 2020 the changes in the primary energy demand/GDP ratio drops significantly.

Generally the trends in the final energy demand correspond to the trends in primary energy demand. Tab. 8 shows the development of the final energy demand in the different scenarios. Again the EU-scenario and the two alternative scenarios „Fossil-Nuclear Energy Mix (FNE)“ of IER and „Sustainability“ of WI, DLR is an exception. In the EU-scenario an increase in the final demand of 10% by 2020 is expected. In other baseline scenarios the final energy demand does not change so much in time. A very high change in the final energy demand is projected in the scenario „Sustainability“ of WI, DLR. In this scenario the final energy demand decreases down to 5,195 PJ. With 7,229 PJ the final energy demand in the scenario „Fossil-Nuclear Energy Mix (FNE)“ of IER is nearly 40% higher than in the alternative scenario of WI, DLR. In the IER-baseline scenario the energy demand drops in the period 2020-2030 by 2.9% and in the period 2020 to 2050 by 14.8%. These rates are significantly lower than the rates for the primary energy demand.

Most of the scenarios show a significant increase in the final/primary energy demand ratio (Tab. 9). A decrease of the final/primary energy demand ratio is expected in the scenarios of IER for the time after 2030. Especially in the scenario „Fossil-Nuclear Mix“ this ratio drops strongly. One reason for that is the fact that in primary energy balances nuclear energy is assessed with an efficiency factor of 33% .

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	9,322	9,751	9,396		
EU 1999	Baseline	9,110	9,902	10,182		
Öko-Institut 2000	Baseline	9,273	9,750	9,393		
ESSO 2000	Baseline	n.a.	9,408	8,880		
Prognos 2001	Baseline	see Prognos, EWI 1999				
ESSO 2001	Baseline	n.a.	n.a.	n.a.		
IER 2002	Baseline	9,357	9,705	9,641	9,362	8,208
WI, DLR 2002	Status Quo	see Prognos, EWI 1999				
STE 2004	Model-Basis		9,758	9,432	9,054	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	9,273	8,739	7,787		
	Potentials	9,273	7,913	6,673		
Prognos 2001	40%-Variante	9,322	9,055	8,231		
IER 2002	Fossil-Nucl. E.	9,357	9,612	9,404	8,886	7,229
	Con.-Efficiency	9,357	9,538	9,280	8,649	6,656
	REG-/REN-Off.	9,357	9,504	9,187	8,481	5,910
HGF 2002	Orientation		8,450	7,650	7,000	6,100
WI, DLR 2002	Sustainability		8,509	7,600	6,755	5,195
STE 2004	40%-Reduction		9,753	9,357	8,903	
	50%-Reduction		9,577	8,839	8,216	

**Tab. 8:** Final energy demand (in PJ)

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	0.65	0.66	0.68		
EU 1999	Baseline	0.64	0.67	0.69		
Öko-Institut 2000	Baseline	0.65	0.67	0.69		
ESSO 2000	Baseline	n.a.	0.66	0.66		
Prognos 2001	Baseline	0.65	0.66	0.68		
ESSO 2001	Baseline	n.a.	n.a.	n.a.		
IER 2002	Baseline	0.66	0.68	0.71	0.74	0.72
WI, DLR 2002	Status Quo		0.66	0.68		
STE 2004	Model-Basis		0.72	0.74	0.77	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	0.65	0.67	0.68		
	Potentials	0.65	0.66	0.67		
Prognos 2001	40%-Variant	0.65	0.68	0.70		
IER 2002	Fossil-Nucl. E.	0.66	0.69	0.67	0.64	0.52
	Con.-Efficiency	0.66	0.69	0.73	0.76	0.66
	REG-/REN-Off.	0.66	0.69	0.73	0.78	0.67
HGF 2002	Orientation		0.67	0.69	0.71	0.77
WI, DLR 2002	Sustainability		0.70	0.76	0.78	0.78
STE 2004	40%-Reduction		0.73	0.78	0.82	
	50%-Reduction		0.74	0.80	0.82	

**Tab. 9:** Final energy demand/primary energy demand ratio

Due to similar CO<sub>2</sub> reduction targets the development of the CO<sub>2</sub> emissions does not vary very much between the alternative scenarios. The baseline scenarios, however, differ greatly: In the EU-scenario the CO<sub>2</sub> emissions increase from 1995 to 2020 by 3% whereas in the baseline scenario of the IER they decrease by 5%. With the exception of the EU-scenario all baseline scenarios expect to almost stabilized CO<sub>2</sub> emissions after 2010.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	895	855	847		
EU 1999	Baseline	848	828	875		
Öko-Institut 2000	Baseline	890	888	892		
ESSO 2000	Baseline	n.a.	846	821		
Prognos 2001	Baseline		845	835		
ESSO 2001	Baseline	n.a.	853	853		
IER 2002	Baseline	876	825	830	816	701
WI, DLR 2002	Status Quo	see Prognos, EWI 1999				
STE 2004	Model-Basis		812	815	784	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	890	778	708		
	Potentials	890	673	549		
Prognos 2001	40%-Variant		707	596		
IER 2002	Fossil-Nucl. E.	876	745	652	506	200
	Con.-Efficiency	876	748	658	504	198
	REG-/REN-Off.	876	751	657	506	200
HGF 2002	Orientation		742	648	499	226
WI, DLR 2002	Sustainability			592	493	197
STE 2004	40%- Reduction		783	709	608	
	50%-Reduction		739	607	507	

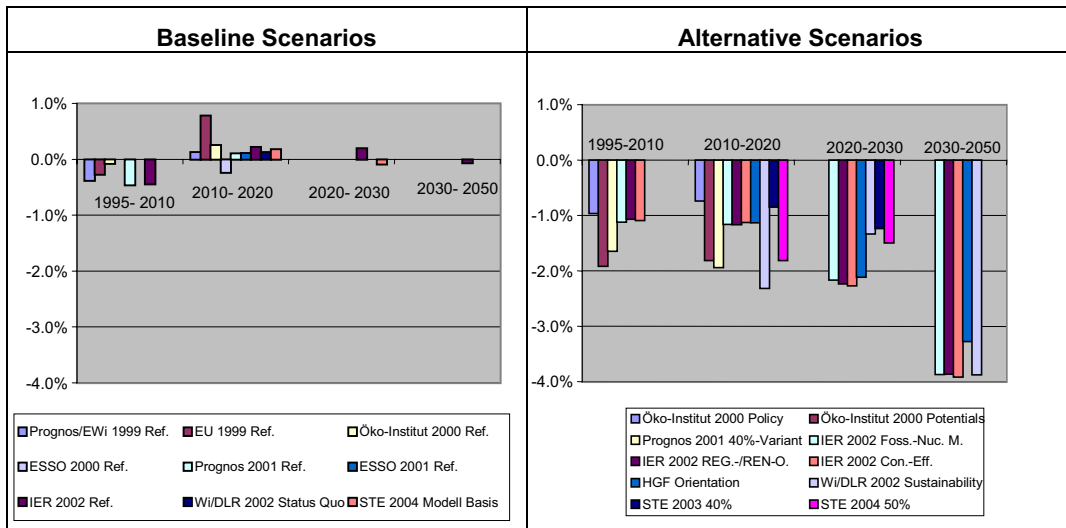
**Tab. 10:** CO<sub>2</sub> Emissions (in Mio. tons)

Tab. 11 shows the development of the CO<sub>2</sub> emissions per capita. In the baseline scenarios this ratio does not vary much in time. Another trend is expected for the alternative scenarios. In these scenarios the CO<sub>2</sub> emissions per capita drop down significantly. For the last period (2030-2050) IER and WI/DLR predict less than 3 tCO<sub>2</sub>/capita, which means a decrease of nearly 70 %. The changes in CO<sub>2</sub> emissions per capita ratio over time are presented in Fig. 2.

In the baselines this ratio does not vary very much over time. But considerable higher changes are expected in the alternative scenarios, especially after 2030.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	10.95	10.34	10.48		
EU 1999	Baseline	10.38	9.97	10.78		
Öko-Institut 2000	Baseline	10.91	10.78	11.05		
ESSO 2000	Baseline	n.a.	10.32	10.07		
Prognos 2001	Baseline	10.95	10.22	10.33		
ESSO 2001	Baseline	n.a.	10.48	10.60		
IER 2002	Baseline	10.73	10.04	10.27	10.47	10.34
WI, DLR 2002	Status Quo		10.35	10.48		
STE 2004	Model-Basis		9.96	10.14	10.5	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	10.91	9.44	8.77		
	Potentials	10.91	8.17	6.80		
Prognos 2001	40%-Variant	10.95	8.55	7.03		
IER 2002	Fossil-Nucl. E.	10.73	9.07	8.07	6.49	2.95
	Con.-Efficiency	10.73	9.11	8.14	6.47	2.91
	REG-/REN-Off.	10.73	9.14	8.14	6.49	2.96
HGF 2002	Orientation		8.98	8.02	6.48	3.33
WI, DLR 2002	Sustainability		9.25	7.32	6.40	2.91
STE 2004	40%- Reduction		9.61	8.82	7.80	
	50%-Reduction		9.07	7.56	6.50	

**Tab. 11:** CO<sub>2</sub> emissions per capita (in tons CO<sub>2</sub>/capita)



**Fig. 2:** Development of the CO<sub>2</sub> emissions per capita ratio

In contrast to the emissions per capita, the emissions per GDP decline continuously in all scenarios. In the alternative scenarios a drop in the specific emissions to 10% of the level of 1995 is expected.

If you take into account the decision to phase out nuclear power in Germany it is remarkable that in the baseline scenario the CO<sub>2</sub> emissions per unit primary energy demand do not rise in the mid term although in this scenarios fossil energy carriers are used to replace nuclear power. This development results due to the assumed technical progress and the trends to use gas instead of coal. (Tab. 13) In accordance with the assumed CO<sub>2</sub> restriction a significant reduction of the specific emissions is projected in the alternative scenarios.

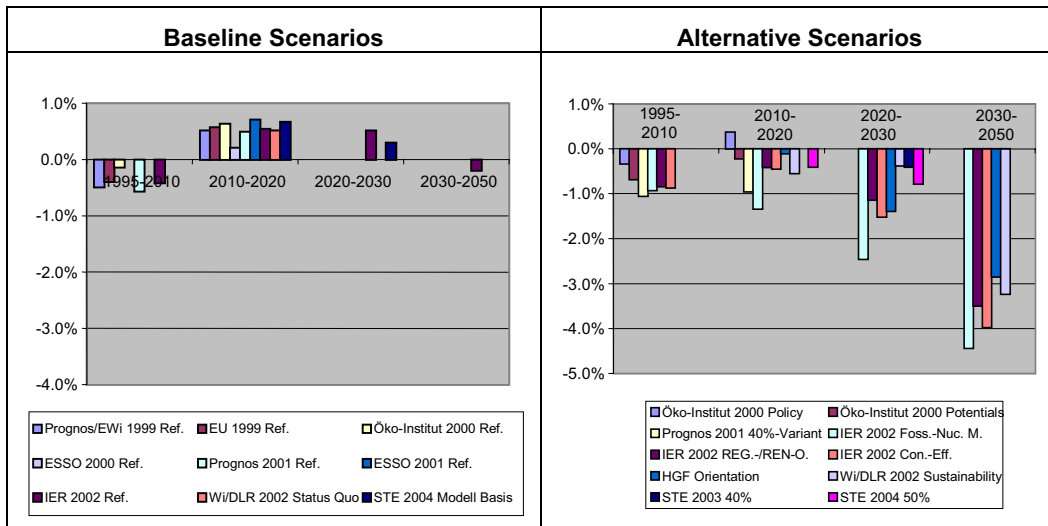
	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	262.2	184.9	155.0		
EU 1999	Baseline	258.4	177.7	158.3		
Öko-Institut 2000	Baseline	260.8	192.1	163.2		
ESSO 2000	Baseline	n.a.	176.4	139.9		
Prognos 2001	Baseline	262.3	182.8	152.8		
ESSO 2001	Baseline	n.a.	179.4	147.0		
IER 2002	Baseline	248.8	178.1	151.6	130.8	92.5
WI, DLR 2002	Status Quo		193.7	162.4		
STE 2004	Model-Basis		175.2	148.7	125.5	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	260.8	168.3	129.6		
	Potentials	260.8	145.6	100.5		
Prognos 2001	40%-Variant	262.2	160.2	109.1		
IER 2002	Fossil-Nucl. E.	248.8	160.9	119.2	81.1	26.4
	Con.-Efficiency	248.8	161.6	120.2	80.8	26.1
	REG-/REN-Off.	248.8	162.2	120.1	81.1	26.5
HGF 2002	Orientation		168.2	124.3	n.a.	n.a.
WI, DLR 2002	Sustainability		172.1	113.4	70.6	23.3
STE 2004	40%-Reduction		168.9	129.4	97.3	
	50%-Reduction		159.4	110.8	81.1	

**Tab. 12:** CO<sub>2</sub> emissions per unit GDP (in g/DM<sub>95</sub>)

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	62.7	58.2	61.3		
EU 1999	Baseline	59.8	56.4	59.7		
Öko-Institut 2000	Baseline	62.4	61.1	65.1		
ESSO 2000	Baseline	n.a.	59.5	60.8		
Prognos 2001	Baseline	62.7	57.6	60.5		
ESSO 2001	Baseline	n.a.	58.7	63.0		
IER 2002	Baseline	61.4	57.7	60.9	64.1	61.6
WI, DLR 2002	Status Quo		58.2	61.3		
STE 2004	Model-Basis		60.2	64.4	66.3	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Policy	62.4	59.3	61.5		
	Potentials	62.4	56.3	55.0		
Prognos 2001	40%-Variant	62.7	53.5	48.6		
IER 2002	Fossil-Nucl. E.	61.4	53.4	46.7	36.4	14.7
	Con.-Efficiency	61.4	53.9	51.5	44.2	19.7
	REG-/REN-Off.	61.4	54.1	52.0	46.3	22.7
HGF	Orientation		58.8	58.1	50.5	28.4
WI, DLR 2002	Sustainability		62.9	59.5	57.2	29.7
STE 2004	40%-Reduction		58.9	58.9	56.5	
	50%-Reduction		57.1	54.8	50.6	

**Tab. 13:** CO<sub>2</sub> emissions per unit primary energy demand (in kg CO<sub>2</sub>/GJ)

The emissions per unit primary energy increase in the baseline scenarios in the second period by 0.5% p. a. (Fig. 3) However this increase does not compensate for the drop of the emissions in the first period. Considerable changes of the emissions per unit primary energy are expected in the alternative scenarios. This development mainly results from the assumed CO<sub>2</sub> targets.



**Fig. 3:** Average change in the CO<sub>2</sub>-emission/ primary energy demand ratio

Tab. 14 shows the development of the share of renewable energies in primary energy consumption. In some studies waste and “other energy fuels” are summed up with renewable energy. So the figures for the different scenarios are only comparable to a limited extend.

The comparisons of the scenarios are also limited due to different kinds of assessments of renewable energies: In some cases they are asses by using the substitution method, in other studies the efficiency approach is used.

In the baseline scenarios the share of renewables increased significantly. A doubling of the share is expected for the year 2020. A faster increase is projected in the alternative scenarios. In most of the alternative scenarios the large and fast increase does not result endogenously rather it occurs due to underlying assumptions.

	Scenario	1995	2010	2020	2030	2050
<b>Baseline Scenarios</b>						
Prognos, EWI 1999	Baseline	2 %	3 %	4 %		
EU 1999	Baseline	2 %	3 %	3 %		
Öko-Institut 2000	Baseline	2 %	3 %	4 %		
ESSO 2000	Baseline	n.a.	4 %	6 %		
Prognos 2001	Baseline		3 %	4 %		
ESSO 2001	Baseline	n.a.	4 %	5 %		
IER 2002	Baseline	2 %	4 %	5 %	7%	11%
WI, DLR 2002	Status Quo		3 %	4 %		
STE 2004	Model-Basis		5%	6%	7%	
<b>Alternative Scenarios</b>						
Öko-Institut 2000	Politics	2 %	4 %	7 %		
	Potentials	2 %	6 %	13 %		
Prognos 2001	40%-Variant		6 %	10 %		
IER 2002	Fossil-Nucl. E.	2 %	6 %	5 %	7 %	20 %
	Con.-Efficiency	2 %	7 %	8 %	13 %	33 %
	REG-/REN-Off.	2 %	7 %	9 %	16 %	46 %
HGF 2002	Orientation		4 %	9 %	17 %	37 %
WI, DLR 2002	Sustainability		5 %	10 %	15 %	31 %
STE 2004	40%-Reduction		5%	6%	9%	
	50%-Reduction		5%	7%	15%	

**Tab. 14:** Share of renewable energies on the primary energy supply

### 3 Scenarios for the EU

#### 3.1 Introduction

The EU Energy-Outlook contains four main scenarios. The first one describes the business-as-usual path. For the second scenario (S0) a stabilization of the CO<sub>2</sub> emissions compared with the level of 1990 was assumed as a target for climate protection. In third one (S3) for the whole EU an emission reduction target down to 3000

tons of CO<sub>2</sub> was set. This target was lowered to 2,880 tons in the fourth scenario (S6).

### 3.2 Key Figures

Tab. 15 shows the assumptions for the development of the population and GDP used for the EU-scenarios.

	Unit	1990	2010	2020
GDP	billion EUR <sub>90</sub>	5,308	8,204	9,836
Population	Million	365	384	385

**Tab. 15:** EU scenarios – Trends in population and GDP

In the EU scenarios an increase of the population of 6% up to 385 million is anticipated. The GDP grows in this scenarios by 85%. The trends in population and GDP leads tendentially to a drastic rise of the energy demand. In the baseline scenario the primary energy demand increases by 22 %. The final energy demand grows by 30 % and CO<sub>2</sub> emissions by 14%. For the alternative scenario the same trends for GDP and the populations were assumed. The rise in the primary and final energy demand is less pronounced in the alternative scenario. Reduction measures for energy and CO<sub>2</sub> emissions are taken in the final demand sectors as well as in the conversion sector. In contrast to the baseline scenario in the scenario S0 the emissions are expected to be down by 12%. A reduction of 15 % and 18 % respectively in comparison to the baseline scenario is projected for the other two alternative scenarios (see Tab. 16).

	Primary Energy Demand (in PJ)			Final Energy Demand (in PJ)			CO <sub>2</sub> Emissions (in Million t CO <sub>2</sub> )		
	1990	2010	2020	1990	2010	2020	1990	2010	2020
<b>Baseline Scenario</b>									
Basel.	55,015	64,979	67,366	35,672	44,087	46,390	3,068	3,289	3,500
<b>Alternative Scenarios</b>									
S0	55,015	62,835	65,008	35,672	42,764	44,859	3,068	3,069	3,066
S3	55,015	62,055	64,132	35,672	42,191	44,256	3,068	2,977	2,975
S6	55,015	61,275	63,256	35,672	41,662	43,606	3,068	2,884	2,881

**Tab. 16:** EU scenarios: Primary energy demand, final energy demand and CO<sub>2</sub> emissions

Tab. 17 shows the development of the primary energy demand per capita, the energy demand per unit GDP and primary energy demand/final energy demand ratio. In comparison to the baseline scenario, a significantly lower primary energy demand per capita and lower primary energy demand per unit GDP is expected. The differences between baseline and the other scenarios rise to 6.5%. In contrast to these indicators, the primary energy demand/final energy demand ratios correspond in all scenarios.

	PED/capita (in GJ/capita)			PED/Unit GDP (in MJ/EUR <sub>90</sub> )			EEV/PED		
	1990	2010	2020	1990	2010	2020	1990	2010	2020
<b>Baseline Scenario</b>									
Base.	151	169	175	10.36	7.92	6.85	0.65	0.68	0.69
<b>Alternative Scenarios</b>									
S0	151	164	169	10.36	7.66	6.61	0.65	0.68	0.69
S3	151	162	167	10.36	7.56	6.52	0.65	0.68	0.69
S6	151	160	164	10.36	7.47	6.43	0.65	0.68	0.69

**Tab. 17:** EU-scenarios – Development of the specific primary energy demand

The development of the specific CO<sub>2</sub> emissions is shown in Tab. 18. Due to the assumed CO<sub>2</sub> targets, in the alternative scenarios the specific CO<sub>2</sub>-emissions are significantly lower than in the baseline scenario.

	CO <sub>2</sub> /capita (in t CO <sub>2</sub> /capita)			CO <sub>2</sub> / GDP (in g/EUR <sub>90</sub> )			CO <sub>2</sub> /PED (in t CO <sub>2</sub> /GJ)		
	1990	2010	2020	1990	2010	2020	1990	2010	2020
<b>Baseline Scenario</b>									
Baseline	8.42	8.58	9.10	578.0	400.9	355.9	55.77	50.62	51.96
<b>Alternative Scenarios</b>									
S0	8.42	8.00	7.97	578.0	374.1	311.7	55.77	48.84	47.16
S3	8.42	7.76	7.73	578.0	362.8	302.5	55.77	47.97	46.39
S6	8.42	7.52	7.49	578.0	351.6	292.9	55.77	47.07	45.54

**Tab. 18:** EU scenarios – Specific CO<sub>2</sub> emissions

In the baseline scenario the share of renewable energies in the primary energy supply increases by 4.8 %. For the reductions scenarios a considerable higher increase in the share of renewables is projected. (Tab. 19).

	1990	2010	2020
<b>Baseline-Scenario</b>			
Baseline	3.8%	4.3%	4.8%
<b>Alternative Scenarios</b>			
S0	3.8%	4.8%	5.9%
S3	3.8%	5.1%	6.2%
S6	3.8%	5.5%	6.5%

**Tab. 19:** EU scenarios - Share of renewable energies in the primary energy supply

## 4 Summary

As the comparison of current scenarios regarding the future energy use and supply in Germany shows that even in the baseline situation a significant reduction in the specific energy consumption is expected. However it has to be into account that most of the studies described above used Prognos/EWI (1999) as the main source for their scenarios. Therefore the results of the baseline scenarios do not differ very much. A comparison of the alternative scenarios, however, shows large differences. The differences result mainly due to different kinds of CO<sub>2</sub> reductions targets, the assumptions about the use of renewable energies, etc. In the baseline-scenario of the EU Energy-Outlook a still high increase of the CO<sub>2</sub> emissions is expected. According to this for a stabilization of the emissions a lot of efforts are necessary.

Regarding the EU Energy-Outlook as well as the national studies you have to keep into mind that a comparison of different studies is only possible to a certain extent due to different assumptions and approaches that were used. The use of an optimization tool, for example, leads to a more optimistic assessment about the demand for energy and the emission trends than the use of tools which were developed for making prognoses.

## 5 Literature

### [DIW, STE, ISI, Öko-Institut 2004]

DIW, STE, ISI, Öko-Institut (2004): Politikszenerarien für den Klimaschutz. Szenarien und Maßnahmen zur Minderung von CO<sub>2</sub>-Emissionen in Deutschland bis 2030.

### [DLR 1999]

Deutsches Zentrum für Luft- und Raumfahrt (1999): Klimaschutz durch die Nutzung erneuerbarer Energien, Berlin.

### [ESSO 2000]

ESSO (2000): ESSO Energieprognose 2000 – Zukunft sichern - Energiesparen, Hamburg.

**[ESSO 2001]**

ESSO (2001): ESSO Energieprognose 2001 - Potential der Öl und Gasvorräte, Hamburg.

**[EU 1999]**

EU-DG Energie (1999): EU - Energy Outlook to 2020, Luxemburg

**[Fahl, Remme, Bleasel 2002]**

Fahl, U. Remme U. and M. Bleasel (2002): Szenarienerstellung für die Enquete-Kommission „Nachhaltige Energieversorgung“ des Deutschen Bundestages, Endbericht, Stuttgart.

**[Fischedick 2002]**

Fischedick, M. et al. (2002): Langfristszenarien für eine nachhaltige Energienutzung in Deutschland, Umweltbundesamt, Forschungsbericht 20097104, Berlin

**[Hohmeyer 2000]**

Hohmeyer, O., R. Menges and S. Schweiger (2000): Arbeitplatzeffekte einer integrierten Strategie für Klimaschutz und Atomausstieg, Flensburg.

**[Matthes, Cames 2000]**

Matthes, F.-C. and M. Cames (2000): „Energiewende 2020: Der Weg in eine zukunftsfähige Energiewirtschaft“, Studien und Berichte der Heinrich-Böll-Stiftung, Berlin

**[Nitsch 2002]**

Nitsch, J. et al. (2002): Schlüsseltechnologie Regenerative Energien Teilbericht im Rahmen des HGF-Projektes „Global zukunftsfähige Entwicklung – Perspektiven für Deutschland“, Stuttgart, Karlsruhe.

**[Öko-Institut 1996]**

Öko-Institut (1996): Das Energiewende-Szenario 2020: Ausstieg aus der Atomenergie, Einstieg in Klimaschutz und nachhaltige Entwicklung, Darmstadt, Freiburg, Berlin.

**[Prognos, EWI 1999]**

Prognos, EWI (1999): Längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt, Untersuchung im Auftrag des BMWi, Basel.

**[Prognos 2001]**

Prognos (2001): Energiepolitische und gesamtwirtschaftliche Bewertung eines 40% Reduktionsszenarios, BMWi-Dokumentation Nr. 492, Berlin.

**[Prognos, WI, IER 2002]**

Prognos, Wuppertal-Institut, IER (2002): Bericht „Szenarienerstellung“ für die Enquete-Kommission „Nachhaltige Energieversorgung“ des Deutschen Bundestages, Kapitel 8: „Welt- und Europaszenarien“, Bericht-Nr. 561-5668.

**[Stein, Strobel 2000]**

Stein, G. and B. Strobel (2000): Politikszenerarien für den Klimaschutz. Szenarien und Maßnahmen zur Minderung von CO<sub>2</sub>-Emissionen in Deutschland bis 2020, Schriften des Forschungszentrums Jülich, Reihe Umwelt, Bd. 20, 2000, Jülich.

**[WI 1999]**

Pfahl, S. et al. (1999): Faktor Vier-Szenario, Wuppertal Institut für Klima Umwelt Energie, Wuppertal.

**[WI, Öko-Institut 2000]**

Wuppertal Institut für Klima Umwelt Energie, Öko-Institut (2000): Bewertung eines Ausstiegs aus der Kernenergie aus klimapolitischer und volkswirtschaftlicher Sicht, Wuppertal, Freiburg.

# Measures for CO<sub>2</sub> reduction in Germany

D. Martinsen\*, P. Markewitz\*, S. Voegelé\*

## 1 Introduction

In Germany there has been a continuous discussion in the last 10 – 15 years about ways of reducing greenhouse gases. Already at the beginning of the nineties different commissions of inquiry of the German parliament did pioneering work to get a solid grounding of the complex of greenhouse gas effect and the necessary greenhouse gas reductions. The Federal Government pledge itself already 1990 to reduce the emissions of CO<sub>2</sub> with about 25 % up to 2005. This unilateral obligation is far sharper than the 21 % "Greenhouse gas basket" - reduction until 2010-2012 within the framework of the Kyoto agreement. However, this national obligation also plays an exceptional role within the framework of the reduction target destination of 8 % within the European Union.

For systems analysis and advisory service for politicians one important thing is to find the effect of different technical measures on CO<sub>2</sub> emissions and identify optimal reduction strategies.

With a model of the national energy system, as for example developed within the framework of the IKARUS project, the impacts on such measures on energy demand, emissions and costs can be found and bundled into a cost effective reduction strategy.

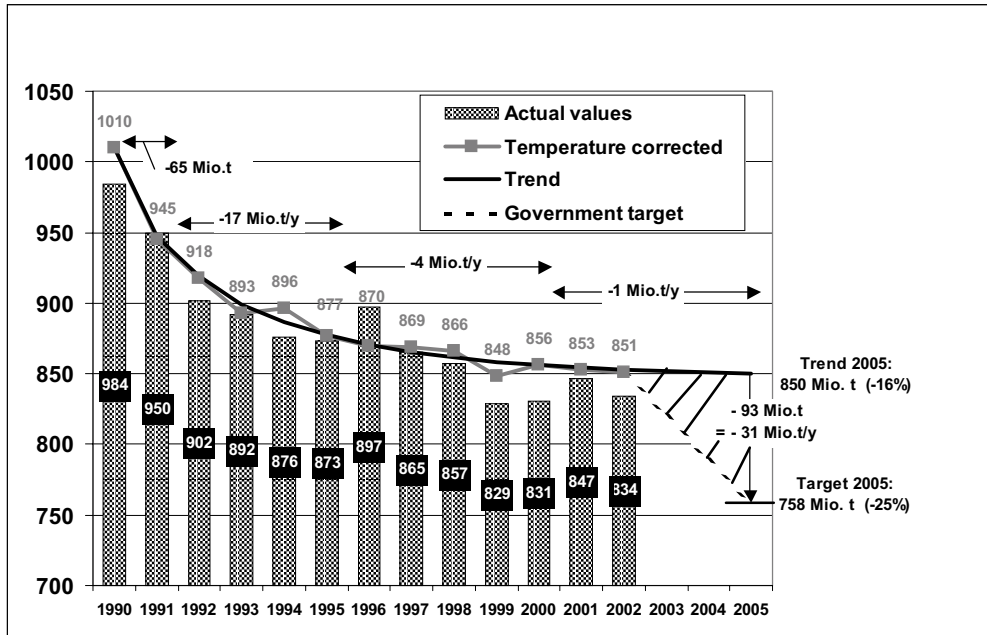
The amount of CO<sub>2</sub> emissions in Germany caused by energy conversion was in the last year (2002) about 834 million tons. This is a reduction of about 15% compared to the emission level of 1990. However, because of the mild climate of the last year, the temperature corrected value was by far higher (851 million tons) (Figure 1).

The high reduction rates in the first half of the nineties was in particular due to measures of restructuring in the newly-formed German states (East-Germany) that among other things led to a drastic reduction of the use of lignite. The annual decrease of the temperature corrected emissions (corrections for climatic variations) shows, however, a clear attenuation in the last years. An extrapolation of the trend of the CO<sub>2</sub> emissions indicates only a minor reduction for the coming years up to 2005. In order to reach the reduction target of -25 % compared to 1990 as earlier projected by the Federal Government for the year 2005, a reduction of more than 90 million tons would be necessary in the next three years. This would mean an average annual

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

reduction of about 30 million tons, which would be even higher than typical reduction rates of the first half of the nineties.



**Fig. 1:** CO<sub>2</sub> emissions in Germany

This illustrates impressively the pretentious goal of the Federal Government, but of course is highly unlikely to happen. Compared to the year 1990 the emissions from the different energy sectors were decreasing except for the traffic sector and residence sector. The rise of the CO<sub>2</sub> emissions in the traffic sector was especially significant and amounted to about 12 % in the period 1990 to 1998.

In their current climate protection program the Federal Government states that, with the reduction measures introduced since 1990 until today, the 25%-reduction target is not to be met by 2005. Examples of important measures introduced up to now are regulations for insulation of houses and a law of the use of renewable energy that allows the financial promotion of technologies using renewables and thus causing a forced penetration of such technologies into the market. Another reduction target is the pledge of the German Federal Republic to reduce the emissions of the six greenhouse gases performed in the Kyoto-record of in total 21 %, according to the country-specific EU distribution key, up to the period 2008 - 2012. However, already in 1990 a German parliament commission of inquiry "Provision to the protection of the atmosphere" stated that for the long term a much higher reduction would be necessary. It recommended a reduction of 50 % up to the year 2020 and even up to 80 % until 2050 when compared to the emissions of 1987.

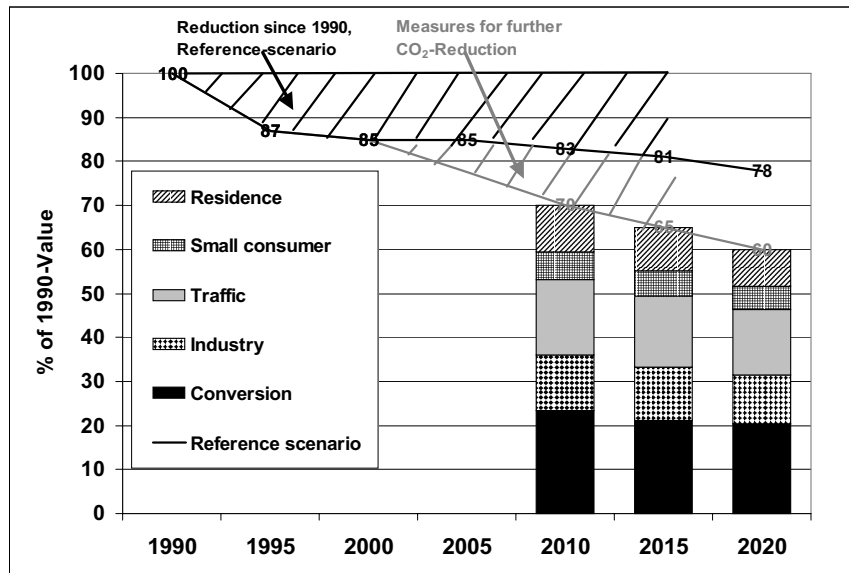
## 2 Formulation of a consistent CO<sub>2</sub> reduction strategy

At the beginning of the nineties the former Federal Ministry for Education, Science, Research and Technology (BMFT) initiated the IKARUS-Project (Instrumente für Klimagasreduktionsstrategien) with the objective to establish a sufficiently homogeneous data base as well as models on which basis consistent climate gas reduction strategies could be formulated and calculated. With the aid of the models climate gas reduction strategies can be developed and evaluated within the frame of energy technology and energy policy. One element of the IKARUS-instruments is an optimization model mapping the energy system of the German federal republic in form of cross-linked processes. Such processes are for example the extraction or the import of primary energy, the transformation in secondary energy (for example electric power production) and their distribution as well as the use of final energy carriers in the end use sectors for the demand of energy services (for example mobility, space to be heated, industrial production). In the model a great number of technological options are included with their corresponding specific emissions and the corresponding costs as well as possible networks of the energy fluxes. In addition general political set-ups are considered (for example the agreement of the dynamics of future shutdown of nuclear reactors). The energy system is formed within the model in such a way that the demand for energy services is fulfilled. With the mathematical method of Linear Programming the future demand for energy services is determined in the model in such a way, that targets expressed by energy- and environmental policy are met with economically minimized costs.

### 2.1 *(Cost) effective CO<sub>2</sub> reduction strategies*

In the following a climate gas reduction scenario is shown in which a CO<sub>2</sub> reduction path is imposed to the model up to the year 2020 taking into account the measures planned and taken until now. A CO<sub>2</sub> reduction of 40 % in the year 2020 was chosen as a very frequently mentioned reduction mark within energy policy. In parallel to that a reference scenario is developed in which no CO<sub>2</sub> restriction is explicitly set. The reference scenario is characterized as a business – as - usual – scenario. However, it must not be understood as a forecast or prediction in the sense of an expectation of future energy supply and demand. The scenarios are based on a great number of assumptions, that are to be considered when valuating the results. For example we assume only a moderate increase of energy prices. In addition our calculations are based on a annual growth rate of the gross domestic product between 2 and 2,5 % for the period to 2020. The demand for energy services in the final consumption sectors is, with the exception of the traffic sector, only slightly increasing. In the traffic sector we expect a strong increase of 50% of the freight traffic as well as a considerable increase of 15 % of the passenger traffic. In addition the reduction measures already introduced by the Federal Government are taken into account (for example energy-saving-regulation, additional use of combined heat and power). Also the political frame set by the Federal Government is to be included in the considerations. For example the agreement between the federal government and utilities concerning the nuclear phase-out, the minimum electrification of lignite in East-Germany or the minimum use of domestic hard coal.

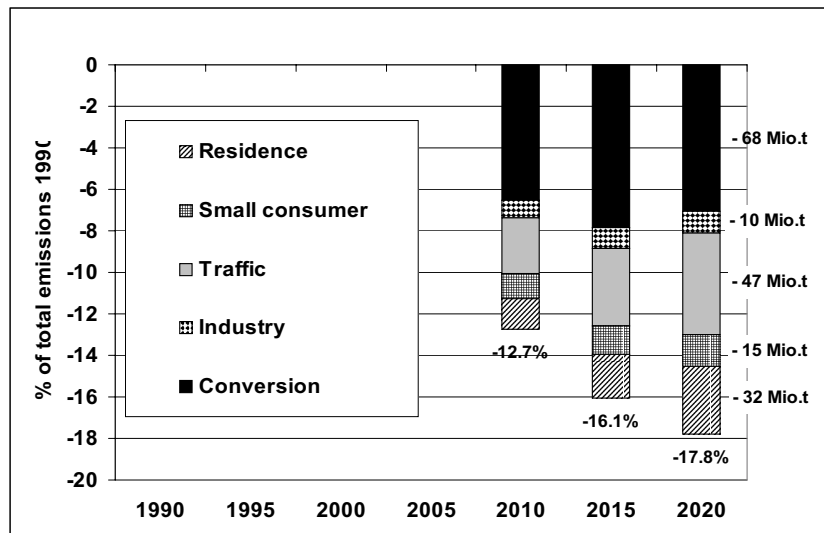
Figure 2 contains the emission projections of the reference- as well as the reduction scenario. The essential difference between the two scenarios is on one hand made up of the CO<sub>2</sub>-reduction targets being put on the reduction scenario. On the other hand further restrictions were set for the traffic sector requiring that traffic-made CO<sub>2</sub> emissions of the year 2010 respectively 2020 must not exceed the emission levels of the years 1995 respectively 1990. The reason for these CO<sub>2</sub>-restrictions especially set for the traffic sector is due to the low load factor of transport vehicles making reduction measures here relatively expensive and therefore normally not chosen by the optimization model.



**Fig. 2:** Projection of CO<sub>2</sub> emissions

In order to include in the calculations the implications of several reduction measures in the traffic sector and since a significant contribution from the traffic sector to the over all CO<sub>2</sub>-reduction is also considered as politically desirable, the corresponding restrictions were made.

Figure 2 shows, that in the reference case without CO<sub>2</sub> targets a reduction of 22 % is achieved up to the year 2020 as compared to 1990. The reduction goal of the Federal Government for the year 2005 is (of course) not met. In order to meet the pretentious mark of -40% in 2020 further measures are necessary. In the corresponding reduction scenario the technical feasibility of such a reduction strategy is shown and necessary measures are identified. Figure 3 illustrates the contributions of the individual sectors to CO<sub>2</sub>-reduction as compared to the reference scenario. Until 2015 the conversion sector takes a share of about 50% of the CO<sub>2</sub> reduction, basically due to changes of electric power production. Up to 2020 this share is reduced to 40 %, and more measures are taken in the final consumption sectors.



**Fig. 3:** Sectorial change of CO<sub>2</sub> emissions

Table 1 makes clear, that about 80 % of total reduction necessary to reach the reduction goal of 40 % in 2020 are in the sectors conversion, residence and traffic. In the following the emphasis of the outline is therefore placed on to these sectors.

<b>Sector</b>	<b>Measures</b>	<b>CO<sub>2</sub>-Reduction in 2020</b>
<i>Conversion</i>	• Additional wind power plants	5,9 Mio. t
	• Power plants and CHP-Plant fired with biogas, biomass and waste	6,6 Mio. t
	• Power plant and CHP-plants (gas combined cycle) substituting coal fired plants	48,8 Mio. t
	• Other savings (also refinery, coal conversion etc.)	6,3 Mio. t
	<b>Total Conversion</b>	<b>67,6 Mio. t</b>
<i>Industry</i>	• Substitution of oil and coal by gas and biomass	5,0 Mio. t
	• Energy saving (different processes)	5,1 Mio. t
	<b>Total Industry</b>	<b>10,1 Mio. t</b>
<i>Small consumers</i>	• Substitution of oil and gas by gas, district heating and renewables, extended use of heat pumps	12,4 Mio. t
	• Energy saving (heat insulation)	2,2 Mio. t
	<b>Total Small Consumers</b>	<b>14,6 Mio. t</b>
<i>Residential</i>	• Substitution of oil and coal and gas by district heating and biomass, use gas condensing boilers	12,6 Mio. t
	• Heat insulation	18,7 Mio. t
	<b>Total Residential</b>	<b>31,3 Mio. t</b>
<i>Transport</i>	• Alternative fuels (biofuel, bioethanol)	10,0 Mio. t
	• LPG and methanol, substitution of gasoline and diesel	1,3 Mio. t
	• Goods transport by train	10,5 Mio. t
	• Energy saving due to high efficient cars	25,3 Mio. t
	<b>Total Transport Sector</b>	<b>47,1 Mio. t</b>
<i>All Sectors</i>	• Increased use of renewables	29 Mio. t
	• Substitution processes	78 Mio. t
	• Energy saving measures	64 Mio. t
	<b>Total (All Sectors)</b>	<b>171 Mio. t</b>

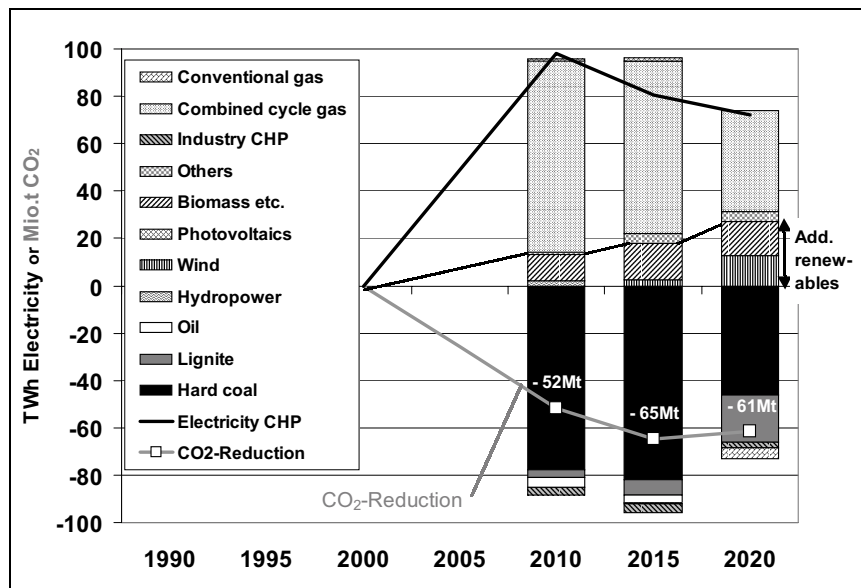
**Tab. 1:** Sectorial CO<sub>2</sub> reductions measurements and their effects

## 2.1 Electricity production

Considering the electricity production Figure 4 shows the differences between the reduction scenario and the reference case. Within the given time horizon the electricity production from Gas Combined Cycles and Renewables is rising significantly, substituting electricity production from coal fired power plants and from nuclear. In the year 2020 Gas Combined Cycle plants are achieving a total capacity of approx. 48 GW, whereas the capacities of coal fired and of nuclear power plants are decreased to 8 GW resp. 5 GW.

Due to the increased contribution to electricity production combined heat and power plants, based on natural gas are playing the dominant role, regarding CO<sub>2</sub> reduction targets.

As a consequence of the German Climate Protection Programme an enlarged use of biofuels is being expected. According to this financial support, lower limit bounds for electricity production by biofuels were introduced. However the model is optimizing within various options for electricity generation, such as biomass, biogas and others.



**Fig. 4:** Changes of electricity production

Until 2020 the share of CO<sub>2</sub> emissions from electricity production is reduced significantly by 13 % (reference case) resp. 35 % (reduction scenario). The difference, which relates to an amount of 60 Mio. t.CO<sub>2</sub>, can be explained by the substitution of coal. The additional investments requested for the application of these measures accumulate to a net yield of 12 billion Euro over the time period considered. Related to specific electricity generation costs, an increase of 0,6 cts/kWh (2020) is expected.

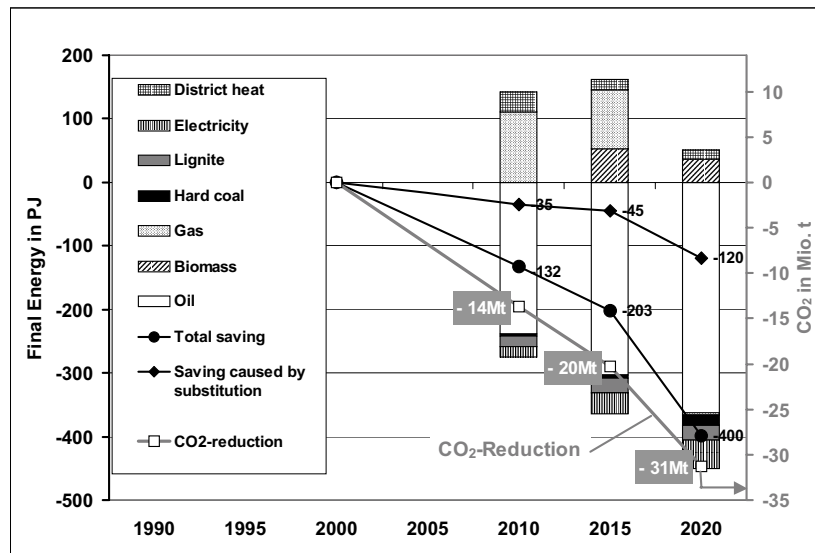
## 2.2 Residence sector

The final energy consumption of the residence sector decreases in the model calculations from 1990 to 2020 continuously. In the reference scenario the decline is 11 %

(in the case of the reduction scenario 26 %), where an essential part of the energy saving after 2010 is caused by measures of thermal insulation. Next to the insulation measures coal and oil are replaced by natural gas and biomass.

Due to energy saving and substitution of energy carriers the percentage of CO<sub>2</sub> reduction in 2020 is even in the reference scenario nearly 30 % as compared to 1990. In the reduction scenario this value increases to about 50 %.

In the reduction scenario additional measures are taken by the model compared to the reference scenario, that is exchange of technique, substitution of energy carriers and energy saving. Figure 5 shows the impact of these additional measures on the final energy consumption respective on the CO<sub>2</sub> emissions in the residence sector. The result is an additional drop of the final energy demand up to 2020 of about 400 PJ corresponding to a reduction of 17 % compared to the reference scenario. The extra measures for thermal insulation contribute to this drop with approx. 70 % (280 PJ). The substitution of conventional heating (fuel oil, coal products) by new systems based on biomass, long-distance heating and particularly natural gas give a further saving of 120 PJ. The additional use of natural gas mainly occurs in efficient gas condensing boilers.



**Fig. 5:** Changes in the residence sector

Compared to the reference scenario the additional CO<sub>2</sub> reduction in the year 2020 is about 30 million tons. This reduction of 28 % is mainly due to measures of heat insulation in buildings.

The potential for saving of space heating is considerably greater for old buildings than for new buildings. In the field of old buildings the space heat saving is between 5 respective 13 kWh/m<sup>2</sup> (in 2010) and 10 respective 35 kWh/m<sup>2</sup> (in 2020) in the reference- respective reduction scenario. Compared to the 1995-value of approx. 142 kWh/m<sup>2</sup> this means a saving of up to 35 %. In the field of new buildings the energy saving - being at most 7 - 8 kWh/m<sup>2</sup> or approx. 9 % (relative to the 1995-value) - is

considerably smaller. Correspondingly the potential of CO<sub>2</sub> reduction in the old buildings is 10 to 30 times greater than in the new buildings. Compared to the reference scenario the total (old and new buildings) CO<sub>2</sub> reduction due to additional measures of insulation of buildings in the reduction scenario is about 20 million tons in the year 2020.

For costs reasons the thermal insulation in the old building will preferably take place within the renovation cycles. At the end of the time period, however, the model also chooses more expensive measures outside of the renovation cycle, in particular in the field of the multiple dwelling.

The corresponding annual investments for the additional thermal insulation in the reduction scenario increase from 2.5 billion Euro in 2010 to about 6.5 billion Euro in 2020. This means that the annual capital costs for the additional thermal insulation measures in old buildings are about 1.5 Euro (in 2020) per square meter of living space, i.e. the additional costs can constitute up to 150 Euro per annum for a 100 m<sup>2</sup> apartment. In the field of new buildings the costs are considerably lower.

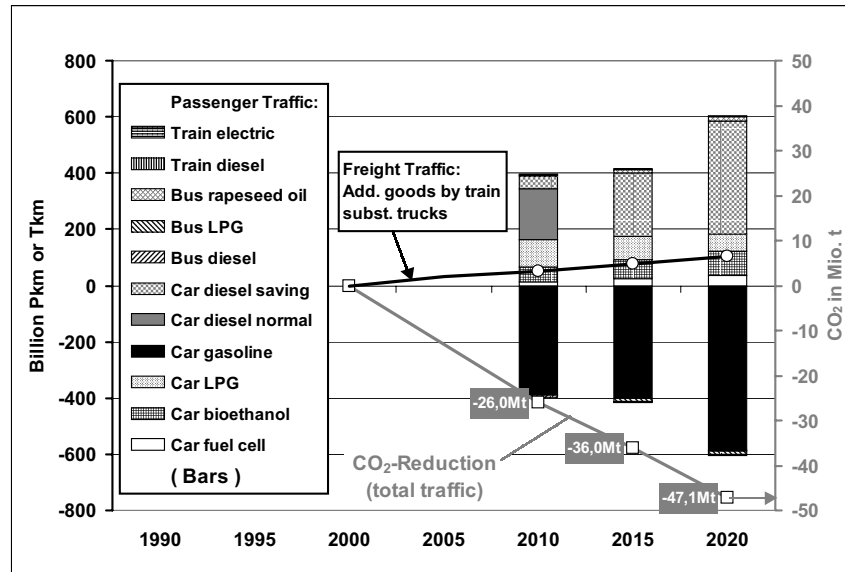
### 2.3 *Traffic sector*

Since 1991 the passenger and freight traffic in Germany has increased with 11 % respective 37 %. As a consequence, the CO<sub>2</sub> emissions in the traffic sector in the decade up to 2000 went up with around 17 million tons or about 10 %. In the model calculations we assume, that the traffic services, in particular the one of the freight traffic, will continue to increase up to 2020. In spite of a noticeable reduction of the specific fuel consumption of vehicles, in the sense of an autonomous technical progress, CO<sub>2</sub> emissions will climb with approx. 47 million tons up to 2020 as compared to 1990. As already mentioned, in the reduction scenario this rise is prevented by limiting the CO<sub>2</sub> emissions in the traffic sector in 2010 respective 2020 to the values of 1995 respectively 1990. The magnitude of these emission restrictions is to a certain extend arbitrary. They serve the purpose to explore the CO<sub>2</sub>-reduction potential of the model with regard to technological changes as well as changes of the traffic carriers (Figure. 6). For this the following options are available:

- Vehicles with energy saving (Strong reduction of the specific fuel consumption combined with higher vehicle costs by preservation of vehicle qualities like size of vehicle, engine power etc. and preferences for comfort and other indicators of behavior),
- Substitution of vehicles or fuels (for example diesel- instead of gasoline engine, or use of alternative fuels such as methanol, bioethanol, etc),
- New technologies (for example fuel cell) and
- Change of the modal split (for example railway instead of road traffic, or public passenger transport instead of private vehicle traffic).

Figure 6 shows that in the field of passenger traffic all options except for a further shift of the modal split are realized by the model (the potential of an extension of railroads and buses is already partly exhausted in the reference case). In the area of passenger traffic a noticeable shift to energy saving diesel cars occurs. Also vehicles

based on alternative fuels like for example Bioethanol and LPG as well as cars with fuel cell technology are chosen. They are substituting conventional vehicles with gasoline engine. These structural changes affect about half (600 billion person-kilometers) of the demand of passenger traffic in the year 2020.



**Fig. 6:** Structural changes in the traffic sector and corresponding CO<sub>2</sub> emissions

In the area of freight traffic trucks with strongly reduced fuel consumption (energy-saving-trucks) will substantially replace the conventional trucks by 2010 in the reduction scenario. At the same time the share of goods transported by railway will increase. After 2010 the street bounded freight traffic clearly decreases and the rail-mounted transportation increases strongly. Latter is in the year 2020 approx. twice as high as in the reference scenario (Figure 6).

## 2.4 Renewable Energy

In the long term energy carriers and -techniques, that in the net balance virtually do not emit any CO<sub>2</sub> or other climate gases are of special importance. The nuclear processes fusion and fission belong to this category as well as the renewable energy carriers like solar-, hydro-, wind power or biomass, rapeseed oil etc. The additional use of renewable energy in the reduction scenario compared to the reference scenario is presented in figure 7, expressed as primary energy equivalent. In the period 2010 to 2020 an extra amount of 250 to 450 PJ replaces a similar quantity of hydrocarbons, corresponding to a share of approx. 7 % to the entire primary energy consumption in the year 2020 (compared to 3% in the reference scenario and less than 2% today). The composition of the basket of renewable energy carriers is quite manifold, including hydro power, biogas, biomass, rapeseed oil and bioethanol. The share of the solar energy (photovoltaic, solarthermal processes), however, is only marginal due to the high capital costs.

With this additive use of renewable energy, taking place in all sectors, we calculate a CO<sub>2</sub> reduction of approx. 15 million tons for the year 2010 growing to nearly 30 million tons up to 2020.

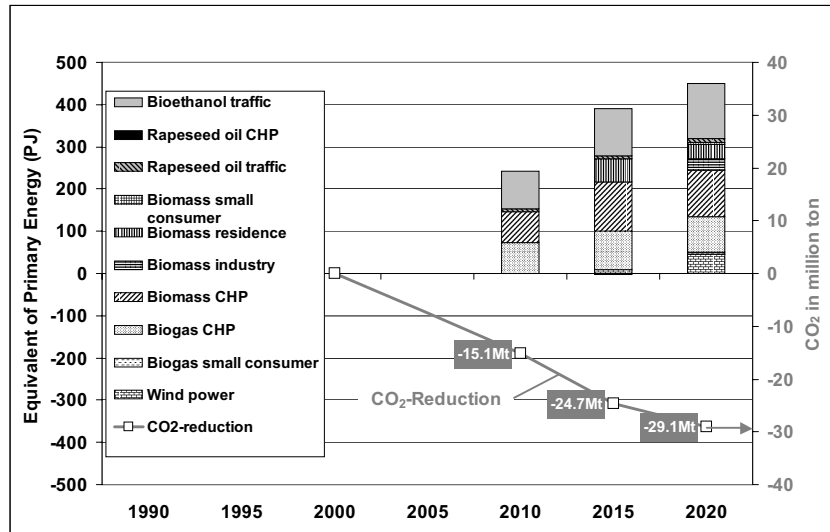


Fig. 7: Additional use of renewable energy and corresponding CO<sub>2</sub>-reduction

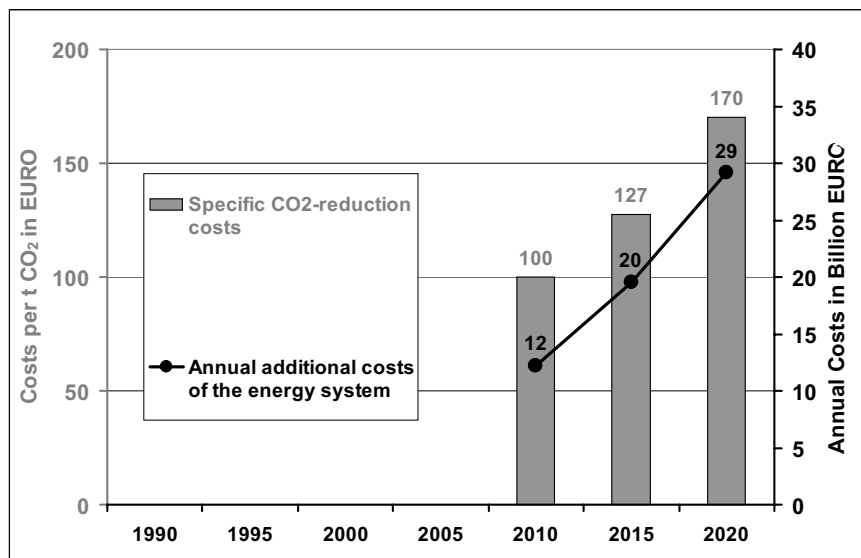
### 3 Costs of the CO<sub>2</sub> reduction

The future evolution of the CO<sub>2</sub> reduction costs is shown in figure 8. The specific values are referred to one ton of CO<sub>2</sub> reduction and is to be understood as mean costs for the respective year. The specific CO<sub>2</sub> reduction costs are formed as a quotient where the total amount of additional costs of the energy system as compared to the reference scenario, that is the integral measure costs, is divided by the corresponding CO<sub>2</sub>-reduction. The costs of CO<sub>2</sub> avoidance in the system increases from 100 Euro/ton to 170 Euro/ton in the period 2010 to 2020. In the year 2010 the entire annual additional costs are approx. 12 billion Euro. Up to the year 2020 these costs climb to 29 billion Euro per year. This corresponds to an additional annual burden per capita in the range of roughly 150 Euro (in 2010) to 350 Euro (in 2020). The magnitude of the additional costs is a measure of the expenditure which must be raised in order to achieve the corresponding CO<sub>2</sub> reduction. The expenditure includes the costs of the technical effort as well as the costs for the national economy by importing energy carriers.

We would like to point out that we left needs for consumption and desire for comfort as well as consumer behavior unchanged compared with the reference scenario. This means for example in the case of the traffic sector that the behavior behind the wheel does not change and the size of the car as well as the auto ride comfort remain as it was. However, a modification of shares of different means of transportation (car, bus, train etc.) is of course possible.

The reason, why changes of behavior are considered only in a very limited way, is the fact that behavioral changes could possibly lead to cost reductions that would then be assigned to the CO<sub>2</sub> reduction in the calculations. This in turn would be methodically questionable, since these changes in the true sense do not represent any (technical) expenditure for an additional CO<sub>2</sub> reduction. Also the purpose of these calculations is to find the impact of technical measures on CO<sub>2</sub> emissions and system costs.

The development of the additional costs in the traffic sector plays for the total reduction costs as represented in figure 8 an important role and reflects among other things the high capital expenditure for vehicle substitutions. The share of costs for measures in the traffic sector to the total additional costs increases from about 60 % in the year 2010 to approx. 70 % in the year 2020. In this case only system costs arising immediately from measures in the traffic sector are assigned to that sector. In order to avoid multiple counts, costs of energy carriers in the model are counted just once in the sector where the energy carrier are produced or imported.



**Fig. 8:** Costs of CO<sub>2</sub> reduction

Altogether the costs in figure 8 appear quite high and represent a noticeable financial burden. However, the order of magnitude is comparable to many other expenses or subsidies in the energy economy. For example the annual ecotax in Germany in the year 2000 amounted to 8.7 billion Euro and is estimated to increase to approx. 16 billion Euro for this year. Another example: For the extraction of domestic hard coal in Germany a subsidy of about 30 billion Euro is planned for the period 1997 to 2005.

The specific carbon reduction costs are of course quite high. Referring to one ton of carbon the average “avoidance costs” come to about 600 Euro in 2020. In comparison, the price of imported hard coal, i.e. “provision costs of carbon”, is about 50 Euro/ton.

## 4 Final remarks

In the scenarios discussed above measures and their impacts on a possible future CO<sub>2</sub> reduction are shown. The results must not be interpreted as an expectation in the sense of a forecast. Within the frame of several assumptions concerning the energy economy (for example economic growth, energy prices, development of passenger and freight traffic etc.) as well as political frames (for example the electrification of German hard coal, the agreement to back out of nuclear energy) scenarios are generated showing possible paths to a substantial CO<sub>2</sub> reduction within the German energy system. The use of an energy system model guarantees the consistency of the analysis (f. ex. the interaction of different measures) and allows the repeatability of scenarios. In addition robust solutions can be identified with the aid of extensive sensitivity runs. Results of such scenario calculations serve as an aid for understanding the effect of certain assumptions in energy economy and represent one element among several within a decision-making process. The political instruments necessary to put the scenario results into action can only be found outside of the model frame.

It has to be stressed that the list of measures established by the model as well as the costs resulting out of it strongly depends on the exogenously assumptions that are set. For example the assumed future demand in the model (passenger traffic, living space, industrial production etc.) is of great importance. An important role plays the dynamic shape of the CO<sub>2</sub> restriction over the period up to the year 2020. For example instead of the annually given CO<sub>2</sub> upper limits for the period 2000 to 2020 one can put a bound on the corresponding cumulated amount of CO<sub>2</sub> for the same period. In this case costs can be reduced substantially (up to 40 %) since in such a case the model can unfold the cumulated CO<sub>2</sub> reduction in a cheaper way. This leads normally to a release of the restriction up to the year 2010 and a tightening thereafter. In that way costs are reduced and used more efficiently.

The scenario results show that the costs of the compliance of the reduction scenario are considerable. Therefore a discussion about the most suitable or most cost-efficient measures for emission reduction should also contain an examination of the frame or boundary put up by energy policy. Changes of this frame can sometimes cause considerable cost reductions.

Not only energy but also capital is a limited resource that has to be used efficiently. From this point of view it is important to consider, whether a greater amount of emission reduction can be achieved with the same invested capital in other countries within the framework of joint-implementation initiative or other Kyoto mechanisms.



# The role of modern fossil power plant concepts in Europe

P. Markewitz\*, S. Voegelé\*

## 1 Introduction

About 50 % of the electricity produced in the European Union is currently generated in fossil-fired power plants. The primary energy input in these power plants corresponds to almost one quarter of total EU-wide primary energy consumption. More than one third of all the European Union's energy-related CO<sub>2</sub> emissions result from the combustion of fossil energy carriers in power plants. Many forecasts and scenarios proceed on the assumption that fossil energy production will also play a considerable role in the future. So in view of the CO<sub>2</sub> reduction commitments undertaken by the EU, significant emission savings will have to be brought about by fossil electricity production.

The power plant concepts which are under research and development indicate promising efficiency increases that could make a decisive contribution towards greenhouse gas reduction. In this connection, the question arises as to when market maturity will be reached for such concepts and whether this will be correlated with the capacity demands predicted.

In the following analysis an inventory updating is performed for some selected EU countries on the basis of currently existing power plants and assuming technical lifetimes. The time span and level of a possible demand for the construction of new power plants is shown by a comparison with actual electricity consumption forecasts. The time dynamics and level of demand for additional plants form the basis for calculating the CO<sub>2</sub> reduction potentials of the power plant concepts under research and development today. The analyses were performed for Austria, France, Spain, Germany, Italy, the United Kingdom and Greece, those countries in which more than 80 % of the EU's fossil electricity production is to be found.

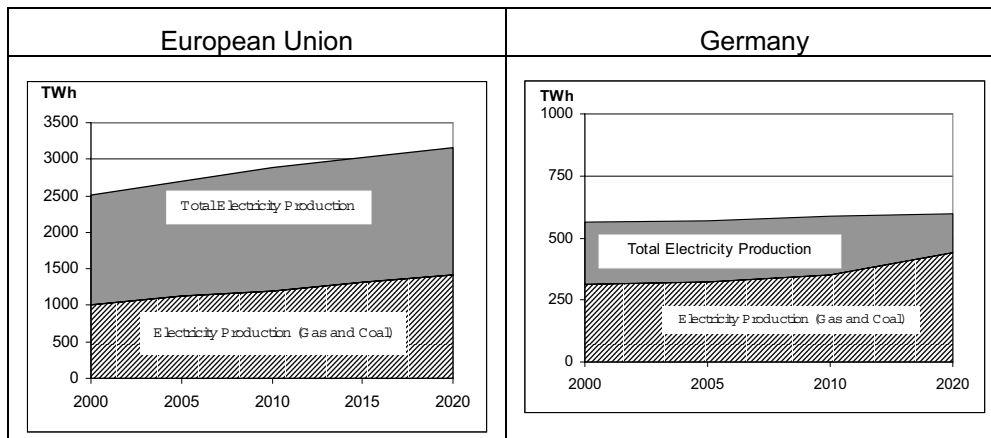
---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

## 2 Basic assumptions

The starting point of the analyses is the country-specifically predicted electricity production according to a study by Eurelectric [Eurelectric 2000]. In some cases (e.g. Germany), for which more detailed or more recent projections and information were available, the analyses departed from the Eurelectric data. In analogy to other EU-wide projections, Eurelectric's prognosis also assumes an increase in electricity consumption. Eurelectric expects an increase of total European electricity production by about 25 % up to the year 2020 (Figure 1). There are considerable differences between the EU member states. It is expected, for example, that electricity consumption rates and thus also the electricity production in the southern European countries will rise much more sharply than on the EU average. In principle, the electricity production forecasts assume an above-average increase of coal- and gas-based electricity production. Compared to the present-day share of about 41 %, a share of approx. 45 % is predicted for the year 2020. This figure is supported, in particular, by the development expected for Germany.

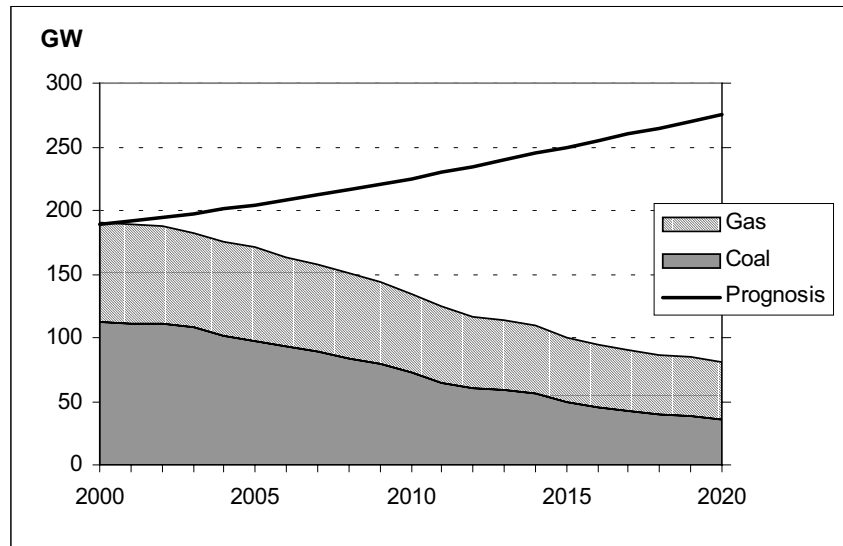
At present, about 27 % of the EU's fossil-based electricity is produced in Germany. This share will increase against the background of Germany's decision in favour of opting out of nuclear power. Projections for the Federal Republic of Germany assume an increase in fossil electricity production by approx. 40 % compared to today. The fossil share in German electricity production will then amount to about 80 % in 2020 (2000: approx. 60 %).



**Fig. 1:** Projections for fossil electricity production [Eurelectric 2000, Prognos/EWI 1999, own calculations]

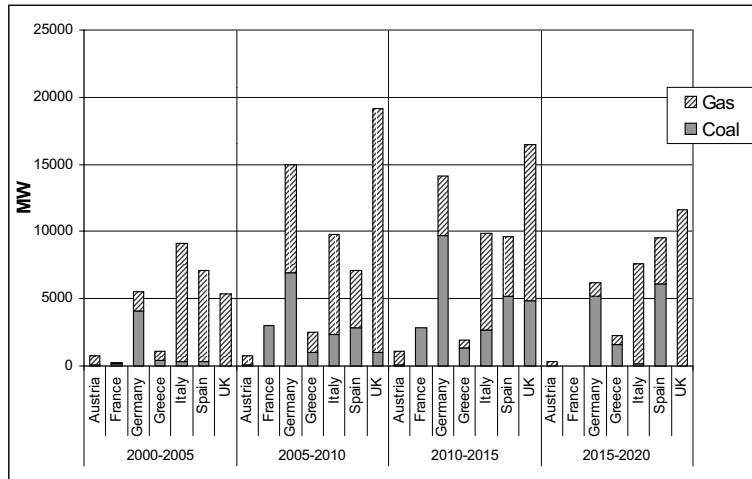
Another important basis for assessing the savings potentials of new power plants is the development of existing power plants, since this decisively influences the construction of new replacement power plants. Figure 2 shows the development of existing gas- and coal-fired power plants for the countries under consideration in this analysis. The mortality line in Figure 2 was determined on the basis of individual power generating units.

Assuming a technical lifetime of 35 – 40 years for fossil power plants, the plants existing today will clearly decrease by 2020 so that only about 40 % of today's plants will then be available. New and replacement capacity building can be derived by combining the mortality line determined with the development predicted by Eurelectric for future fossil electricity production (Fig. 2).



**Fig. 2:** Development of fossil power plants existing today and of fossil capacity demand (without oil-fired power plants) for selected countries of the EU

The difference in the demand for fossil generating capacity and in the development of existing plants shown in Figure 3 corresponds to the generating capacity to be added and/or replaced. Figure 3 shows new generating capacity building differentiated according to energy carriers for the respective 5-year periods. Considerable capacity replacement and new capacity building is to be expected, in particular, for the period up to the year 2015, if the anticipated prognostic assumptions (e.g. electricity consumption) and the mortality line of existing power plants are taken into account. Both the level of capacity building and the application of energy carriers are very different in the respective countries. Moreover, it should be noted that the construction of gas-fired power plants predominates.



**Fig. 3:** Future capacity building and replacement (coal- and gas-fired power plants)

### 3 Reference development

In order to be able to assess the possible savings potentials of more efficient power plant technologies, the assumption of a technical reference development is required. The given reference development is the state of the art of the individual energy-carrier-specific power plant types. These are power plant types planned from the present perspective or currently under construction or expected to be put into operation in the near future. The assumed efficiencies for the individual power plant types are shown in Table 1. For the reference development, these efficiencies are practically frozen und updated at a constant rate up to the year 2020, i.e. it is anticipated hypothetically that the efficiencies of new power plants will remain unchanged.

Hard coal	45 - 47.5 %
Lignite	45 %
Natural gas (Combined cycle)	58 %

**Tab. 1:** Net efficiencies (state of the art) [BMW 1999]

	Pressurized Fluidized Bed Combustion	Pulverized Combustion (Hard Coal)	Pressurized Pulverized Combustion	Intergrated Gasification Combined Cycle	Pulverized Combustion (Lignite)	Natural Gas Combined Cycle
Enquete 2001	-	51%	-	54% 48% (with CO <sub>2</sub> capture)	50% <sup>3)</sup>	61.5 %
Pruschek 2000	< 45% (limited by TIT ≤ 850°C) 54% <sup>2)</sup> (calculated)	2002: 300 bar/650°C (Komet 650) 2015: 375 bar/700°C, 52 – 55%, (advanced 700°C power plant)	-	51.5% (calculated)	50% <sup>3)</sup>	63% (TIT: 1400°C)
AGFW 2001	-	2025: 51%	-		2025: 50% <sup>3)</sup>	2025: 63%
Benesch 2001	47%	50%	51%	50%		
Bergmann et al. 2001	55 % <sup>2)</sup>	50%	2015: 55 % 2020: 60% (with impr. gas turbines)		50% <sup>3)</sup>	65%
BMWf 1999	2015: 55% <sup>2)</sup>	2010: >50%	2015: 55% 2020: 60%			
ATLAS 1997		2005: 300 bar, 600°C, 46% 2010: 350 bar, 700°C, 50%				
DACES 2001		2020: 49 – 50%		2020: 50 – 51%		
IKARUS 2001	48% <sup>2)</sup>	2005: 300 bar, 600°C, 45.5%		2005: 48%		2005: 58%

Notes: 1) with additional natural gas combustion  
2) second generation (hybrid), no temperature limit, combustion gas production by pre-gasification  
3) improved coal-drying process by using low caloric heat with heat recovery  
TIT: turbine inlet temperature

**Tab. 2: Future efficiencies of modern fossil plants**

## 4 Future efficiency potentials

The specification of efficiency potentials for conventional power plant technology and for new technology lines is naturally associated with corresponding uncertainties since these technologies do not yet exist. In many cases, these efficiencies are therefore calculated. Moreover, the high degree of uncertainty in the data on new technology lines should be mentioned, since these are, in part, still on the laboratory scale. Table 2 shows an overview of efficiency estimates as currently specified in the literature for modern power plant concepts based on fossil energy carriers. On the basis of these estimates, the efficiencies listed in Table 3 were defined for the following analyses.

	2005	2010	2015	2020
<i>Hard Coal - Pulverized Combustion</i>	48 %	50 %	52.5 %	53-55 %
<i>Hard Coal - Pressurized Pulverized Combustion</i>	-	-	55 %	55-60 % <sup>2)</sup>
<i>Hard Coal <sup>1)</sup> - Pressurized Fluidized-Bed Combustion</i>	-	47 %	55 % <sup>1)</sup>	55 %
<i>Hard Coal - Integrated Gasification Combined Cycle</i>	48 %	49 %	50 %	52 %
<i>Lignite</i>	45.5 %	46.5 %	48.5 %	50 %
<i>Natural Gas - Combined Cycle</i>	59 %	60 %	61 %	63 %
Notes: 1) from 2015 second generation (hybrid version), no temperature limits 2) improved efficiency due to improved gas turbines				

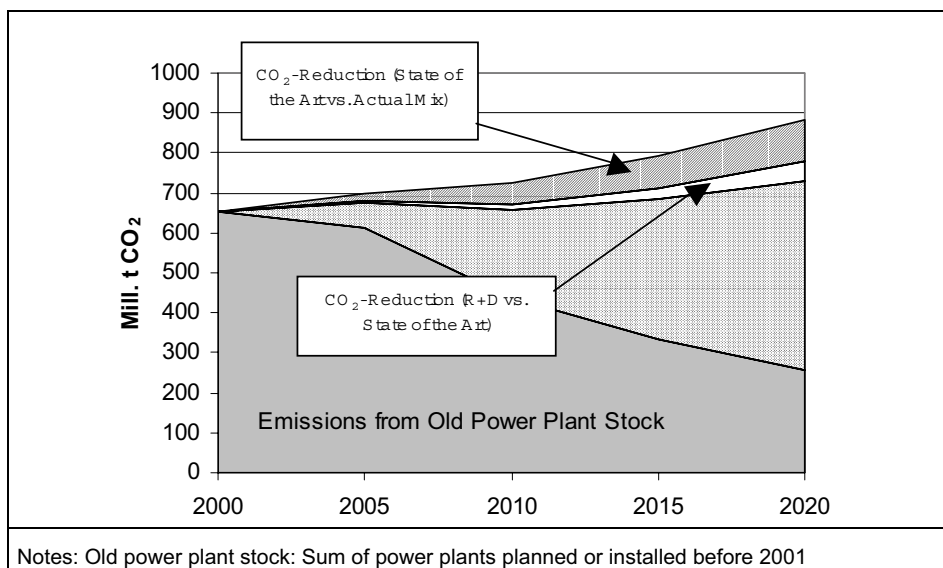
**Tab. 3:** Net efficiencies of future fossil power plant concepts

A central issue influencing the emission projections is the availability or market maturity of future power plant technologies and concepts. Table 2 also contains relevant information according to the experts' estimates. Accordingly, pressurized pulverized coal combustion will not be available before 2015 with an efficiency of about 55 %. An efficiency increase to 60 % by the year 2020 is definitely considered possible. The application of pressurized fluidized-bed combustion is regarded as realistic from the year 2010. For the transition to the so-called "second generation" enabling a further increase in efficiency, the year 2015 is specified as the earliest possible point in time. The change to higher steam parameters in "conventional" hard coal power plants, on the other hand, is to be conceived as a slowly progressing process which, however, is also promoted by large-scale national and EU-wide collaborative research projects (e.g. Komet 650, "Advanced 700°C Power Plant") and enables corresponding efficiency improvements.

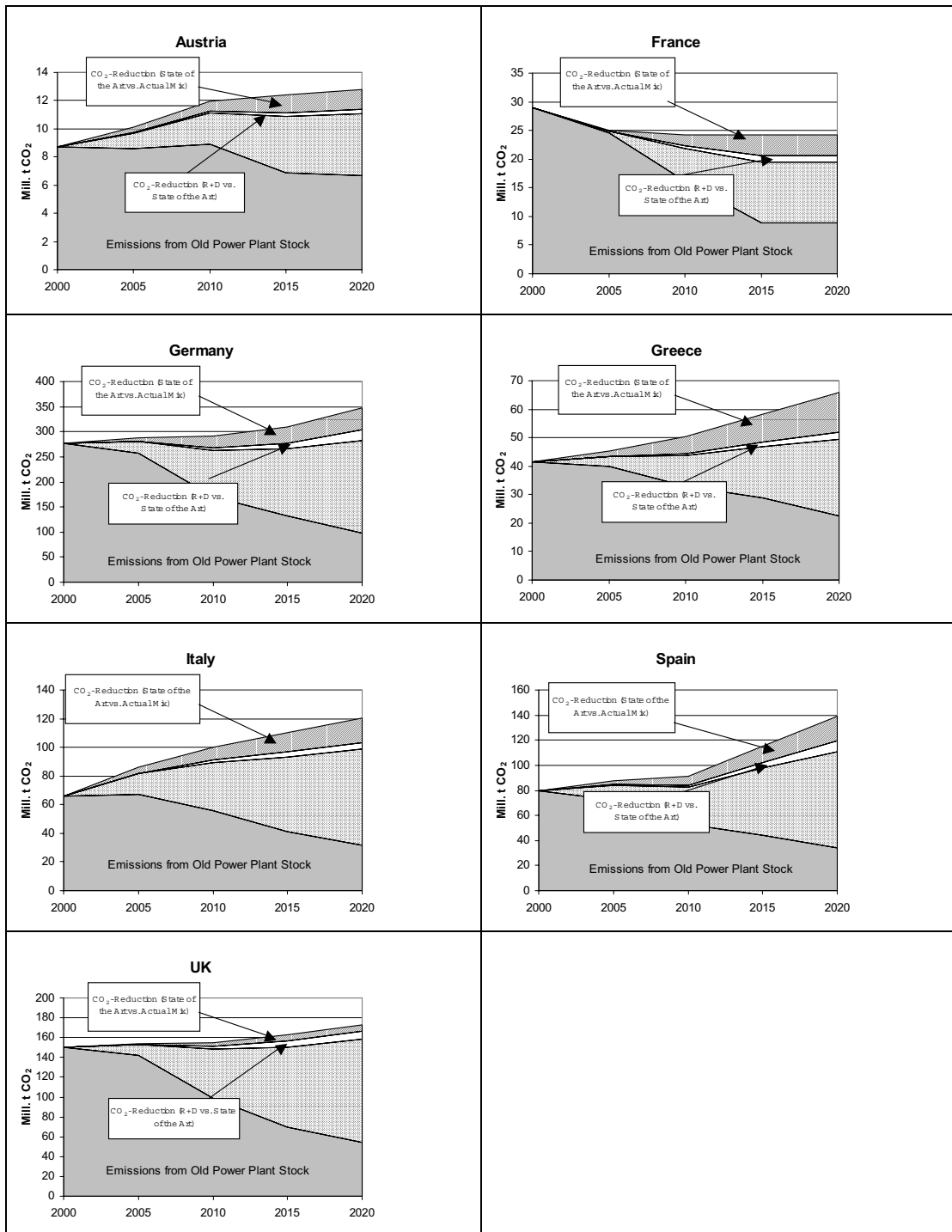
#### 4.1 CO<sub>2</sub> savings due to future efficiency potentials

Figure 4 shows the emission curves determined for the countries considered in the analysis on the basis of the assumptions explained above. In principle, a differentiation must be made between the emissions from the declining (old) power plant stock and those from new power plants. For a comparison between the state of the art and the existing range of power plants, a variant was additionally calculated in which the average efficiencies of today's power-plant mix (hard coal, lignite, natural gas) were updated country-specifically as "frozen efficiency" up to the year 2020.

The emission evolution thus calculated corresponds to the upper curve behaviour. If no efficiency improvement compared to the present power plant mix occurred, CO<sub>2</sub> emissions would rise to about 880 million t in 2020. A construction of new power plants corresponding to the state of the art causes a significant emission reduction. The emissions in 2020 would then amount to about 780 million t. The cumulative CO<sub>2</sub> savings over 20 years (integral over 20 years) are approx. 1000 million t in this case (shaded area).



**Fig. 4a:** Aggregated Emission savings due to the exploitation of possible efficiency potentials (Austria, Spain, France, Greece, Germany, Italy, UK)



**Fig. 4b:** Emission savings due to the exploitation of possible efficiency potentials (country - specific)

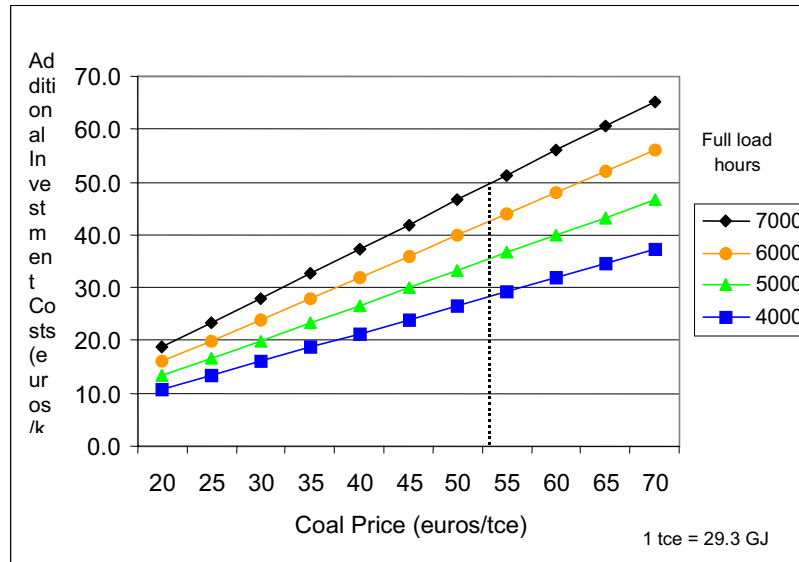
The application of currently R&D-funded technologies and the associated efficiency potentials, compared to the state of the art, can additionally provide an emission reduction potential leading to annual emission decreases of approx. 45 million t in 2020. The cumulative emission quantity over 20 years is in the range of 330 million t, and it can be seen that the level of saved emissions also correlates with the point in time of the required new capacity building and the market maturity of the future technologies. As can be seen from Figure 3, a large proportion of the new power plants required will already be built before the year 2015. This means that the efficiency potentials of promising technology lines such as pressurized pulverized coal combustion or the second generation of pressurized fluidized-bed combustion will not take full effect since their market availability and market maturity are not given before that time.

Last, but not least it should be pointed out that considerable emission reduction potentials could also be tapped by improving the efficiency of existing plants. This comprises both the replacement of individual components (e.g. boilers, steam turbines) and optimization measures with possible capacity expansion (e.g. repowering, topping, boosting) [cf. Hourfar 2001]. Measures of this type would also prolong the lifetime of plants, since they generally involve an upgrading. A replacement-induced demand for new capacity building would thus be shifted into the more distant future.

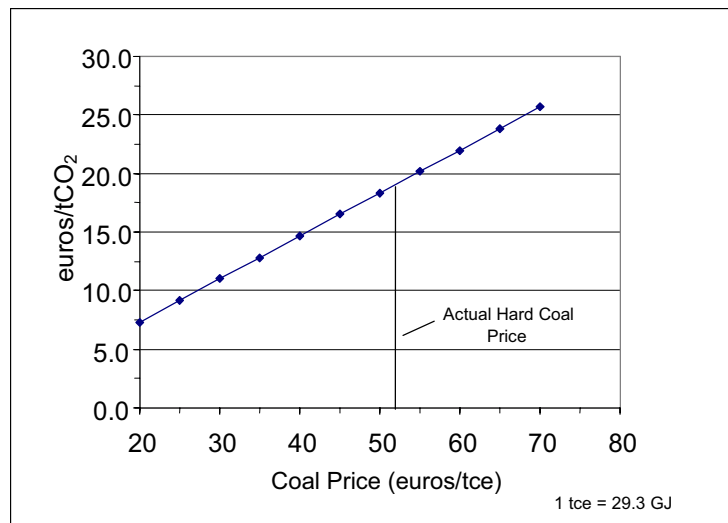
In comparison to the specification of efficiencies for future measures and technologies, the specification of costs is much more difficult. Reliable cost data are not found in the relevant literature. An attempt will therefore be made in the following to provide a cost estimate on the basis of maximum allowable costs to remain competitive. Based on the simplifying hypothesis that measures for efficiency improvement imply higher investment costs, so-called maximum additional investment costs can be calculated via the fuel price and the load of a power plant, i.e. the amount of fuel saved due to the efficiency gain and thus reduced fuel costs are recalculated as maximum additional investment costs.

Figure 5 shows maximum additional investment costs by the example of a hard coal power plant (efficiency increase from 47 to 50 %) as a function of fuel prices and plant load. Relative to the present hard coal import price (about 52 euros/tce) the maximum additional investment costs are in the range of 25 to 50 euros per kW. With declining fuel prices the maximum investment costs are reduced analogously. The costs per percent of efficiency improvement are then calculated as amounting to about 7 to 17 euros.

From fuel saving it is then possible to determine the saved CO<sub>2</sub> emissions by multiplication by the specific CO<sub>2</sub> emission factor. The specific CO<sub>2</sub> avoidance costs are calculated as a function of the fuel price by dividing the saved fuel costs by the saved CO<sub>2</sub> emissions (Fig. 6). With an import hard coal price of currently approx. 52 euros/tce, the specific reduction costs are in the range of 19 euros/tCO<sub>2</sub>.



**Fig. 5:** Maximum additional investment costs for a hard coal power plant (efficiency improvement from 47 % to 50 %)



**Fig. 6:** Specific CO<sub>2</sub> reduction costs for efficiency improvements to a hard coal power plant (calculated via the maximum allowable fuel price to remain competitive)

#### 4.2 Market potential

As shown by the analyses, there is a considerable demand for power plant replacement capacity in the EU from a medium-term point of view. Following current projections, moreover, there is an additional capacity demand motivated by corresponding

electricity consumption forecasts. If this capacity demand is cumulated up to the year 2020, a total investment volume of about 120 billion euros is calculated with today's power plant prices.

In addition, mention should also be made of the considerable potential outside the European Union. In its World Energy Outlook 2000 [IEA 2000] the IEA specifies the future global capacity demand (new and replacement) up to 2020 as approx. 3000 GW, of which about 600 GW (20 %) is replacement capacity, whereas 80 % is attributable to a higher global demand for electricity. Assuming that the efficiencies of globally existing power plants compared to those of existing power plants in Europe are much lower, the emission reduction potentials should be considerable.

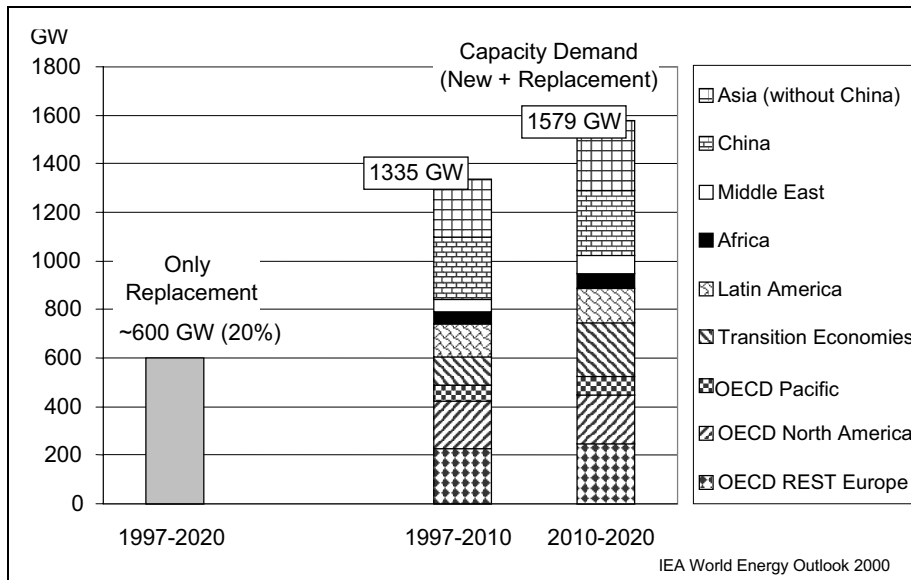


Fig. 7: Worldwide capacity demand until 2020

## 5 Summary and outlook

Following current projections, fossil-fired power plants will also be very important within the EU in the future. This is particularly true against the background of the uncertain fate of nuclear power in some member states. The analyses show that a considerable CO<sub>2</sub> reduction potential can be tapped by existing efficiency potentials in fossil power plants. Especially up to the year 2015, a considerable proportion of obsolete power plants must be replaced in the countries considered. The extent to which existing efficiency potentials can be exploited will decisively depend on the time of market maturity of future power plant concepts, which are, in part, still at the R&D stage today. A precondition is, on the one hand, the streamlining of R&D activities. On the other hand, the construction of demonstration plants is necessary, with which operating experience (e.g. availability, load cycles etc.) can be gained and competitiveness with conventional concepts can be demonstrated. If these activities are not streamlined, major opportunities would be lost and considerable emission

reduction potentials would not be tapped in view of the long re-investment cycles typical of the power plant sector.

## 6 References

### **[AGFW 2001]**

Strategien und Technologien einer pluralistischen Fern- und Nahwärmeversorgung in einem liberalisierten Energiemarkt unter besonderer Berücksichtigung der Kraft-Wärme-Kopplung und regenerativer Energien. AGFW-Hauptstudie – erster Bearbeitungsabschnitt, Volume 3 Technologieentwicklung und –bewertung. AGFW (ed.), 2001

### **[Atlas 1997]**

The ATLAS Project. Main Report 1997

### **[Benesch 2001]**

Benesch W.A.: Planning New Coal-fired Power Plants. VGB Power Tech 6/2001, pp. 37-44

### **[Bergmann et al. 2000]**

Bergmann, H., Hannes, K.: Fortschrittliche Brennstoff-Umwandlungstechniken in zentralen und dezentralen Anlagen. VGB Kraftwerkstechnik 4/2000, pp. 29- 34

### **[BMWi 1999]**

Kohlekraftwerke der Zukunft: sauber und wirtschaftlich. Dokumentation des Bundesministerium für Wirtschaft und Technologie, Berlin 1999

### **[Daces 2001]**

Utrecht Centre for Energy Research: Daces 2050 – Database clean Energy Supply 2050. Final report of Phase I, Utrecht 2001

### **[Enquete 2001]**

Private Communication 2001

### **[Eurelectric 2000]**

Statistics and prospects for the European electricity sector (1980 – 1998, 2000 – 2020), 28<sup>th</sup> Edition, Eurprog Network of Experts, Ref. 2000-030-0294, August 2000

### **[Hourfar 2001]**

Hourfar, D.: Efficiency and Capacity Potentials in Existing Power Plants. VGB PowerTech 8/2001, pp. 53 – 56

### **[IEA 2000]**

International Energy Agency (IEA): World Energy Outlook 2000, Paris 2000

### **[IKARUS 2001]**

IKARUS-Datenbank. Stand 2001 Fachinformationszentrum Karlsruhe

**[Prognos/EWI 1999]**

Prognos AG, Energiewirtschaftliches Institut Köln (EWI): Die längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt. Gutachten im Auftrag des BMWi, Basel 1999

**[Pruschek 2000]**

Pruschek, R.: Perspektiven für die Energieumwandlungstechnologien bei Einsatz fossiler und nuklearer Brennstoffe. In: Energiezukunft 2030. Publications of Research Centre Jülich, Series Umwelt/Environment Volume 26, pp. 65 – 94

**[Riedle 2000]**

Riedle, K: Entwicklungen im Kraftwerksbau. BWK Bd.52 (2000) No. 3, pp. 44- 49

**[Riedle et al. 2001]**

Riedle, K., Traud, R.: Research and Development in Power Plant Engineering. VGB PowerTech 1/2001, pp. 38-45



# CO<sub>2</sub> capture and storage

G. Kolb\*

## 1 Introduction

The background information given below is taken mainly from [IEA 2003] unless cited otherwise: Human activity in the modern world has disturbed the composition of the atmosphere. This has led to some of the major environmental issues of our time - ozone depletion, acid rain, and global warming/climate change, which is potentially the most serious. The experience of learning to deal with acid rain and ozone depletion should be borne in mind when considering how to tackle climate change.

### 1.1 *The greenhouse effect and the climate change problem*

The natural greenhouse effect raises the temperature of the planet by 33°C, thus making it habitable. Naturally occurring greenhouse gases include water vapour, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O).

Any factor which alters the amount of radiation received from the sun or lost to space, may influence the climate. Thus any significant enhancement of the greenhouse effect is a cause for concern. Human activity is emitting extra amounts of greenhouse gases, especially CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub> and chloro-fluoro-carbons (CFCs), which will alter the amounts of radiation trapped by the atmosphere and so may have an effect on climate.

CO<sub>2</sub> is the main greenhouse gas emitted by human activity. It is responsible for over half the enhancement of the greenhouse effect. The main sources are shown in Table 1. The largest single contributor to emissions from fossil fuels is power generation. Transport is another major contributor. Table 1 also shows the natural processes (or sinks) which remove CO<sub>2</sub> from the atmosphere. The difference between total emissions and the known sinks is described as the inferred sink, which is probably partly due to the extra growth of plants, stimulated by higher concentrations of CO<sub>2</sub> in the atmosphere. The distribution of stationary CO<sub>2</sub> emission sources by industry sector is shown in Figure 1. Power plants dominate the statistics with 54% of all identified stationary CO<sub>2</sub> emission sources. The next highest category is the cement industry with 15% of all sources and the gas processing sector, 12% of all sources. The largest emitters of CO<sub>2</sub> from stationary sources are: China, 25% (3.4 Gt/y), North America, 20% (2.69 Gt/y) and OECD Europe, 13% (1.75 Gt/y). All other

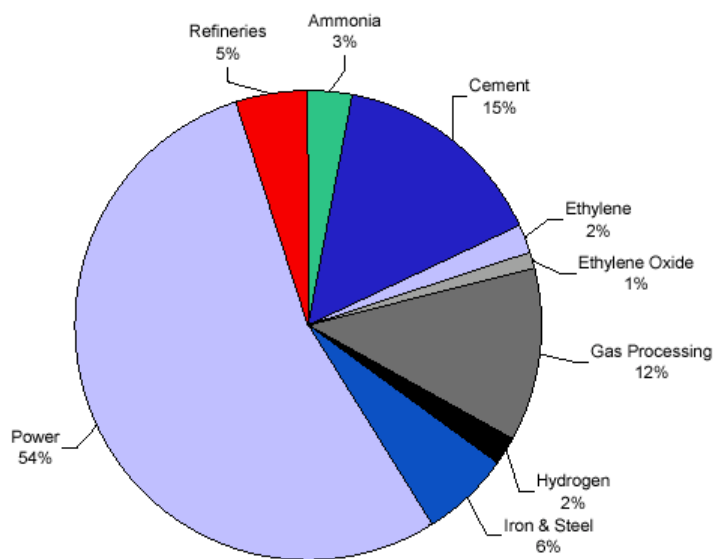
---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

regions emit less than 10% of the total CO<sub>2</sub> emission from stationary sources in 2000. [Gale 2002].

	Amount (GtC/ y)
<b>CO<sub>2</sub> Sources</b>	
1 Fossil fuel combustion and cement production	5.0 - 6.0
2 Changes in tropical land use (mainly before Station)	0.6 - 2.6
3 Total emissions from human activity (1+2)	6.0 - 8.2
<b>CO<sub>2</sub> Sinks</b>	
4 Storage in the atmosphere	3.1-3.5
5 Ocean uptake	1.2 - 2.8
6 Northern hemisphere forest regrowth	0.0 - 1.0
7 Inferred sink 3-(4+5+6)	0.2 - 2.8
<i>GtC = 1 09 tonnes of carbon. Source: IPCC, 1996a</i>	

**Tab. 1:** Annual average carbon budget from human activity for 1980-89 [IEA 2003]



**Fig. 1:** Distributions of global CO<sub>2</sub> emission sources by industry sector [Gale 2002]

The mean global surface temperature has increased by about 0.3° to 0.6°C since the late 19th century - when the instrumental record began - and by about 0.2° to 0.3°C since 1955. The warming occurred large-ly between 1910 and 1940, and since the mid-1970s. Recent years have been among the warmest since 1860. The Intergovernmental Panel on Climate Change (IPCC) concluded that 'the balance of evidence suggests a discernible human influence on the global climate [IPCC 1996].

### *1.2 The structure of the report*

After the introduction of the background problem of the climate change threat the report proceeds to the aspects of projected anthropogenic CO<sub>2</sub> emissions (chapter 2) and then presents the basic technical options to respond to the climate change problem (chapter 3). Chapter 4 (CO<sub>2</sub> capture and storage – “CC&S”) is the main section with sub-sections treating capture, transport, storage and reuse of CO<sub>2</sub>. The significant aspects of economic considerations and perspectives of CC&S are subject of chapter 5. The report ends in chapter 6 with conclusions about the required R&D efforts and other prerequisites of a market penetration of CC&S technologies.

## **2 Projected anthropogenic CO<sub>2</sub> emissions**

Emissions of the main anthropogenic greenhouse gas, CO<sub>2</sub>, are influenced by:

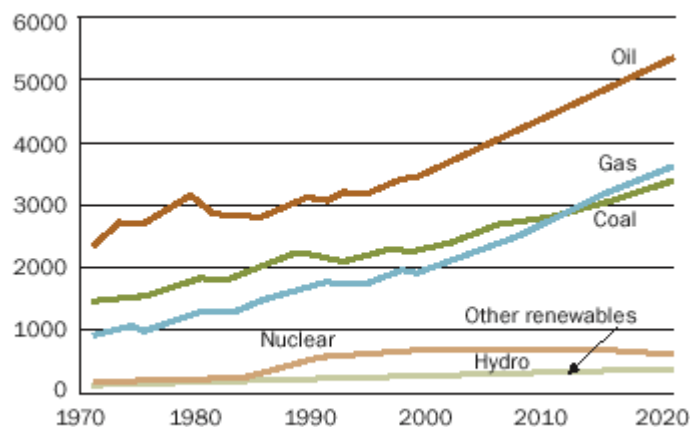
- the size of the human population,
- the amount of energy used per person,
- the level of emissions resulting from that use of energy.

Similar factors affect the levels of emissions of the other greenhouse gases [IEA 2003]

Given projected growth in world population and energy demand — particularly in developing countries — one of the most challenging issues facing the international community in the 21 st century is how to simultaneously attain energy security, economic growth, poverty mitigation and environmental protection for all its citizens. Currently, fossil fuels (coal, oil, and natural gas) supply over 85 percent of the world's commercial energy, account for 65 percent of the world's electricity and 97 percent of the energy for transportation.

As world population multiplies from a current 6 billion people to about 9 billion in 2050 and demand for energy to fuel economic growth increases, energy supply projections point to the fact that abundant, affordable fossil fuels will fuel economic growth well up to and beyond 2020 (Figure 2) [IEA 2002].

The production and use of fossil fuels contribute to 64 percent of anthropogenic (man made) greenhouse gas (GHG) emissions worldwide and fossil fuel power generation currently accounts for over one-third of global annual carbon dioxide (CO<sub>2</sub>) emissions. Although CO<sub>2</sub> is the least potent GHG on a molecular basis, given its sheer abundance and increasing emissions levels, the need to reduce its concentrations in the atmosphere is generally agreed upon [IEA 2002].



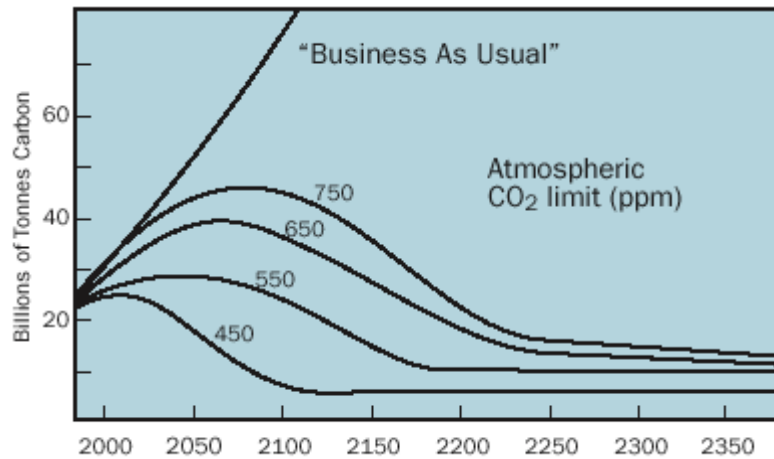
**Fig. 2:** Projected world energy demand by fuel according to [IEA 2000] (taken from [IEA 2002])

Atmospheric CO<sub>2</sub> levels have increased by nearly 30 percent from the late 18th century to the present and are now at 365 parts per million by volume (ppmv) and rising. The Intergovernmental Panel on Climate Change (IPCC) has forecasted that, under “business as usual” conditions, known as IS92a, global emissions of CO<sub>2</sub> could more than triple over this century, from 7.4 billion tons of carbon per year in 1997 to approximately 26 billion tons per year by 2100. Any concentration ceiling can be attained through various global emission paths. The paths indicated in Figure 3 below are designed to achieve stabilization at different CO<sub>2</sub> concentration ceilings. Limiting global CO<sub>2</sub> emissions to 550 ppm would require a reduction of more than 60 percent compared with the “business as usual scenario” [IEA 2002]. (Note: CO<sub>2</sub> emissions are generally measured in metric tons of carbon equivalent. One metric ton (1 tonne) of carbon equivalent equals 3.667 tons of carbon dioxide gas.)

Given expected increases in population, economic growth and energy demand, a continued rise in emissions is expected unless fundamental technology change occurs in world energy systems dominated by fossil fuels. However, these energy systems are complex and capital intensive - trillions of dollars of infrastructure investments have been made for fossil fuel extraction, transportation, conversion and distribution and more investments are to come.

In the next twenty years, fossil fuels will account for almost all new electric power generating capacity - 78 percent in the developing world, as much as 97 percent in transition economies, and 89 percent in the developed world. The useful life of most fossil fuel power plants can be up to 50 years or more; therefore, investment choices made over the next couple of decades could have impacts lasting well past the middle of the 21st century [IEA 2002].

Fundamental changes to the world energy system cannot take place rapidly and a sustained energy research and development (R&D) effort that includes a broad portfolio of technologies will be required to achieve the massive reductions in emissions needed to stabilize GHG concentrations as shown in Figure [IEA 2002].



**Fig. 3:** Scenario-dependent emissions trajectories, designed to achieve stabilisation at different CO<sub>2</sub> concentration levels in the atmosphere (taken from [IEA 2002])

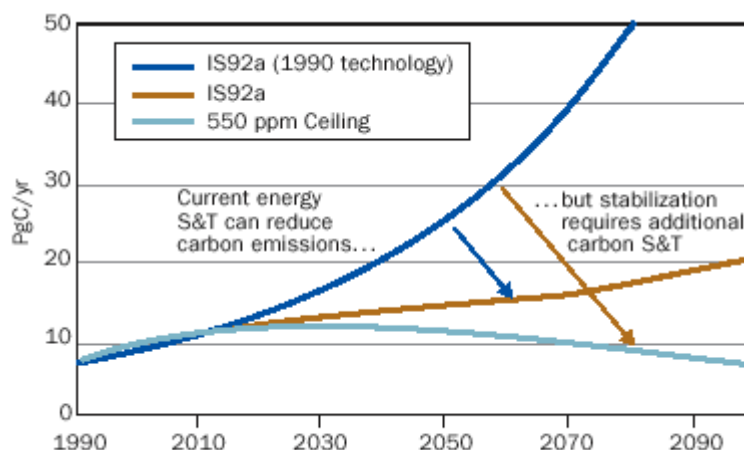
### 3 Technical options to respond to the climate change problem

A variety of technical options are also available which could reduce emissions, especially from use of energy. Reducing CO<sub>2</sub> emissions can be achieved through [IEA 2003]:

- improved energy efficiency,
- fuel switching,
- use of renewable energy sources,
- nuclear power,
- capture and storage of CO<sub>2</sub>.

These options are most easily applicable to stationary plants (here: power plants), which is the focus of the discussion below. Another class of measure involves increasing the rate at which natural sinks take-up CO<sub>2</sub> from the atmosphere - for example by increasing the amount of forests.

Reductions in emissions of other greenhouse gases can also be achieved using technology. For example, methods of reducing methane emissions include reductions in leakage and capture of fugitive emissions, with destruction or utilisation of the methane. Technical responses to climate change deserve serious consideration as means of limiting greenhouse gas emissions whilst continuing to satisfy human aspirations for improved quality of life [IEA 2003].



**Fig. 4:** Assessments of required contributions of technology in order to stabilise the carbon content in the atmosphere (taken from [IEA 2002])

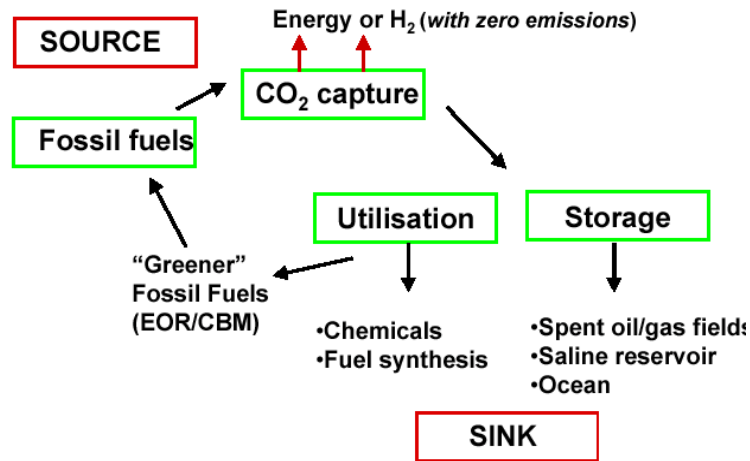
Further improvements in energy efficiency and deployment of renewable technologies are essential to advance conventional technology based mitigation. The shift from high carbon to low carbon fuels (e.g. natural gas, synthesis gas and hydrogen) and the use of nuclear energy also play a role. However, in light of the projected world energy supply mix in which fossil fuels will continue to dominate for decades, advancements in research, development and demonstration (RD&D) of **zero emissions technologies for fossil fuels** are critical. These technologies are a key component of a portfolio of complimentary strategies and technology options that will help build a bridge to a low carbon future [IEA 2002].

Relevant R&D for the zero emissions technologies for fossil fuels that builds on a wealth of industry experience has been underway throughout the world for a little more than a decade. For example, CO<sub>2</sub> capture technologies are routinely used by the oil, gas, and chemical industries. These technologies were not initially developed for carbon sequestration but the contribution they can make to achieve deep reductions in GHG emissions is now widely recognized.

While CO<sub>2</sub> capture and sequestration is still in its infancy and receives substantially less R&D funding than other mitigation options, a number of research programs have been established and initial R&D investments have been made by both government and industry. Furthermore, a diverse and expanding array of technical processes are in different stages of development, a handful of demonstration projects are underway or being planned and some commercial success has been achieved. The most important issues facing the R&D community and industry are reducing costs and developing effective, verifiably safe and environmentally sound storage options that are acceptable to the public. Another major issue is the limited and declining investments in energy R&D [IEA 2002]. While zero emissions technologies for fossil fuels cover all pollutants, the focus of this paper is on technologies that primarily address CO<sub>2</sub>. This report includes basic descriptions of both CO<sub>2</sub> capture technologies and the

various storage options, and provides the current status of each technology and discusses cost issues [IEA 2002].

Figure 5 shows schematically pathways for zeroing CO<sub>2</sub> emissions by CC&S from source (fossil fuels) to sinks (utilisation or final disposal, called “storage”) [Thambimuthu 2002]:

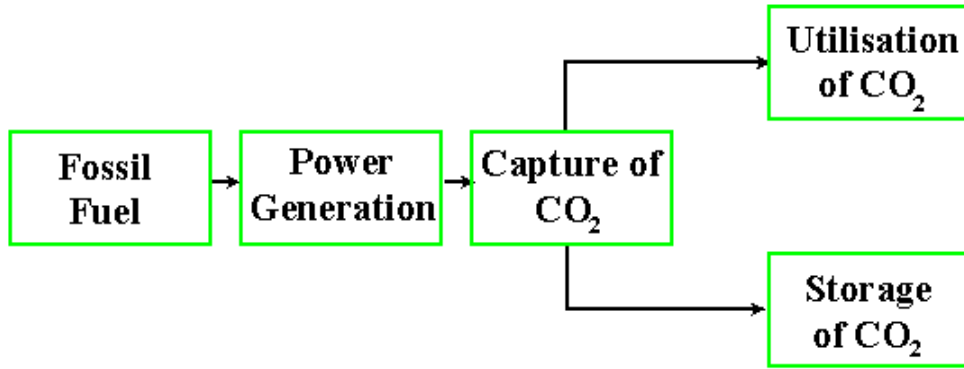


**Fig. 5:** Scheme of pathways for zero CO<sub>2</sub> emissions by CC&S from source (fossil fuels) to sinks (utilisation or final disposal). EOR = enhanced oil recovery, CBM = coal bed methane recovery [Thambimuthu 2002]

#### 4 CO<sub>2</sub> capture, storage and reuse

Capture and storage of CO<sub>2</sub> is an important option for tackling greenhouse gas emissions. It will enable production of electricity from fossil fuels with 80% less emissions of CO<sub>2</sub>. Also referred to as **CO<sub>2</sub> sequestration**, the technology is already in use for other, related purposes (e.g., food industry), so the technical risks are low [IEA 2003].

The main steps in the process of capture and storage of CO<sub>2</sub> are shown in Figure 6 below for a conventional fossil-fuel fired power plant. After the fossil fuel has been burnt to produce power, the CO<sub>2</sub> is separated from the flue gas stream. Then the CO<sub>2</sub> would be stored, for a long time, if it cannot be put to some useful purpose [IEA 2003].



**Fig. 6:** The main steps in the process of capture and storage of CO<sub>2</sub> for a conventional fossil-fuel fired power plant (indicating capture after combustion for power generation) [IEA 2003].

#### 4.1 CO<sub>2</sub> capture

There are three main techniques for capture of CO<sub>2</sub> in power generation [Thambimuthu 2002a]:

- Post-combustion capture
- Pre-combustion capture
- Oxy-fuel combustion

Figure 7 gives a scheme of the CO<sub>2</sub> capture options and their interference from the use of fossil fuels for energy conversion up to power (or possibly hydrogen) production including storage or use of CO<sub>2</sub> [Thambimuthu 2002]. Oxy-fuel combustion needs prior to energy conversion an air separation unit (ASU) for oxygen production. These procedures are described briefly below, after introduction of the capture systems:

Systems are already available for capturing CO<sub>2</sub> but there is only limited choice at present and so the technologies evaluated include a number still under development.

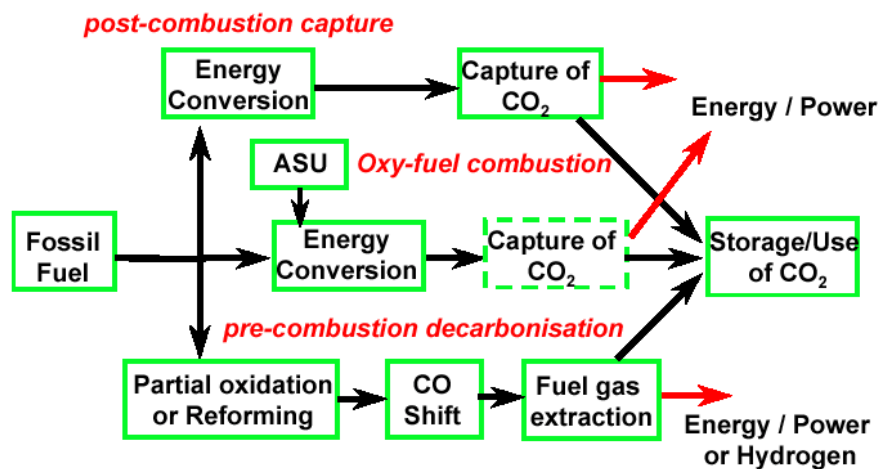
Each capture technology is considered to be applied to the flue gas stream of the power plant. The main conclusions about the various capture options are [IEA 2003]:

- **Adsorption of the gas by use of molecular sieves** - a key aspect is how to release the gas after it has been captured; in all the cases studied, varying the pressure to release the gas is preferable to varying the temperature, because the adsorber can be freed of gas and put back into service faster. The removal of CO<sub>2</sub> by an adsorbent is most effective when the concentration in the flue gases lies between 400 ppm and 15000 ppm, lower than is normally the case with power stations; coupled with limited capacity and poor selectivity, this makes adsorption unattractive for CO<sub>2</sub> capture from power generation.
- **Physical and chemical absorption** - 3 solvents were evaluated for each of the base case power plants. For low concentrations of CO<sub>2</sub> in the flue gases, a

chemical solvent such as monoethanolamine (MEA) is preferred. Alternatives are methyldiethanolamine (MDEA) and diethanolamine (DEA) [Kranzmann 2002]. Where the CO<sub>2</sub> concentration is high, a physical solvent is favoured; in either case, additional processing will be required if there is much SO<sub>2</sub> in the flue gases (as with a coal-fired plant) to avoid excessive loss of solvent.

- **Use of low temperature (cryogenic) processes** is only worth considering where there is a high concentration of CO<sub>2</sub> in the flue gas, as could be achieved in future IGCC designs. Cryogenic processes have the advantage of producing liquid CO<sub>2</sub> ready for transportation to the disposal site.

**Membranes** – gas separation or gas absorption, although used commercially, for example in hydrogen separation, development is required before they could be used on a significant scale for the capture of CO<sub>2</sub>; the extent to which their cost could be reduced is unclear.



**Fig. 7:** Scheme of the CO<sub>2</sub> capture options and their interference from the use of fossil fuels for energy conversion up to power (or possibly hydrogen) production including storage or use of CO<sub>2</sub> [Thambimuthu 2002] ASU = air separation unit

In the following the CO<sub>2</sub> capture options are briefly described:

#### Post combustion capture [Thambimuthu 2002a]:

The CO<sub>2</sub> concentration in power station flue gas ranges from about 4% (by volume) for natural gas fired combined cycle plants to about 14% for pulverized coal fired boilers. Natural gas contains less carbon than coal and natural gas combined cycle power plants have higher thermal efficiencies than coal fired plants. The quantity of CO<sub>2</sub> produced per MW of electricity generated is therefore half about as much in a natural gas combined cycle plant as in a coal fired plant but the volume of flue gas is about two thirds greater.

The preferred technique at present is to scrub the flue gas with an amine solution. The amine from the scrubber is heated by steam to release high purity CO<sub>2</sub> and the CO<sub>2</sub>-free amine is then reused in the scrubber. Post-combustion capture can also be applied to coal and oil fired power stations but some additional measures are needed to minimize contamination of the CO<sub>2</sub> capture solvent by impurities in the flue gas, such as sulphur and nitrogen oxides. In many respects, post-combustion capture of CO<sub>2</sub> is analogous to wet flue gas desulphurisation (FGD) techniques, which is widely used on coal and oil fired power stations to reduce emissions of SO<sub>2</sub>. Figure 8 (upper section) shows a simplified diagram.

#### **Pre-combustion capture** [Thambimuthu 2002a]:

The low concentration of CO<sub>2</sub> in power station flue gas means that a large volume of gas has to be handled, which results in large equipment sizes and high capital costs. A further disadvantage of the low CO<sub>2</sub> concentration is that powerful chemical solvents have to be used to capture CO<sub>2</sub> and regeneration of the solvents to release the CO<sub>2</sub> requires a large amount of energy. If the CO<sub>2</sub> concentration and pressure could be increased, the CO<sub>2</sub> capture equipment would be much smaller and different physical solvents could be used, with lower energy penalties for regeneration. This can be achieved by pre-combustion capture.

The fuel is reacted with oxygen or air, and in some cases steam, to give mainly carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO<sub>2</sub> and more hydrogen. The CO<sub>2</sub> is separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process is, in principle, the same for coal, oil or natural gas, but when coal or oil are used there are more stages of gas purification, to remove particles of ash, sulphur compounds and other minor impurities. Figure 8 (middle section) shows a simplified diagram.

#### **Oxy-fuel combustion** [Thambimuthu 2002a]:

The concentration of CO<sub>2</sub> in flue gas can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or gas turbine. The oxygen would be produced by a cryogenic air separation unit (ASU), which is already used on a large scale, for example in the steel industry. If fuel is burnt in pure oxygen, the flame temperature is excessively high, so some CO<sub>2</sub>-rich flue gas would be recycled to the combustor to make the flame temperature similar to that in a normal air-blown combustor. The advantage of oxygen-blown combustion is that the flue gas has a CO<sub>2</sub> concentration of typically > 90%, compared to 4-14% for air blown combustion, so only simple CO<sub>2</sub> purification is required. It may be possible to omit some of the flue gas cleaning equipment which currently has to be included in power stations, such as flue gas desulphurization, which would reduce the net cost of CO<sub>2</sub> capture. Some sulphur compounds and some other impurities would remain in CO<sub>2</sub> fed to storage, which may be acceptable in some circumstances. The oxygen and CO<sub>2</sub> recycle combustion process has also a further benefit in suppressing NO<sub>x</sub> formation with attendant benefits in the post combustion removal of NO<sub>x</sub>. The disadvantage of oxy-fuel combustion is that a large quantity of oxygen is required, which is expensive, both in terms of capital cost and energy consumption. Advances in oxygen production processes, such as new and improved membranes that can operate at high temperatures could improve overall plant efficiency and economics. Oxy-fuel com-

bustion aimed at power generation applications has so far only been demonstrated in small scale test rigs. Larger scale applications have seen use in glass and steel melting furnaces.

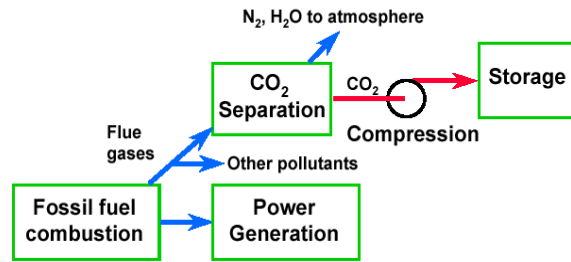
Oxy-fuel combustion could be an attractive option for retrofit of existing steam cycle power stations. The modifications that would need to be made at the power station would be relatively minor and in some places supplies of oxygen could be obtained from existing commercial air separation plants.

Oxy-fuel combustion could also be applied to gas turbines or for the conversion of fuel gas fed to fuel cells. However, gas turbines that use CO<sub>2</sub> as the working fluid would be substantially different to conventional gas turbines that use air and retrofit of existing gas turbines would not be feasible. Substantial investment would be needed to develop an oxygen fired gas turbine and there would need to be the prospect of a large market to persuade manufacturers to make such an investment. Novel gas turbine and fuel cell based cycles involving oxy-fuel combustion and condensation of CO<sub>2</sub> have been proposed. Such cycles could be attractive, but they would involve even more development work. Figure 8 (lower part) shows a scheme of this capture option for CO<sub>2</sub> [Thambimuthu 2002a].

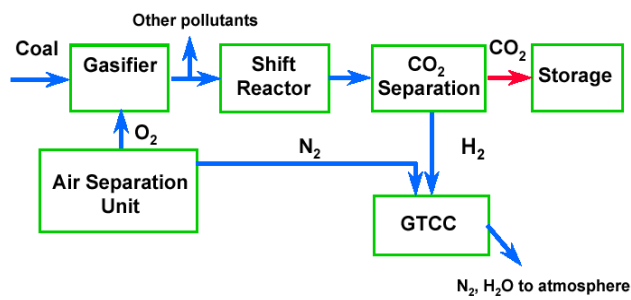
The power generation sector is, as already mentioned, a major source of CO<sub>2</sub> emissions world-wide. Types of power plant studied in some detail include [IEA 2003]:

- **Pulverized (coal) fuel with flue gas desulphurisation**, representing the most commonly used type of plant; this provides a marker against which other power generation technologies can be compared. The plant uses steam at sub-critical conditions but the impact of more recent super-critical steam cycles is also considered. Variants include enhanced removal of "acid gases" (e.g. SO<sub>2</sub> and NO<sub>x</sub>).
- **Natural gas-fired combined-cycle generation** which is another widely available technology; in this case, natural gas is burnt in a gas turbine operated in conjunction with a steam turbine to improve overall efficiency. This is the most efficient option studied, emits the least amount of CO<sub>2</sub> (per kWh generated) and, with low cost supplies of gas, is the cheapest means of generating electricity.
- **Integrated gasification combined-cycle (IGCC)**, a representative of emerging technology, appropriate for a future when CO<sub>2</sub> mitigation is practised. The base case involves a coal-slurry fed gasifier; many variations are also evaluated, including the type of gasifier and conversion of the carbon monoxide in the gasifier's output to CO<sub>2</sub>.
- **Combustion of coal in an atmosphere of oxygen and recycled CO<sub>2</sub>**, a potential option for the longer-term. Schemes of this type have been suggested because they raise the concentration of CO<sub>2</sub> in the exhaust gas, thereby making capture easier.
- **Fuel cells** are another low emission technology. There are many possible types of fuel cell so, from an initial survey, the IEA GHG Programme selected one type, the molten carbonate fuel cell, for investigation as a possible large-scale power plant with CO<sub>2</sub> removal. When compared with more conventional plants (both using CO<sub>2</sub> removal), the molten carbonate fuel cell showed no advantage.

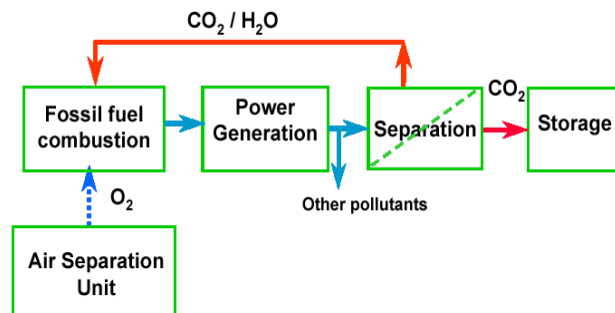
### Conventional power plant



### Coal-fired power plant (IGCC)



### Power generation plant



**Fig. 8:** Schemes of these three capture options for CO<sub>2</sub> from power generation [Thambimuthu 2002a]

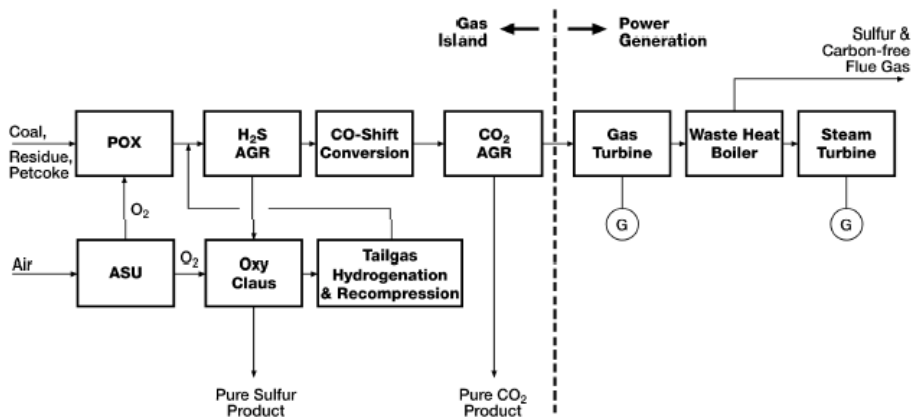
With respect to cost and economy most studies relate to the first three options due to their advanced development status (see also chapter 5) [Freund 2002]. Figure 9

shows for demonstrative purposes the scheme of an IGCC plant with pre-combustion capture [Koss 2002].

#### 4.2 CO<sub>2</sub> transportation

After capture, CO<sub>2</sub> would be transported by high-pressure pipeline or by tanker to a long-term land-based geologic site, or off-shore to the deep ocean. There is about 3000 km of large land-based CO<sub>2</sub> pipelines in existence throughout the world, primarily in North America, that have been transporting CO<sub>2</sub> since the early 1980s. Most pipeline systems are designed so that recompression is not required beyond the power plant. Additionally, considerable offshore oil and gas pipeline infrastructure exists that may have the potential to support offshore CO<sub>2</sub> storage sites [IEA 2002].

Internationally recognized standards for the design construction and monitoring of CO<sub>2</sub> pipelines are in place in the U.S. and Canada and largely represent an extension of industry best practices for natural gas and other hazardous gas pipelines.



**Fig. 9:** Scheme of an IGCC plant with pre-combustion capture [Koss 2002]

While it is not current practice to transport CO<sub>2</sub> by ship to storage sites, it is considered an alternative to pipeline transport. Tanker capacity and distance to the storage site are the determining factors. CO<sub>2</sub> is currently transported in ships in North Western Europe with typical CO<sub>2</sub> transport capacity currently around 300,000 tonnes. The design of a CO<sub>2</sub> tanker is similar to existing LPG carriers and there are plans to commercialize vessels with larger volumes (i.e. up to 1 million tonnes) if the vessel can be used solely for CO<sub>2</sub> transport [IEA 2002].

Table 2 [Freund 2002] shows the cost of transmission of CO<sub>2</sub> by pipeline (US\$/t CO<sub>2</sub>) in dependence from throughput and pipeline length:

Throughput	Length of pipeline		Specific Cost
	100 km	400 km	\$/t/100 km
0.1 million t/y	13	51	13
5 million t/y	1.1	4.2	1.1
50 million t/y	0.4	2.2	0.4 - 0.5

**Tab. 2:** Cost of transmission of CO<sub>2</sub> by pipeline (US\$/t CO<sub>2</sub>) [Freund 2002]

The strong dependence on scale of operation can be seen in the final column of Table 2, which shows the specific cost per 100 km. To handle the CO<sub>2</sub> from a few 500 MW power plant (i.e. 5 million t/y) costs about \$1.1/t/100 km. However, looking at sources smaller than this (e.g. an ammonia plant), if there is only 100 000 t/y available, then the cost of transporting a tonne of CO<sub>2</sub> is considerably greater. However, increasing the capacity by a factor of 10 (to 50 million t/y) only halves the specific costs [Freund 2002].

It is typically cheaper to pipe CO<sub>2</sub> than to transmit the equivalent amount of electricity. It would therefore be cheaper to site power stations close to electricity demand and transport the CO<sub>2</sub> as necessary to the storage site.

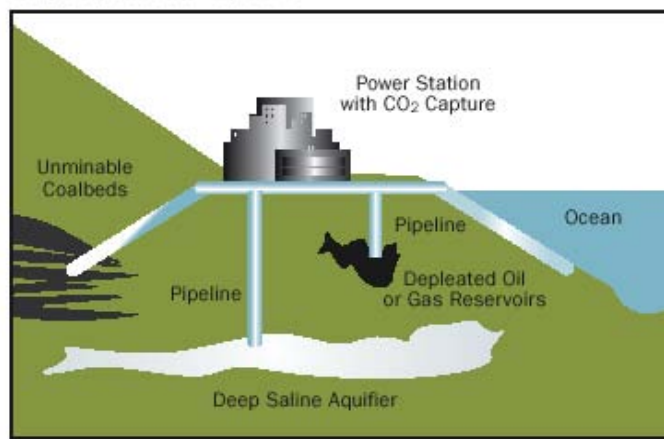
Another way of transporting CO<sub>2</sub> would be by ship, as a pressurised cryogenic liquid, for example at a pressure of 6 bar and a temperature of -55°C. Ships would be more flexible than pipelines, they would avoid the need to obtain rights of way and they may be cheaper, particularly for longer distance transportation. Ships similar to those currently widely used for transportation of liquefied petroleum gas (LPG) could be used to transport CO<sub>2</sub>. The cost of transmitting CO<sub>2</sub> in this way is estimated to be about US\$ 2/t CO<sub>2</sub>, not including costs of holding tanks at the port and the injection facility [Freund 2002].

### 4.3 CO<sub>2</sub> storage

After the CO<sub>2</sub> has been separated from the flue gases, it must either be stored or put to some use. Several conceptual schemes for storage have been evaluated, the major ones being [IEA 2003]:

- in the oceans
- in deep saline reservoirs (aquifers)
- in depleted oil and gas reservoirs
- in unminable coalbeds
- as a solid on land

Figure 10 [IEA 2003] shows schematically the basic CO<sub>2</sub> sequestration options:



**Fig. 10:** Scheme of the basic CO<sub>2</sub> capture options [IEA 2002]

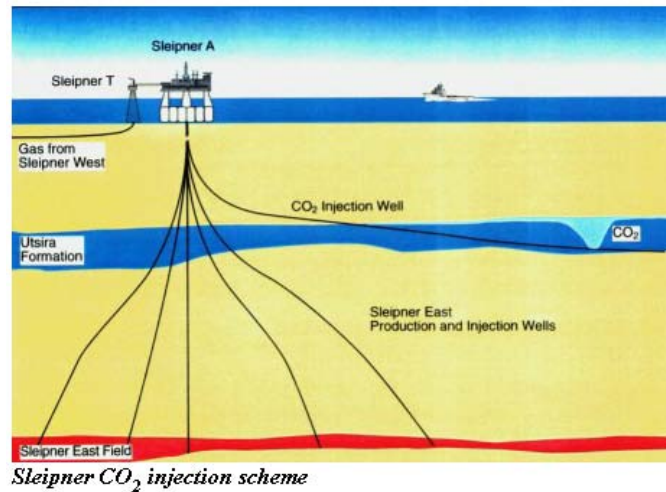
Studies have shown that there is substantial potential capacity for CO<sub>2</sub> storage in natural reservoirs underground (such as deep saline reservoirs) or in the deep ocean, and could be achieved using available technology. This stage of the process would be considerably less expensive than the prior stage of capturing the CO<sub>2</sub> from the flue gas stream. However, all such schemes are more or less site specific and, at present, there may be significant uncertainties about their environmental impact. Such issues are indicative of a need for further research; collaborative programmes are being developed in many of these areas. Table 3 shows the estimated global ranges of the CO<sub>2</sub> storage potential [IEA 2003]:

Storage Option	Range of Values (GtC)
Ocean	1400-2x10 <sup>7</sup>
Aquifers	87 - 2700
Depleted gas	140-310
Depleted oil	40-190

**Tab. 3:** Range of estimates for CO<sub>2</sub> global storage potential [IEA 2003]

#### 4.3.1 Deep-saline reservoirs

The first commercial-scale storage in a deep saline reservoir commenced operation in 1996, offshore Norway. This has been established by the Norwegian company Statoil as part of their development of the Sleipner gas field. In this plant, 1 million tonnes/year of CO<sub>2</sub> are being removed from a natural gas stream using a solvent absorption process and injected into the Utsira reservoir, 800 metres below the seabed. Figure 11 shows its basic scheme [IEA 2003]:



**Fig. 11:** Scheme of the CO<sub>2</sub> injection in the Norwegian Sleipner gas field [IEA 2003]

#### 4.3.2 Ocean storage of CO<sub>2</sub>

The oceans are the ultimate natural sink for CO<sub>2</sub> and have the greatest potential capacity in the long-term as a CO<sub>2</sub> store but not all countries have suitable access to deep ocean and the environmental implications are not adequately understood. The IEA GHG Programme has identified certain key questions which must be answered in order to progress this option:

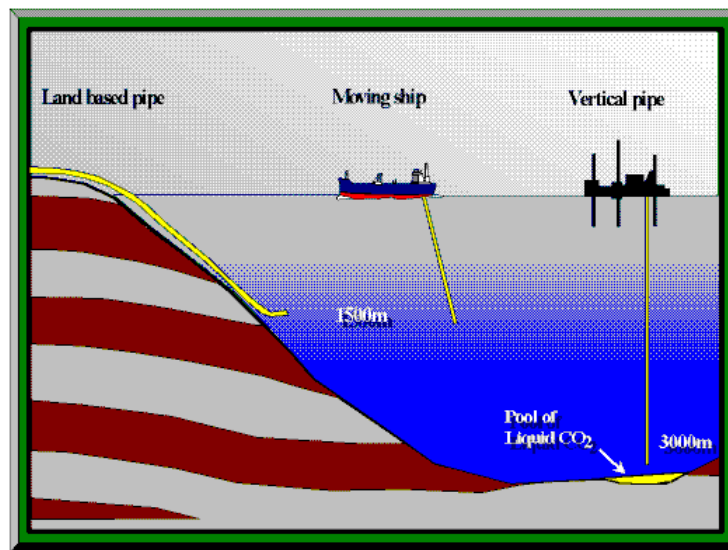
- how well can the performance be predicted?
- what will be its environmental impact?
- can such schemes can be successfully engineered?
- are there major legal and jurisdictional obstacles?
- what is likely to be the public attitude to such schemes?

These questions have been addressed through a series of expert workshops, bringing together researchers working on ocean storage of CO<sub>2</sub> with specialists in other, related fields. Each workshop produced a set of recommendations about work needed; in some cases these have developed into plans for collaborative research; in each case, these workshops stimulated interest amongst experts not yet working in this field, so broadening the base of expertise available [IEA 2003].

Figure 12 shows the three main concepts under investigation for ocean storage of CO<sub>2</sub>: dispersion from pipeline or ship, and production of a lake of CO<sub>2</sub> in the deep ocean [IEA 2003]:

Ocean global circulation models are the only means of predicting the performance of CO<sub>2</sub> storage over hundreds of years. Through workshops, an opportunity has been found to test these models against each other. The workshops also highlighted the need to study the biological impact of ocean storage of CO<sub>2</sub>; constructive suggestions have been put forward about minimising the impact of such schemes. No sub-

stantial obstacles were identified which would impede the engineering of CO<sub>2</sub> storage. The need to gain public acceptance for this CO<sub>2</sub> sequestration concept has been highlighted. These workshops pave the way for development of robust plans for ocean storage research, which is now envisaged by a number of countries [IEA 2003].



**Fig. 12:** Three investigated main concepts for ocean storage: dispersion from pipeline or ship, and production of a lake of CO<sub>2</sub> in the deep ocean [IEA 2003]

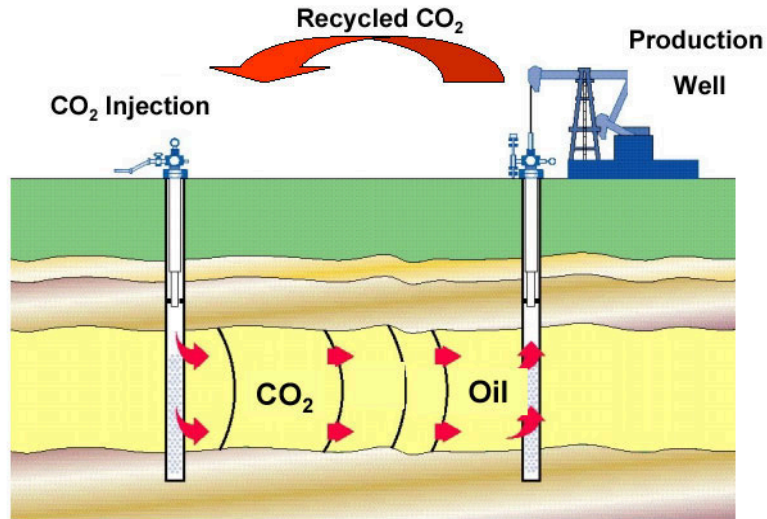
#### 4.3.3 Other storage options

Disused oil and gas reservoirs also have large storage capacities. They have the potential advantage of known geology to provide a seal to contain the CO<sub>2</sub> in the store; these represent an immediately available option.

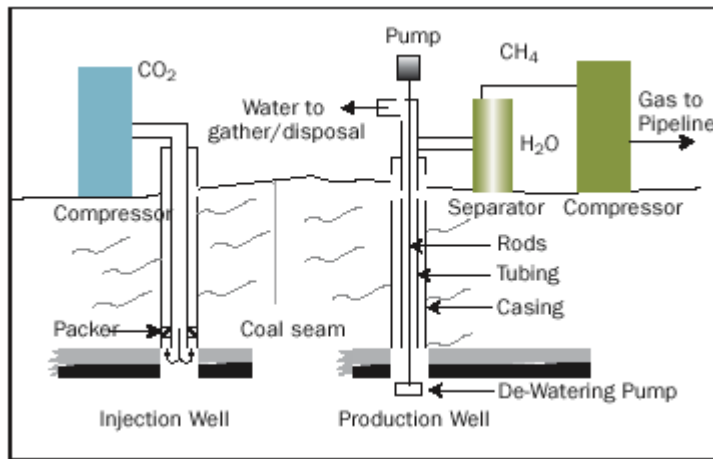
Terrestrial disposal of solid carbon dioxide is precluded currently on grounds of cost.

Injection of CO<sub>2</sub> into operating oil fields can **improve oil production (EOR)** and much of the CO<sub>2</sub> will be left in the reservoir when it is abandoned. In an analogous way, the concept has been proposed of **enhancing production of coal bed methane using CO<sub>2</sub> injection**; the CO<sub>2</sub> may be preferentially adsorbed by the coal, thereby enhancing release of trapped methane at the same time as sequestering CO<sub>2</sub>. This is the subject of practical R,D&D at present [IEA 2003].

Figure 13 [Thambimuthu 2002] and Figure 14 [IEA 2002] show the schemes of EOR and enhanced coalbed methane (ECBM) recovery of CO<sub>2</sub>:



**Fig. 13:** Enhanced oil recovery by injection of CO<sub>2</sub> [Thambimuthu 2002]



**Fig. 14:** Scheme of the enhanced coalbed methane (ECBM) recovery by CO<sub>2</sub> injection [IEA 2002]

#### 4.3.4 Enhancing natural sinks

Finally it should be mentioned that there are also options (“indirect” CO<sub>2</sub> capture or sequestration) using natural processes and possibly enhancing them by technical measures [IEA 2003]:

Natural sinks remove CO<sub>2</sub> from the atmosphere (using energy from the sun, typically via photosynthesis). Trees provide a major terrestrial sink and there are many pro-

posals to enhance this. Oceanic sinks might also be open to enhancement but there is much greater uncertainty about this at present.

Forestry sequestration of CO<sub>2</sub> [IEA 2003]:

Useful amounts of carbon could be sequestered for long periods of time in growing forests. This can be achieved by:

- prevention of deforestation
- more effective management of existing forests
- reforesting areas which were previously forested
- planting trees in areas not previously forested

Enhancing the ocean sink [IEA 2003]:

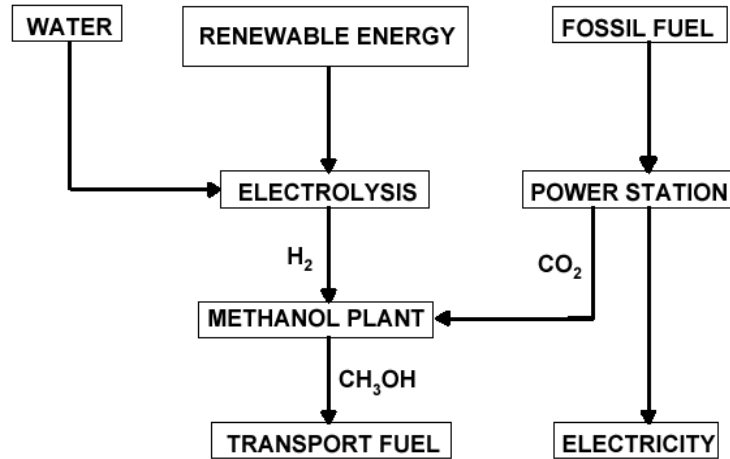
Artificial fertilisation of the oceans has also been proposed as a way of sequestering carbon; this might either be by localised fertilisation with iron of areas deficient in this key mineral, or by large-scale fertilisation with nitrogen. The IEA GHG Programme has reviewed these options and found that there is need for substantially greater basic understanding of marine processes before either of these techniques could be deployed on a large-scale with confidence.

#### 4.4 *Utilisation of CO<sub>2</sub>*

Captured CO<sub>2</sub> could also be used for commercial purposes, for example as a feedstock from which to make chemicals. If feasible, this would offer the twin benefits of sequestering the gas as well as replacing other, manufactured feedstocks. CO<sub>2</sub> is already used for a wide range of purposes in the food and oil industries although, in most cases, the gas is not permanently stored in the products but is lost to the atmosphere at a later date. The income generated from sale of the products would help offset the cost of capturing carbon dioxide. Nevertheless, significant costs would be incurred in producing a chemical product and such processes generally require input of energy, thereby emitting more CO<sub>2</sub> (if the energy comes from fossil fuels). Utilisation of CO<sub>2</sub> to make chemicals is only effective as a mitigation option if, overall, less CO<sub>2</sub> is released than would have otherwise have been the case [IEA 2003].

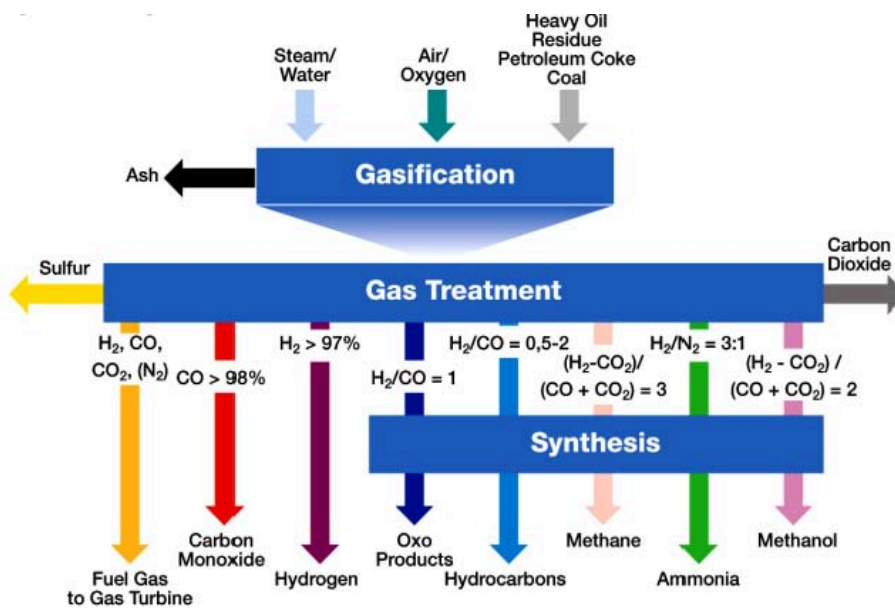
As already mentioned in the former chapter 4.3.3 enhanced oil recovery (EOR) has a very large potential for utilising CO<sub>2</sub> and is employed commercially in a number of oil fields (using naturally occurring CO<sub>2</sub>). Although there is little economic incentive to use CO<sub>2</sub> recovered from power stations for this purpose, various schemes are on the drawing board. Whilst the storage time should be long, there is a danger that future oil field operations might release the stored CO<sub>2</sub> into the atmosphere [IEA 2003].

Figure 15 exemplarily shows a scheme of the production of transport fuels by sequestered CO<sub>2</sub> and added (renewable) energy, but it could be any non-fossil energy [Freund 2002]:



**Fig. 15:** Schematic production of methanol from captured CO<sub>2</sub> and renewable energy [Freund 2002]

Figure 16 shows in some more detail options of chemical synthesis based on use of (captured) CO<sub>2</sub> as pursued by the German company Lurgi (Frankfurt/Main) [Koss 2002]:



**Fig. 16:** Options of chemical synthesis based on use of (captured) CO<sub>2</sub> as pursued by the German company Lurgi (Frankfurt/Main) [Koss 2002]

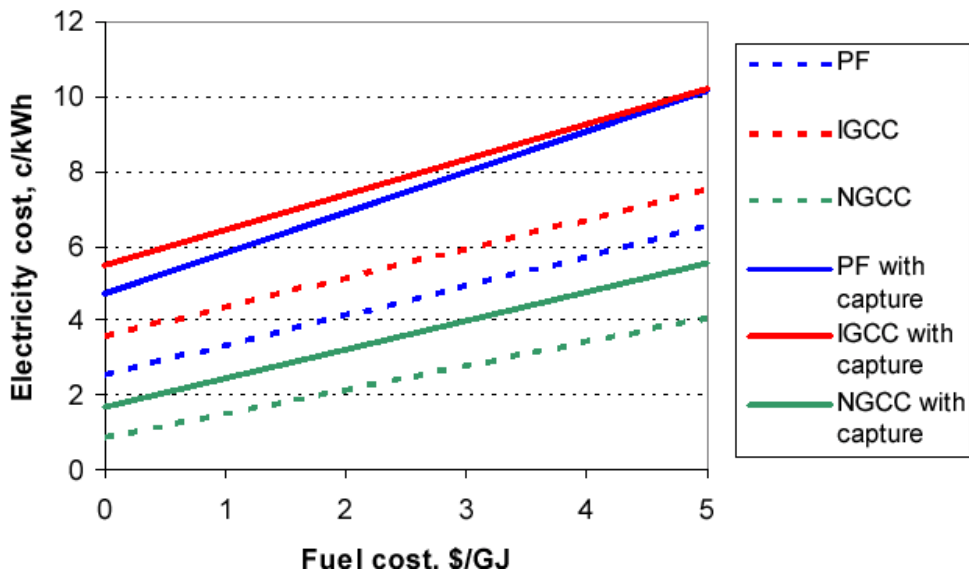
## 5 Economic aspects

### 5.1 Overall costs of CO<sub>2</sub> capture

The cost of capture and storage of CO<sub>2</sub> can be understood as built up from 3 distinct components: the cost of capturing CO<sub>2</sub>, the cost of transmission and the cost of storage. The cost of compression are incorporated in the cost of capture.

The cost of capture tends to be the dominant item for current technology. The cost of transmission is a function of the amount of CO<sub>2</sub> being shipped and of the distance. The cost of storage is a function of capacity, which varies from country to country and between types of storage reservoir. Costing of CO<sub>2</sub> storage tends to be more site-specific and less open to generalisation [Freund 2002].

The costs of CO<sub>2</sub> capture in terms of c/kWh or \$/t (US-cents and US-\$) of CO<sub>2</sub> are mainly a function of the energy loss and the capital cost. Costs are presented based on standard economic assessment criteria, which include a 10% discount rate, 25 year plant life and base load operation (85-90% load factor depending on the technology). Costs of electricity generation with and without CO<sub>2</sub> capture at a range of fuel prices are shown in Figure 17 [Thambimuthu 2002a]:



**Fig. 17:** Costs of electricity generation with and without CO<sub>2</sub> capture (excluding costs of CO<sub>2</sub> storage) at a range of fuel prices (US-cents, US-\$) [Thambimuthu 2002a]

At a gas cost of \$2/GJ, CO<sub>2</sub> capture increases the cost of gas fired electricity generation by 1.1 c/kWh, or 50%. CO<sub>2</sub> capture increases the cost of electricity generation in a pulverized coal plant by 2.6 c/kWh or 70% and by 2.1 c/kWh or 45% in an IGCC

plant. At typical fuel prices these costs in c/kWh would translate into a capture cost of about \$40 per tonne of CO<sub>2</sub> avoided and is broadly similar for both gas and coal-fired power plants. These costs exclude the costs of CO<sub>2</sub> storage, which depends on how the CO<sub>2</sub> is stored and the distance between the capture and storage sites. A cost of US\$10/tonne of CO<sub>2</sub> stored would add 0.9 c/kWh to the cost of electricity from a pulverized coal plant and 0.4 c/kWh to the costs from a natural gas combined cycle plant [Thambimuthu 2002a].

The data given above are for new power stations at greenfield sites. CO<sub>2</sub> capture could also be applied as a retrofit to existing power stations. However, when the efficiency of the existing power plant without CO<sub>2</sub> capture is relatively low, combined with reduced opportunities for better energy integration of the capture plant, the energy penalty for CO<sub>2</sub> capture represents a greater proportion of the net power output. In a study on retrofit of CO<sub>2</sub> capture to an existing power station in the USA, the efficiency of the power station was 38.7% (LHV basis) without CO<sub>2</sub> capture, 23.2% with MEA scrubbing, 25.5% with combined MEA/MDEA scrubbing and 25.5% with oxy-fuel firing [Thambimuthu 2002a].

## 5.2 Potential cost reductions

The main contributor to the cost of this mitigation option is the cost of capturing the CO<sub>2</sub>, so opportunities for cost reduction are most sought in this area. As well as improvements in performance or finding less expensive ways to build and operate the capture equipment, the main options are to change the method of capture or to change the process. As more of this type of plant is constructed, there will also be economies of scale in construction and further economies of scale will arise from using larger units. Many of these changes are recognised under a generic phrase "technology learning", a technique which can give an overall impression of the cost reductions achievable over time based on past examples of similar technologies. Similar reductions will apply in the other areas of the process but to lesser extent. Economies of scale will certainly affect the cost of transmission. Also, to some extent, there will be opportunities for technology improvements in injecting and managing CO<sub>2</sub> underground. This paper quoted the costs of post-combustion and pre-combustion capture techniques but has not considered oxy-fuel processes or any other more speculative concepts since the design of these processes has not yet been established with sufficient accuracy to enable them to be costed with as much confidence as the two established processes. However, it is expected that the cost per tonne of CO<sub>2</sub> avoided would be similar for post-combustion capture, pre-combustion capture and those oxy-fuel processes which have so far been demonstrated. Only new build power plant has been considered as this provides a more straightforward basis for costing so the results can be interpreted more easily. New build also has advantages over retrofit application in that the plant would have longer life and the efficiency would be higher. Anyway, projects are being developed based on retrofit of existing power plant, where high efficiency plant is available [Freund 2002].

## 6 Conclusions

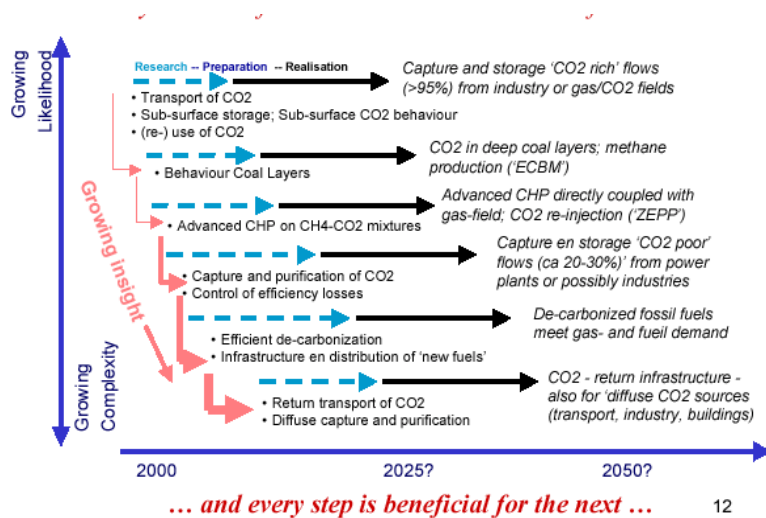
The contents of the chapters above are summarised in the following conclusions [Neef 2002]:

### Political and physical background:

- Fossil fuels will remain dominant in the 21<sup>st</sup> century
- Social considerations and energy security aspects require control of the environmental impacts of fossil fuels use.
- Zero emissions technologies offer an opportunity to make the use of fossil fuels clean.

### CO<sub>2</sub> sequestration aspects:

- CO<sub>2</sub> capture and sequestration can for economic reasons be applied only to large scale energy generation. Large scale power generation can only tackle about one quarter of the emissions.
- Most of the growth in emissions of energy usage comes from the transportation sector, also forcing to produce carbon-free fuels from fossil energy carriers.
- Fossil fuels have to overcome their environmental difficulties anyway, stimulating **the development of zero emission technologies for fossil fuels.**
- The approach:
  - 1. priority: Higher efficiencies
  - 2. priority: Improve the local environment
  - 3. priority: Zero emissions of CO<sub>2</sub>:
    - CO<sub>2</sub> capture: Reduce costs
    - CO<sub>2</sub> transportation: Needs public acceptance
    - CO<sub>2</sub> storage: Develop capacities, look for public acceptance
  - The strategy will include:
    - Increased national and international RD&D
    - Realisation of early opportunities
    - Development of policies for economic incentives
    - International knowledge exchange and communication
- Two significant aspects:
  - Energy investments within the next decades will be an important time window to ensure the approach.
  - Risks and lead times involved require **concerted policy actions now.**



**Fig. 18:** A potential roadmap to a clean de-carbonated fossil fuel use [Neef 2002]

Figure 18 shows the scheme of a potential roadmap to a clean de-carbonated fossil fuel use [Neef 2002]. It demonstrates clearly that CO<sub>2</sub> sequestration very probably will not be commercially available before 2025 due to the required research, development and demonstration steps.

## 7 References

### [IEA 2003]

IEA Greenhouse Gas R&D Programme (2003): [www.ieagreen.org.uk](http://www.ieagreen.org.uk)

### [Gale 2002]

Gale, J. (2002): Overview Of Sources, Potential, Transport And Geographical Distribution Of Storage Possibilities, IPCC Workshop on Carbon Dioxide Capture and Storage, Proceedings, Regina, Canada, 18-21 November 2002. Published by ECN, pp. 15-29

### [IPCC 1996]

IPCC (1996): Climate change 1995 - the science of climate change, summary for policymakers and technical summary of the working group I report. Cambridge University Press, Cambridge, UK, pp. 56

### [IEA 2002]

IEA (2002): Solutions for the 21<sup>st</sup> Century: Zero Emissions Technologies for Fossil Fuels, Technology Status Report, May 2002

**[IEA 2000]**

IEA (2000): World Energy Outlook 2000; IEA Publications, Paris

**[Thambimuthu 2002]**

Thambimuthu, K. (2002): Some recent projects by the IEA Greenhouse Gas Programme, BMWi-Workshop on CO<sub>2</sub> Separation, Use and Storage for Fossil Fuel-Fired Power Stations, 03-04 July 2002, Lurgi AG, Frankfurt/Main

**[Thambimuthu 2002a]**

Thambimuthu, K.; Davison, J.; Gupta, M. (2002): CO<sub>2</sub> Capture and Reuse, IPCC Workshop on Carbon Dioxide Capture and Storage, Proceedings, Regina, Canada, 18-21 November 2002. Published by ECN, pp. 31-52

**[Kranzmann 2002]**

Kranzmann, A. (2002): Kohlendioxid-Abtrennung und -Entsorgung, BMWi-Symposium "Wege zum emissionsfreien fossilen Kraftwerk", 5.-6. Februar 2002, Berlin

**[Freund 2002]**

Freund, P.; Davison, J (2002): General Overview of Costs, IPCC Workshop on Carbon Dioxide Capture and Storage, Proceedings, Regina, Canada, 18-21 November 2002. Published by ECN, pp. 79-94

**[Koss 2002]**

Koss, U. (2002): State of the Art Gas Technologies for Zero Emission IGCC's, BMWi-Workshop on CO<sub>2</sub> Separation, Use and Storage for Fossil Fuel-Fired Power Stations, 03-04 July 2002, Lurgi AG, Frankfurt/Main

**[Neef 2002]**

Neef, H.-J. (2002): IEA Zero Emissions Technologies Strategy for Fossil Fuels, BMWi-Workshop on CO<sub>2</sub> Separation, Use and Storage for Fossil Fuel-Fired Power Stations, 03-04 July 2002, Lurgi AG, Frankfurt/Main



# The residential building sector – potentials and constraints of CO<sub>2</sub> mitigation

M. Kleemann\*

## 1 Introduction

The Kyoto-protocol obliges the European Community to reduce the greenhouse gas emissions by 8 % until 2008/2012 in the whole community. In the framework of the European burden sharing Germany took over a guiding role and declared its reduction goal to be 21 per cent by 2008/2012. The German minister for environment declared recently: Despite all predictions to the contrary we are well on the way to achieve our goal of 21 per cent reduction by 2010. Discussions and scientific investigations on long-term CO<sub>2</sub> reduction goals aim at mitigation levels of 30 per cent by 2020.

The building sector plays a key role in this context. Residential and non-residential buildings account for about one third of the of total final energy use in Germany. The building sector is the largest energy consumer. But on the other hand, there exist tremendous energy saving potentials. About 75 per cent of the building stock is older than 25 years. According to the present regulations 50 to 75 per cent of the energy consumption of these buildings could be reduced. The government has initiated an energy saving and CO<sub>2</sub> reduction process. But due to various constraints the effect of this policy was moderate until now. A more stringent policy is necessary.

The aim of this paper is to present background information on the building sector, stock data, demand indicators, energy consumption patterns and CO<sub>2</sub> emissions. Then, implemented reduction measures, constraints and further recommendations are discussed. But at first an overview of the German energy situation is given.

## 2 Background information on the overall development of energy use and carbon dioxide emissions

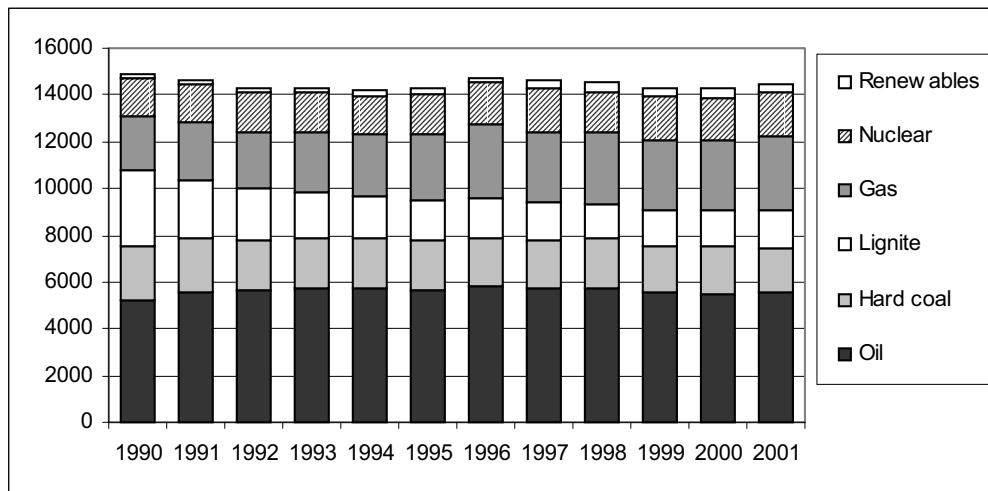
### 2.1 *Pattern of primary energy consumption*

Figure 1 shows the development of the primary energy consumption from 1990 until 2001 in Germany. The effects of warm and cold winters have been eliminated. The consumption declined from 1990 to 1994. This is due to the utilization of more efficient technologies and the restructuring of the economy in East Germany after reuni-

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

fication in 1989. After 1994 economic growth slightly accelerated the consumption, but the total level remained in 2001 about 3 per cent below the 1990 level.



**Fig. 1:** Development and pattern of primary energy consumption in PJ [BMWA 2003]

But the individual development of the various fuels is quite different. The use of oil increased from 5,238 PJ in 1990 to 5,577 PJ in 2001, which is equal to a 6.5 per cent increase. This growing demand has been forced mainly by the increasing traffic sector. Hard coal use declined by 17.4 per cent. The extreme high production costs for German hard coal are responsible for this development. Lignite faced an extreme reduction. Its utilization came down from 3,201 PJ to 1,630 PJ, which is a reduction rate of nearly 50 per cent. The main reason for this decline is the restructuring of the East German economy, which was heavily dependent on lignite before the reunification. Natural gas is the winner in this competition. Its utilization increased by 35 per cent. This fuel is easy to handle, relatively cheap and environmentally compatible. These excellent properties guarantee an increasing demand. Nuclear power contributed a slightly growing share of about 12 per cent. This is caused by the increasing annual availability of the existing power plants. No new capacities have been installed during the last decades. The share of renewable energies increased from 1.2 to 2.7 per cent, but the overall contribution is still low.

These figures show clearly, that Germany's present primary energy consumption highly depends on fossil fuels. About 24.3 per cent are met by coal, about 38.5 per cent by oil and about 21.5 per cent by natural gas. The total fossil share amounts to 84.3 per cent. This results in a relatively high carbon dioxide emission level.

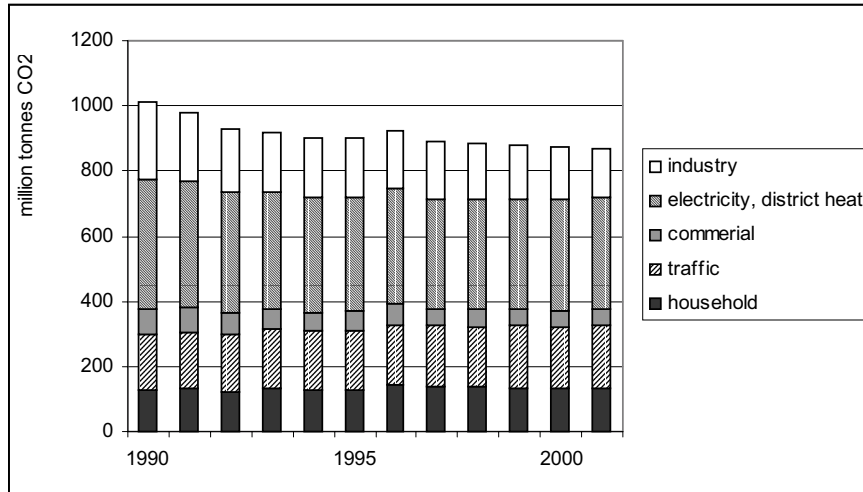
The present energy policy of the recent German government aims in general at:

- A reduction of hard coal and lignite use,
- An increase of natural gas utilization,
- A strong preference of renewable energies,
- A phasing out of nuclear energy,

- A reduction of energy consumption.

## 2.2 Carbon dioxide emissions

The reduction rate of carbon dioxide emissions is higher than the corresponding rate of primary energy decline. The fuel switch from lignite, hard coal and fuel oil to natural gas has caused this additional CO<sub>2</sub> mitigation. Additional but relatively low reduction effects are caused by increasing use of renewable energies.



**Fig. 2:** Development of carbon dioxide emission and reduction goals

The level of the total carbon dioxide emissions decreased from 1,015 million tonnes in 1990 to 860 million tonnes in 2001. The 155 million tonnes correspond to an overall reduction rate of 15.2 per cent. The speed of reduction declined considerably. During the five years period from 1990 to 1995 the emission was reduced by 116 million tonnes. But in the following six years from 1995 to 2001 the carbon dioxide reduction amounted to not more than 39 million tonnes. The high level from 1990 to 1995 was partly caused by the restructuring of the East German economy after reunification.

The carbon dioxide emissions of the various economic sectors show different developments from 1990 until 2001. A high reduction of 16.5 per cent has been achieved in the electricity generation sector (see Figure 2). About 32.5 per cent have been reduced in the industrial sector, which is the highest rate of all sectors. The household and commercial sectors reduce together 11.6 per cent. But it should be noticed that the trends in both sectors are completely different. The commercial sector strongly declines whereas the household sector remained nearly constant. The most unfavourable development happened in the traffic sector. Here the carbon dioxide emissions did not decrease but increase by 9.9 per cent.

### 3 Energy consumption in the residential building sector

#### 3.1 Projection of demand indicators

The most significant factors affecting the growth of energy consumption and subsequent CO<sub>2</sub> emissions are summarized in Table 1. In the long-term it is expected that the resident population after a small increase will decline and fall below the present level by 2020. But in contrast to this development there will be an increase of approximately 1.0 million households.

		2000	2010	2020
Resident population	10 <sup>6</sup>	81.9	82.1	80.7
Number of households	10 <sup>6</sup>	37.3	37.8	38.2
Persons per household		2.21	2.17	2.12
Total units of accommodation	10 <sup>6</sup>	36.9	38.0	38.1
Total floor space	10 <sup>9</sup>	3.1	3.3	3.4
Floor space per unit of accommodation	m <sup>2</sup>	85	88	89
Floor space per capita	m <sup>2</sup>	38	40	42

**Tab. 1:** Expected development of floor space and units of accommodation [1,6,8]

This will result in about 38 million households by 2020, compared to 37 million in 2000. During the same time period the per capita floor space demand will increase from 38 square metres per capita to a level of 42. These effects cause a growth of the national floor space from 3.1 billion square meters by 2000 to about 3.4 billion square meters in 2020. This is equal to an increase by about 10 per cent.

#### 3.2 Structure of energy consumption in the residential sector

The total final energy consumption in the residential sector amounted to 2689 PJ in Germany in 2000 (see Table 2). About 78 per cent of this energy has been used for space heating. Only 10 per cent are consumed for warm water preparation and 10 per cent for electric appliances and lighting. The remaining 2 per cent served as cooking energy.

According to Table 2 space heating and warm water preparation are dominated by light fuel oil and natural gas. But the share of light fuel oil declines steadily whereas the share of natural gas increases. It is expected that these trends will continue in the future. Warm water preparation and especially cooking are based on electricity to a considerable share. Solid fuels are expected to disappear from the fuel market for residential supply in the long run. "Other" includes renewable energies such as solar energy and biomass.

	Final energy PJ	Breakdown %	Total %
<b>Space heating</b>	<b>2.104</b>	<b>100</b>	<b>78</b>
District heat	141	7	
Light fuel oil	848	40	
Natural gas	906	43	
Coal and other	95	5	
Electricity (night storage)	114	5	
<b>Warm water preparation</b>	<b>260</b>	<b>100</b>	<b>10</b>
District heat	21	8	
Light fuel oil	78	30	
Natural gas	101	39	
Coal and other	5	2	
Electricity	55	21	
<b>Cooking</b>	<b>58</b>	<b>100</b>	<b>2</b>
Natural gas	17	29	
Coal and other	1	2	
Electricity	40	69	
<b>Electric appliances and lighting</b>	<b>267</b>	<b>100</b>	<b>10</b>
Electricity	267	100	
<b>Total</b>	<b>2.689</b>	<b>100</b>	<b>100</b>
District heat	162	6	
Light fuel oil	926	34	
Natural gas	1.024	38	
Coal and other	101	4	
Electricity	476	18	

**Tab. 2:** Pattern of final energy consumption in the residential sector [PROGNOS 1999]

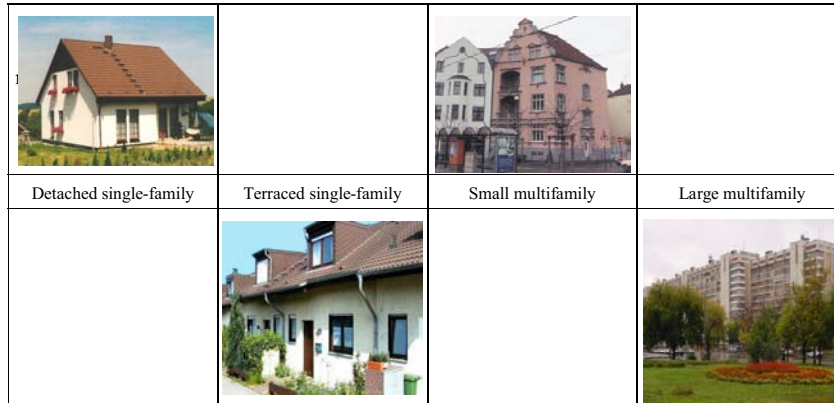
## 4 The building stock

### 4.1 Building size distribution

More than 17 million single-family and multifamily houses encompass the residential building sector. The total current floor space of these buildings amounts to 3.1 billion square meters.

This building stock can be divided into the following four basic types of houses:

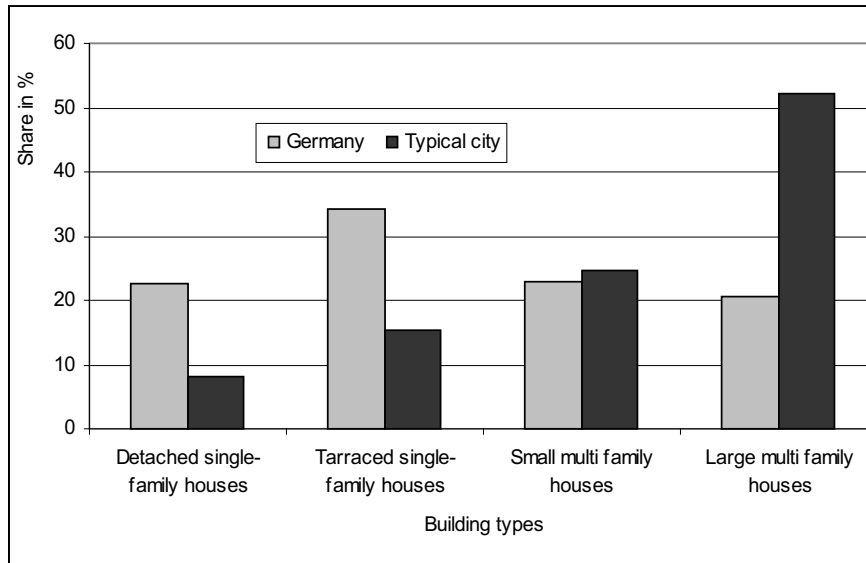
1. Detached single-family houses (one or two flats).
2. Terraced single-family houses (one or two flats).
3. Small multifamily houses (three to six flats).
4. Large multifamily houses (more than six flats).



**Fig. 3:** Examples of the four building types

The thermal efficiency of the building envelope increases from detached single-family houses to large multifamily houses. Large and compact houses have a low ratio of surface to volume. This causes only low thermal losses.

Figure 4 presents the distribution of building types on the national level and on the level of a German city. In cities large multifamily houses dominate the building stock. The share reaches about 50 per cent. All multifamily houses contribute 75 per cent to the urban building stock. Single-family houses play a minor role in cities, but not in the whole country. Here the share amounts to nearly 60 per cent.



**Fig. 4:** Distribution of building types (share based on floor space area)

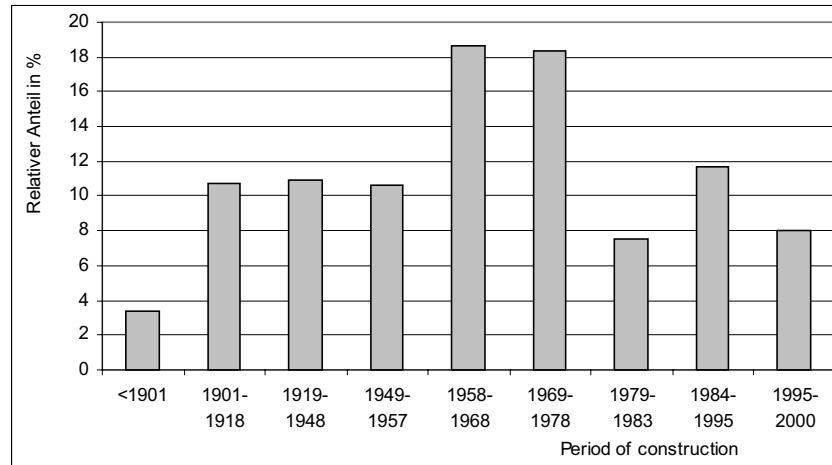
#### 4.2 Age of the building stock

The age class reflects historical events, which determine the availability of building materials, and periods when new regulations came into force (Table 3).

Age class <sup>1)</sup>	Comment
≤ 1900	Listed buildings
1901 - 1918	Regular buildings, end of First World War
1919 - 1948	Period before foundation of the Federal Republic of Germany
1949 - 1957	Post war period (lack of material)
1958 - 1968	DIN 4108 came into force
1969 - 1977	Supplement to DIN 4108 came into force
1978 - 1983	First Thermal Insulation Ordinance came into force (1. WSVÖ)
1984 - 1994	Second Thermal Insulation Ordinance came into force (2. WSVÖ)
1995 - 2001	Third Thermal Insulation Ordinance came into force (3. WSVÖ)
≥2002	Energy Saving Ordinance came into force (EnEV)

**Tab. 3:** Age classes in the German building sector

The following Figure 5 illustrates the distribution of floor space age at the national level.



**Fig. 5:** Distribution of age classes (based on floor space area)

A relatively high share was built after the Second World War in the period from 1949 to 1978. About 80 % of the floor space was built before 1984 when the Second Thermal Ordinance came into force. Especially these buildings have very high energy consumption levels due to their insufficient thermal insulation, which mostly has not been upgraded. While a certain portion of the stock in these age classes has undergone some renovation, experiences suggest that much of this renovation activity did not fully incorporate energy efficiency measures.

## 5 Energy saving potentials in the residential building sector

### 5. Heating systems

#### 5.1.1 Oil and gas boilers dominate the stock

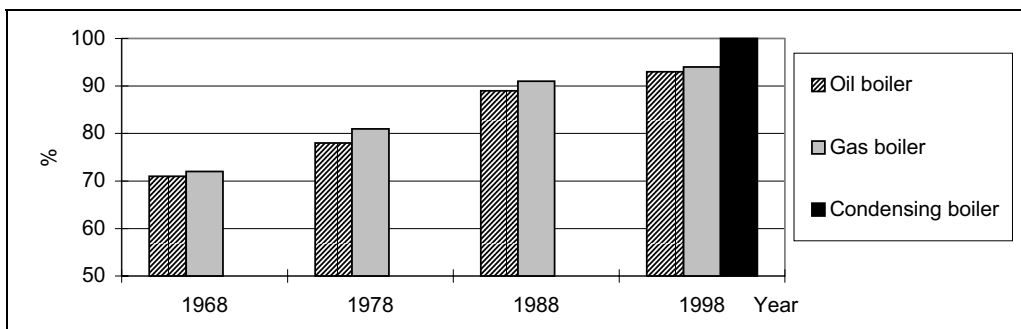
The heating system stock is dominated by oil and gas fired boilers. They heat about 83 % of the floor space (see Table 2). Most of the systems are central units (76 %). The share of decentralized heating systems is steadily declining and more gas-fired central heaters are used. Centralized systems represent a higher life style, they are easier to handle and better to control. There exist indications that the switch from decentralized to centralized units leads to a higher per capita consumption, because the people like to enjoy the higher comfort of the centralized system.

#### 5.1.2 Development of boiler efficiency

Due to the large share of oil and gas boilers the following considerations focus on this two types. Figure 6 demonstrates the technological progress achieved in heating boiler development. From 1968 to 1988 a relative increase of the efficiency of about

10 per cent per decade could be realized for regular oil and gas boilers. The step during the period from 1988 to 1998 has been distinctly smaller. It amounted only to 4 per cent. This is due to the fact that the technology has already reached a very high state of the art, which cannot be improved significantly.

In general the efficiencies of regular gas boilers are 1 to 2 per cent higher compared to oil boilers, which is due to the better burning conditions. But the highest efficiencies can be achieved in gas condensing boilers. These systems use the latent heat of the exhaust gas and can reach efficiencies above 100 per cent. This is possible, because the efficiency is related to the lower calorific value. If the upper calorific value would be used as a reference, then the efficiency would be about 100 per cent. The development of the boiler efficiencies is important in connection with the age structure of the boiler stock.



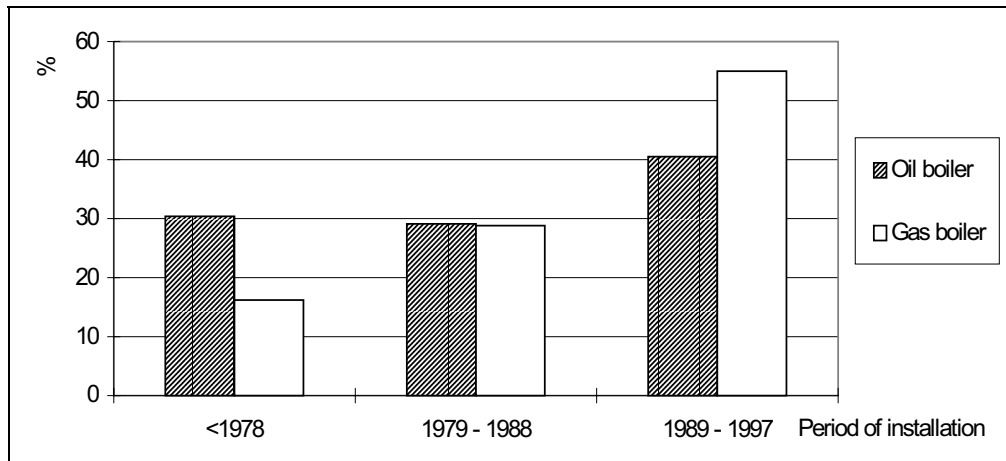
**Fig. 6:** Development of average heating boiler efficiency [Kleemann 1999]

### 5.1.3 Age structure and savings through boiler replacement

According to Figure 7 about 30 per cent of the oil fired boilers are between 10 and 20 years old. These units have efficiencies between 78 and 89 per cent. But another 30 per cent are older than 20 years, with an average efficiency in the range of 71 to 78 per cent. These boilers should be replaced, because with new units about 25 per cent of the final energy could be saved.

The share of very old gas boilers is only half the percentage of the very old oil units. If these old regular gas boilers would be replaced by new gas condensing boilers, then about 30 per cent of the final energy demand of a building could be saved.

Gas condensing boilers become more and more popular. The market is increasing. The main reasons for this development are: the environmental friendliness of gas, the high boiler efficiencies, the compact boiler design and various financial support programmes for this technology.

**Fig. 7:** Age structure of heating boilers

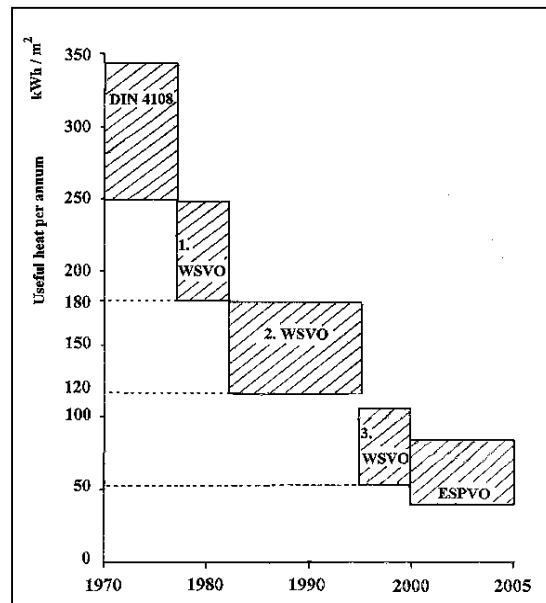
## 5.2 Development of the German thermal insulation standard

Figure 8 shows the development of the various ordinances during the last 30 years. In average the regulations have been tightened every five to six years. The allowable annual useful heat consumption has been reduced in average from 300 kWh/m<sup>2</sup> to 65 kWh/m<sup>2</sup>.

The range of the figures (difference between upper and lower limit) is due to the ratio of building surface to building volume. The higher the ratio, the higher are the thermal losses. This effect of the building geometry is taken into account in the standards. The lower bounds are for compact buildings with a low ratio of surface to volume, such as multifamily houses. Detached single-family houses with a relative large surface compared to the volume are allowed to meet the upper bounds.

The present "Energy Saving Ordinance" (EnEV) came into force in 2002. For measures in existing buildings the ordinance sets forth certain requirements. If the renovation of an existing building exceeds a certain limit, then the insulation measures must be nearly equivalent to those customarily applied in new buildings. The new "Energy Saving Ordinance" is stricter and will reduce the allowable heat demand by another 25 per cent, related to the previous ordinance.

But one should keep in mind that new buildings, even with a low energy demand, cannot reduce the overall consumption of the total housing stock if not a respective number of old buildings is demolished at the same time. At present only an amount of about 10 per cent of the newly built floor area is demolished in old buildings. Therefore new buildings will increase the overall energy demand even if they meet the present high standard. The overall reduction effect of new low energy standards has a considerable delay time due to the long lifetime of the existing buildings.



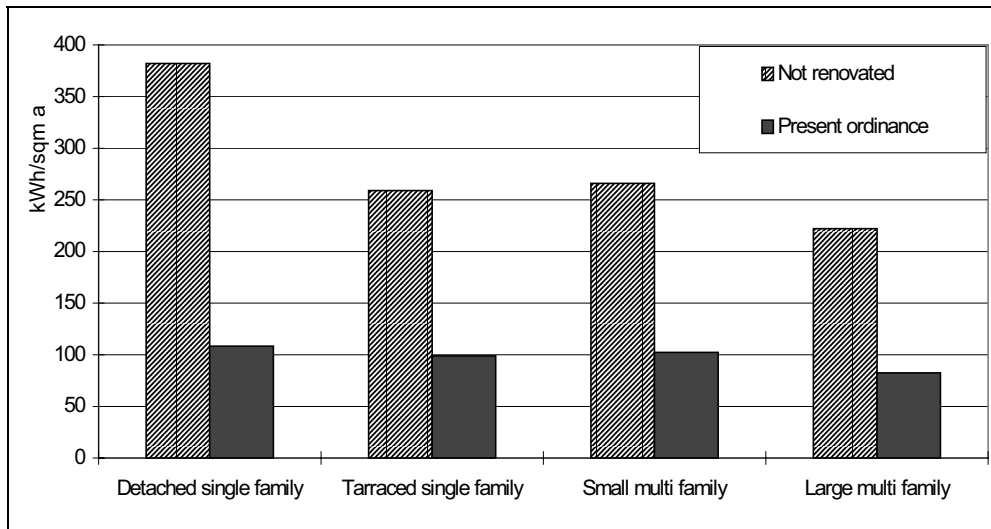
**Fig. 8:** Development of German heat efficiency standards

### 5.3 Saving potential of building renovation

The thermal properties of various building sizes are compared in Figure 9 for the age class 1949-1957. The left columns show the annual final energy demand for space heat and warm water in a not renovated condition in kWh/m<sup>2</sup> floor space area. Not renovated means it's assumed that the building is in the original condition. Detached single-family houses have the highest ratio of building surface to building volume and hence they tend to the highest specific heat consumption. Terraced single-family houses and compact multifamily house have a low surface to volume ratio and hence a lower heat demand compared to detached single-family houses.

The right columns in Figure 9 present the demand of the fully renovated building according to the present standard. Fully renovated means improved insulation of outer walls, cellar walls and roof and the replacement of the old windows. The technical saving potential related to final energy is about 70 per cent for detached single-family houses and around 60 per cent for the other building types.

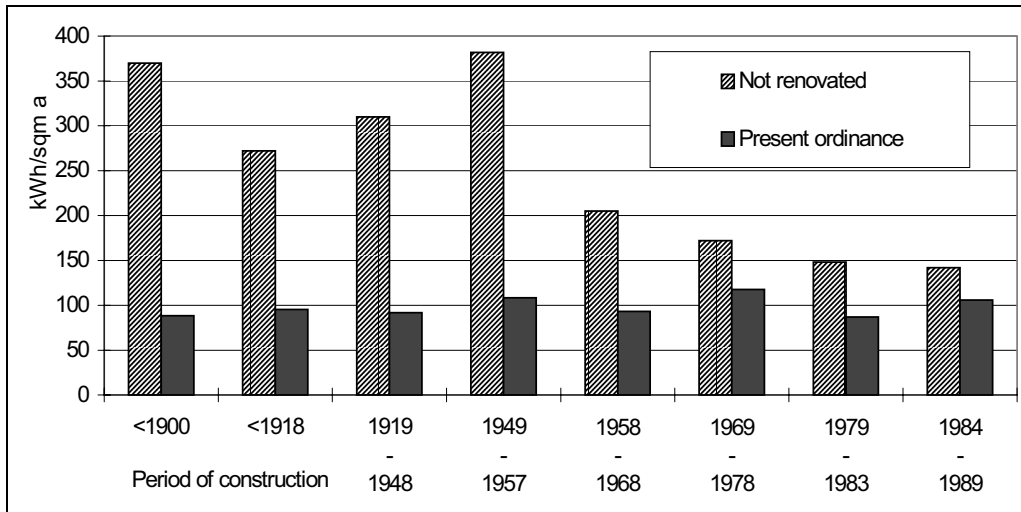
The influence of the age of a detached single-family house on the final energy demand is summarized in Figure 10. The very old buildings, constructed before 1958, have a very high demand in the range of 270 to 380 kWh/m<sup>2</sup>. When these buildings were constructed no thermal insulation ordinance was in force. Due to the lack of good construction materials the age class of the post war period from 1949 to 1957 has the highest thermal demand of 380 kWh/m<sup>2</sup>a. Compared to fully renovated buildings exist technical energy saving potentials from 65 to 75 per cent for the buildings constructed before 1957.



**Fig. 9:** Final energy saving potential for various building types of the age class 1949 – 1957

After 1957 recommendations and regulations were implemented successively in Germany. They became more and more stricter (see Figure 8). The annual final energy demand of the detached single-family house types built after 1957 is in the range of 140 to 200 kWh/m<sup>2</sup>a. Compared to fully renovated houses according to the present standard there exist saving potentials between 25 to 55 per cent.

It's estimated that about 80 per cent of the older housing stock do not meet the current standard. This means that in the whole residential building stock exists average energy saving potentials of at least 50 %.



**Fig. 10:** Final energy saving potential of single-family house types of all age classes

## 6 Obstacles

The practice of building renovation shows, that it is very difficult to exploit the above-specified energy saving potentials because of several obstacles. The most important constraints are briefly discussed in the following paragraphs.

### 6.1 *Lack of public awareness, acceptance and information*

The risk and reality of climate change have become more and more apparent. Scientists, politicians and environmental groups have paid an increasing attention. Various regulations have been established in between to tackle the problem. But in practice climate protection activities are not widely accepted by the population as a whole. There is a lack of awareness and a lack of willingness to pay or to do more than the regulations demand. Accordingly in many cases the renovations do not meet the energy efficiency requirements of the regulation, because the authorities do not inspect or control the executed renovation.

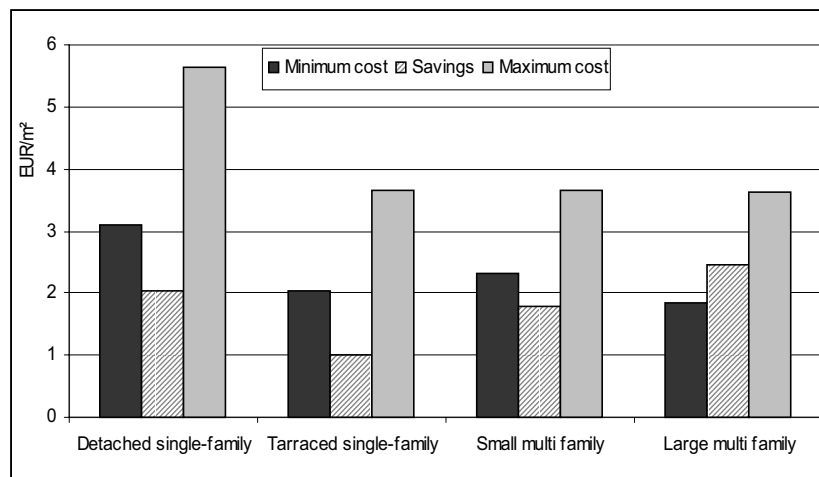
Therefore a broad and more effective public participation in residential CO<sub>2</sub> reduction measures is absolutely necessary.

Various investigations have shown that many of the consumers face a lack of information on the thermal condition of their buildings, the available technologies and the costs. Here a comprehensive improvement of the consulting infrastructure is indispensable.

## 6.2 Low energy prices and lack of attractive incentives

The by far most severe obstacle is the missing cost effectiveness of many of the energy saving measures. Reasons are the low costs of the fuels and the relatively high costs of the insulating measures. Figure 11 shows a comparison of costs and savings per square meter living space floor for an outer wall insulation of four building types.

All cases shown in Figure 11 meet the current thermal standards. The costs for insulations can vary according to type, design and quality. Therefore a range of costs is given. The left column for each building presents the minimum costs and the right one the maximum. The costs include only the expenditures for the insulation; other general renovation costs of the building are not included. The obtained energy cost savings are drawn in the middle.



**Figure 11:** Costs of outer wall insulations and the achieved energy cost savings (Depreciation 15 years, interest rate 6 %)

A comparison of costs and savings shows that only the low-cost insulation for multi-family houses is economically competitive. This is valid for a depreciation time of 15 years. But if the cost calculation is done with a depreciation time of 40 years, then the low-cost insulations are competitive for all buildings. The high-cost insulations are generally not competitive.

The running financial supporting programmes are considered not to be attractive enough for the investors [Kleemann 2003]. New and more attractive support programmes for energy efficient upgrading of existing buildings are necessary.

### 6.3 *Other constraints*

The residential floor space increased by 7 per cent between 1990 and 2000. This causes the respective growth in energy demand and CO<sub>2</sub> emissions. A part of the mitigation effects in the building stock has been compensated.

The low annual renovation rate, due to the high lifetime of building components, creates another problem. According to the experience in Germany an average residential building is renovated completely once within 50 years. Therefore the average annual renovation rate reaches only 2 per cent of the building stock. Hence the total system changes very slowly. A quick CO<sub>2</sub> reduction cannot be expected in the residential building sector.

## 7 **CO<sub>2</sub> mitigation measures**

### 7.1 *Already implemented measures*

It is commonly agreed that the residential-building sector holds the greatest reduction potentials. Therefore the previous national report on climate protection in Germany mentioned already a considerable number of implemented political measures [BMU 2002, IMA 2000, Kleemann 1999]. The package includes regulatory, financial support and motivation measures. Some selected measures are considered in the following sections.

#### *Amendment of the thermal insulation ordinance*

The new Energy Saving Ordinance for buildings (EnEV) came into force in 2002. The ordinance is expected to reduce the heating demand for new buildings by up to 25 %, thus reducing CO<sub>2</sub> emissions by a similar amount. At the same time it is aimed at improving energy efficiency in existing buildings.

#### *Ecological energy tax*

This measure is in fact an intersectoral measure. In 1999 the fuel oil prices for residential heating increased by 2 Cents per litre. For comparison: The price of a litre fuel oil is in the range of 30 to 40 Cents.

#### *Housing modernisation programme in East Germany*

This programme was established in 1990. It provides low-interest loans for renovation and modernisation of houses. This includes also energy-saving measures. Up to now about 4 million dwellings have been supported in East Germany. This figure amounts to about 50 % of the total number of apartments in this part of the country. Now the programme has been extended to total Germany.

#### *Low-interest programmes for CO<sub>2</sub>-reduction in existing buildings*

The programme finances especially measures in existing residential buildings to reduce energy consumption and CO<sub>2</sub> emissions. The support is provided in form of low-interest loans for improvement of thermal insulation, for new efficient boilers and for the use of renewable energies.

*Information and motivation programmes*

Various ministries, agencies, institutions and many other organisations provide guidance to the owners of the buildings in selecting and executing appropriate modernisation and energy saving measures.

*Climate protection and energy saving programmes of local authorities.*

These programmes include financial support for the renovation of old buildings, the construction of "low-energy" houses, the creation of consulting centres, the organisation of training courses for architects engineers and craftsmen and the execution of pilot projects. But the available funds for these purposes are limited.

**7.2 Additional measures required**

Despite all the already implemented measures the overall CO<sub>2</sub> reduction in the household sector from 1990 until 2001 amounts to only 2.9 per cent. This is by far not enough to reach the reduction goals. To overcome the constraints additional reduction measures are necessary. This requires a more stringent climate protection policy. Scientists and politicians discuss the following additional enforcement measures:

- A more effective control and inspection if the requirements of the building regulations are met.
- A further increase of the thermal insulation standards.
- More attractive financial incentives for the building owners.
- A more intense use of high efficient heat generation technologies.
- The further increase of renewable energy use.

**8 Summary and conclusions**

The most important goals of all CO<sub>2</sub> reduction measures are to avoid unnecessary energy consumption by reducing thermal losses of the building envelop, by installing efficient heating systems and by stimulating a responsible heating behaviour of the building users. Efficient use of energy is the most safest and environmentally compatible way to contribute to protection of the global climate. It contributes not only to climate protection but also reduces simultaneously the burden of other environmental effects.

The technologies for high-grade thermal insulation of walls and windows and the boilers for efficient heat generation are available on the market. Because of this reason energy saving measures are rapidly feasible from a technical point of view. In the total residential building stock more than 50 per cent of the heating demand could be saved with available insulation technologies, based on the present thermal insulation standard.

However, the specified saving potentials are only exploitable with reasonable economic expenditures. The costs for energy saving measures can be minimized if the measures for upgrading energy efficiency are coupled to the general renovation of the respective building components.

Further and more attractive financial support programmes for thermal insulation measures are indispensable due to current low energy prices. Under the present conditions the capital recovery of energy saving investments takes place over a long period, whereas many building owners expect a short-term return. Financial support can improve this situation and motivate building owners. In the case of rental housing the financial obstacles must be compensated, so that modernization provides acceptable rents for the investor and attractive benefits for the tenant as well.

Up to now the German climate protection policy has achieved a good progress with an overall reduction level of 15.2 per cent in the time span 1990-2001. But in the residential sector the reduction level reached only 2.6 per cent. With the implemented measures it's unlikely that the 21 per cent reduction goal of the Kyoto protocol can be managed until 2010. Therefore additional measures have to be introduced. In the long run a stricter climate protection policy is urgently necessary. This requires an appropriate mix of supplementary regulatory, information and funding concepts and measures in the near future.

All the reduction measures implemented and recommended have to form a matched bundle, which can only take full effect in the case of a joint application. The measures reinforce each other by synergy effects. This guarantees that the ambitious reduction goal can be reached finally.

## **9 References**

### **[Kleemann 2001]**

Kleemann M. et al. The long term development of heat demand in the building sector (in German), *Energiewirtschaftliche Tagesfragen* 51. Jg. (2001) Heft April.

### **[BMU 2002]**

BMU (2002), Federal Ministry for the Environment, Climate Protection in Germany, Third report of the government of the Federal Republic of Germany pursuant to the United Nations Framework Convention on Climate Change, Berlin 2002.

### **[BMWA 200]**

BMWA (2003), Federal Ministry for Economics and Labour, Energy Data 2002 (in German), Berlin 2003.

### **[IMA 2000]**

IMA, National Climate Protection Programme, in German, Interministerieller Ausschuss, Berlin, 2000.

### **[PROGNOS 1999]**

PROGNOS, The long term development of energy markets, in German, Basel, 1999.

**[ENQUETE 2001]**

ENQUETE Kommission "Nachhaltige Energieversorgung unter den Bedingungen von Liberalisierung und Globalisierung", Deutscher Bundestag, Drucksache 14/7509, Berlin 2001.

**[Kleemann 1999]**

Kleemann M. (1999): Programme of Measures to Reduce CO<sub>2</sub> Emissions in Germany. In: Strategies and Technologies for Greenhouse Gas Mitigation, An Indo-German Contribution to Global Efforts, ed. by Hake J. F., Bansal N. and Kleemann M., pp 33-48, Ashgate Publishing Ltd., Aldershot England.

**[Kleemann 2000]**

Kleemann M. et al.: The Development of the Heat Market for the Building Sector until 2050, Schriften des Forschungszentrums Jülich, Reihe Environment, Volume 23, Jülich 2000, ISBN 3-89336-262-2.

**[Kleemann 2003]**

Kleemann M. et al.: Climate Protection and Jobs, Evaluation of the KfW Low Interest Loan Programmes (in German), Schriften des Forschungszentrums Jülich, Reihe Environment, Volume 34, Jülich 2003, ISBN 3-89336-262-2.

# Scenario study: Development of emissions in the German transport sector

J. Linssen\*, M. Walbeck\*

## 1 Greenhouse gas emissions of the transport sector in Germany

The largest proportion of the motorised traffic is powered by internal combustion engines (ICE) fuelled with mineral oil fuels. With the burning of petrol products or other carbon-containing fuels a number of different pollutants are emitted to the ambient air. Besides water and carbon dioxide, which represent the greatest percentage of reaction products, many other combustion products arise. These air pollutants can damage human life, ecosystems and even real assets. The negative effects of air pollutants do not only depend on their characteristics, but also on the quantity, the place of their release, their transformation and finally on the resulting gas concentrations at possible places of impact (immission problem).

The combustion of fossil energy carriers leads to the hazardous gases carbon monoxide (CO), nitrogen oxide (NO<sub>x</sub> as NO and NO<sub>2</sub>), non methane hydrocarbon (NMHC) and sulphur dioxide (SO<sub>2</sub>). On basis of the historical development of transport sector emissions (see [Radke 2003]) an ongoing reduction of hazardous gases is probable. The main reason for this is the successive restriction of the emission legislation for new vehicles and cleaner fuels (e.g. content of sulphur) in the European Union (Auto-Oil-Programme I & II).

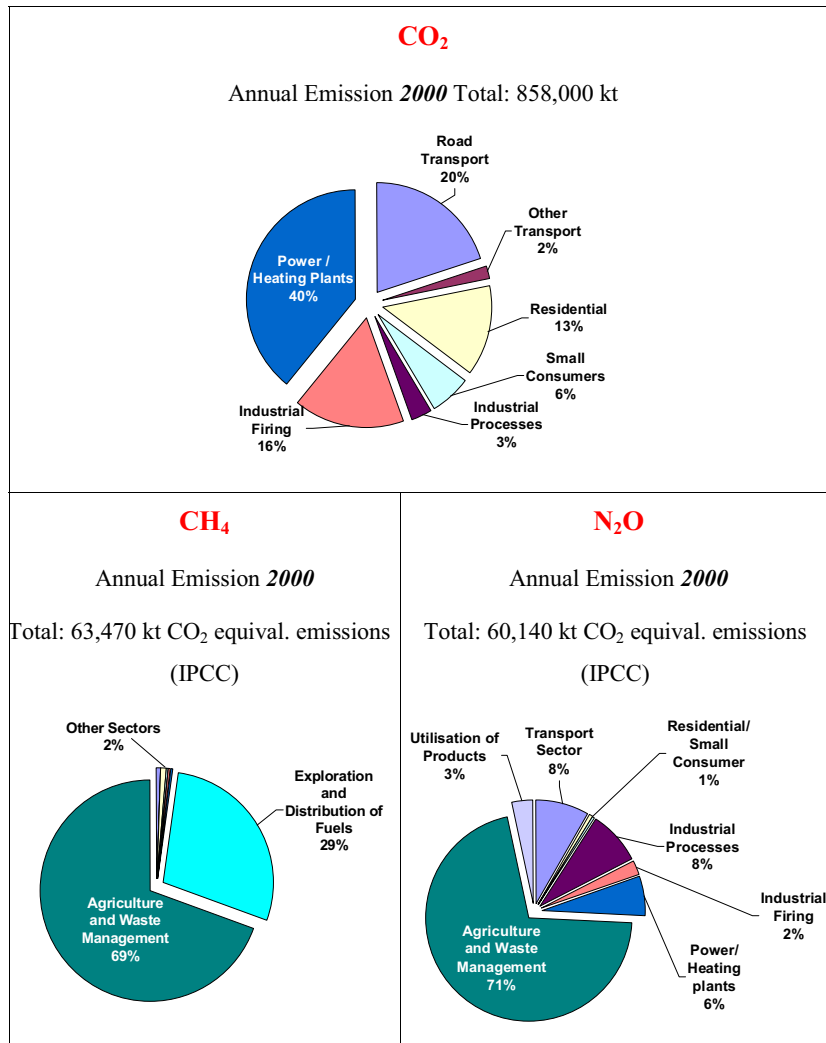
A comparable mitigation of greenhouse gases in the historic development of the transport sector is not apparent. For example, the CO<sub>2</sub> emissions from the transport sector in Germany increase from 1990 to 2000 by around 21 %. In contradiction to the hazardous gases carbon dioxide can only be reduced by lower fuel consumption or by using carbon-free or carbon-reduced fuels. The emission of climate harmful gases is one of the urgent problems in the passenger and goods transport which have not been solved up to yet. The anthropogenic emission of these gases increases the concentration of trace gases in the lower atmosphere and leads to a heating up of the troposphere ("green-house effect"). This process may lead to a global climate change. So with respect to the overall concept of "Sustainable Devel-

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

opment" the target must be to establish extensive measures to reduce these anthropogenic emissions in the transport and other sectors. The most important greenhouse gas emissions of the transport sector are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O).

A comparison of German greenhouse gas emissions in different sectors in the year 2000 indicates a differentiated development (see figure 1). Road traffic has a mean share of about 22 % of the total CO<sub>2</sub> emissions in Germany. While the absolute CO<sub>2</sub> emissions in the sectors industrial firing and processes have regressive tendencies the total transport carbon dioxide emissions still increase till 1999 (Radke 2003).



**Fig. 1:** German greenhouse gas emissions in the year 2000 differentiated according to sectors [Radke 2003]

In order to evaluate the global warming potential of the methane and nitrous oxide the total emissions of these greenhouse gases are converted into CO<sub>2</sub> equivalent emissions with the global warming potential factors of the Intergovernmental Panel on Climate Change (IPCC). The largest emission source of CH<sub>4</sub> and N<sub>2</sub>O is the agriculture and waste management sector. The transport sector causes about 13 % of the total nitrous oxide and 0,6 % of the methane emissions. The development of the CH<sub>4</sub> transport emissions in the nineties was regressive. In contrast to this the nitrous oxide emissions from the transport sector increase slightly with the tendency to stagnation. In comparison to the CO<sub>2</sub> emissions in the transport sector it must be mentioned that the methane and nitrous oxide emissions and their warming potentials are at a low level.

In figure 2 the emission of the hazardous gases carbon monoxide, non methane hydrocarbon and nitrogen oxide in the different sectors are compared. The transport sector was in 2000 the largest emission source of CO and NO<sub>x</sub> but with a strong tendency to decrease.

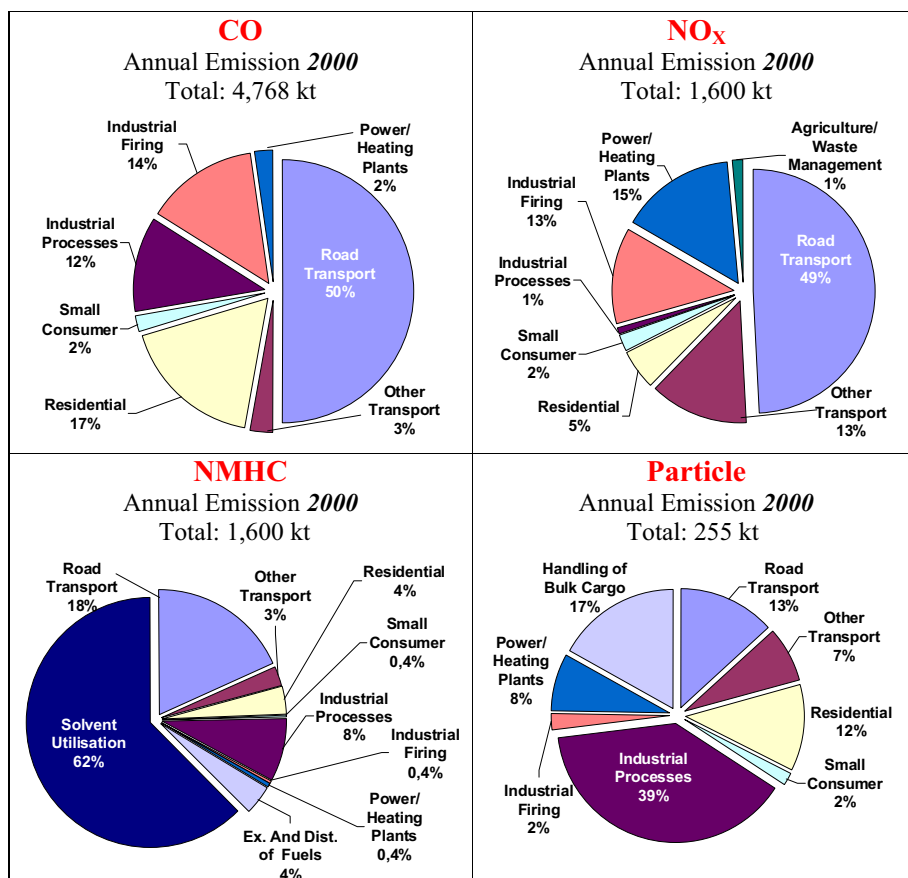


Fig. 2: German limited emissions in the year 2000 differentiated according to sectors [Radke 2003]

The emission of particles especially in the transport sector, the exhaust of soot particle, is an other problem that can cause damage on health. Main source of the soot particles emission in the transport sector is the internal combustion of diesel fuel. A further intensifying of the soot particle limiting values for passenger cars and trucks is presently in discussion.

## 2 IKARUS Transport Model

For the reduction of the emissions in the transport sector a multiplicity of measures and conceivable interventions exists. For example emission-optimised conventional passenger cars can be introduced into the market, or transport volumes can be shifted to emission-reduced means of transportation like railways. The great variety of impacts of these measures are often hard to retrace. In order to get information about the effects of measures, interventions, strategies and especially about the combination of measures which depend on each other, the Programme Group "Systems Analysis and Technology Evaluation" (STE) of the Research Centre Jülich, Germany, has developed an emission model for the transport sector. This model was created in the IKARUS joint research project funded by the German Federal Ministry of Education and Research. It gives the opportunity to demonstrate the impacts on the environment and helps to find solutions which help to decrease these harmful impacts.

The basis of the model is an extensive economic, strategic and technical database. The technical database includes emission coefficients of different means of transportation, types of vehicles and drive trains differentiated according to driving patterns and traffic modes. Within the whole databases the user of the transport model can change a multitude of possible parameters with a high level of detail in discrete time steps (years). In cooperation with the German Technical Control Board for Safety and Environmental Protection (TÜV Rheinland/ Berlin-Brandenburg) STE has created the necessary database and revises it continuously.

The IKARUS Transport Model offers the following variation possibilities:

- change of vehicle data (fuel consumptions, costs, emissions)
- adding or deleting of vehicle types, -classes and power trains
- change of economic data (vehicle population, fuel costs, interest rate)
- change of strategic data (demand of transport, modal split, types of vehicles, driving patterns, traffic mode)

The scenario calculation offers the results for different time steps

- annual emission of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, NO<sub>x</sub>, NMHC, soot particles and SO<sub>2</sub>,
- energy consumption and
- operating costs of different modes of transport

This model can show the trend of the future development of the whole transport sector and parts of it. The trend calculations cannot fulfil the requirements of a prognosis because of the strong temporal dynamics in the transport sector. A comparison of the scenario results is strongly associated with the comparison of strategic and economic data like transport capacity or average vehicle occupancy.

### 3 Scenario calculations

The performed calculations of this scenario study point out the emission trend of the transport sector in future with the already visible and future characteristics of advanced vehicle drive trains and new fuel supply chains. The basic scenario contains business as usual assumptions concerning frame data of the passenger and goods transport like vehicle population and means of transport.

#### 3.1 Basic Scenario

Starting point of the scenario calculations is a frame dataset concerning economic and demographic development of Germany for the next 30 years. With the help of a macro economic information system demands of transport for the passenger and goods traffic are predicted. Table 1 indicates the assumed frame dataset and calculated demands of transport.

Frame Data	2000	2005	2010	2020	2030	2000	2005	2010	2020	2030
Population [Mio.]	82,0	81,8	81,5	80,3	78,0					
Annual Rate Gross Domestic Product		2.0 % (2000 / 2005)	1.8% (2005 / 2010)	1.7% (2010 / 2020)	1.3% (2020 / 2030)					
<b>Passenger Transport</b>	<b>Demand of Passenger Transport [Mrd. Pkm]</b>					<b>Modal Split [%]</b>				
Pedestrian	30,0	31,3	31,3	31,7	31,2	3,1	3,0	2,9	2,7	2,5
Bicycle	23,9	25,4	25,4	25,8	26,2	2,4	2,4	2,4	2,2	2,1
Motorised Individual Trans.	731,2	771,6	790,1	846,0	888,2	74,6	73,9	73,3	72,2	71,2
Public Transport	88,5	91,5	93,1	99,7	103,7	9,0	8,8	8,6	8,5	8,3
Railway Transport	63,9	68,3	70,8	76,6	81,9	6,5	6,5	6,6	6,5	6,6
Air Transport	42,7	56,4	68,0	92,6	115,6	4,4	5,4	6,3	7,9	9,3
Total	980,2	1044,5	1078,6	1172,4	1246,8					
<b>Goods Transport</b>	<b>Demand of Goods Transport [Mrd. tkm]</b>					<b>Modal Split [%]</b>				
Road Transport	346,3	384,0	434,2	532,3	620,7	70,8	70,7	70,9	71,1	71,3
Railway Transport	76,0	81,8	91,2	110,6	128,8	15,5	15,1	14,9	14,8	14,8
Ship Transport	66,5	77,3	86,7	105,3	121,4	13,6	14,2	14,2	14,1	13,9
Total	488,8	543,1	612,0	748,2	870,8					

**Tab. 1:** Demographic and economic data and resulting demands of passenger and goods transportation

Figure 3 and figure 4 illustrate the demand of transport and the Modal Split of the passenger and goods transport according to table 1. In comparison to other scenarios or studies like [IFO 2001] or [Prognos 1999] here the pedestrian and bicycle transport is included in the total demand of transport. The balance of the air transport only considers flights with takeoff and landing on German airports according to the domestic principle.

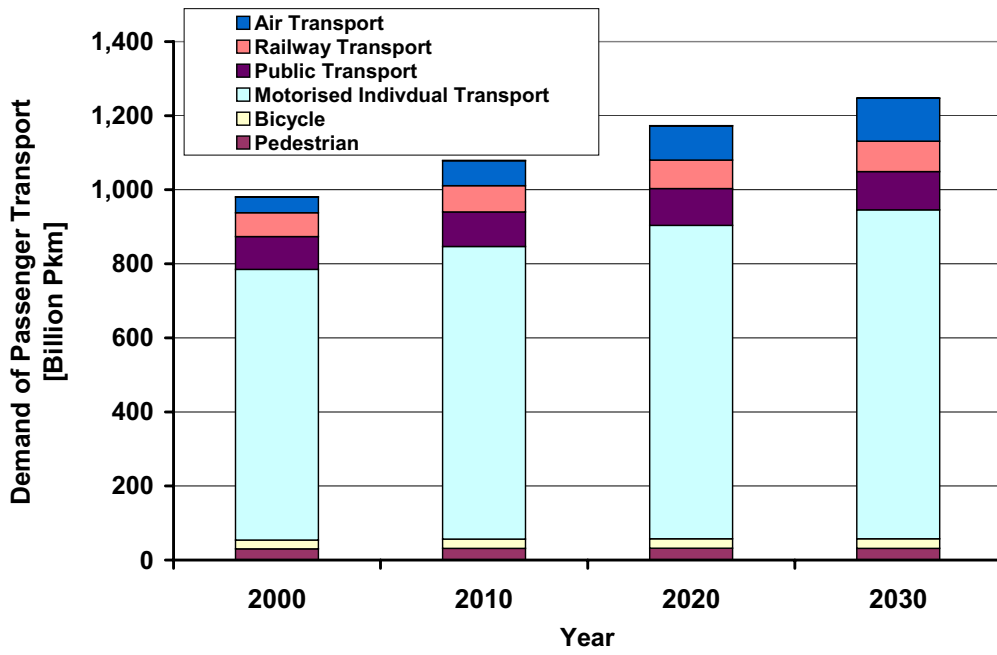


Fig. 3: Assumed development of the passenger transport; Basic Scenario

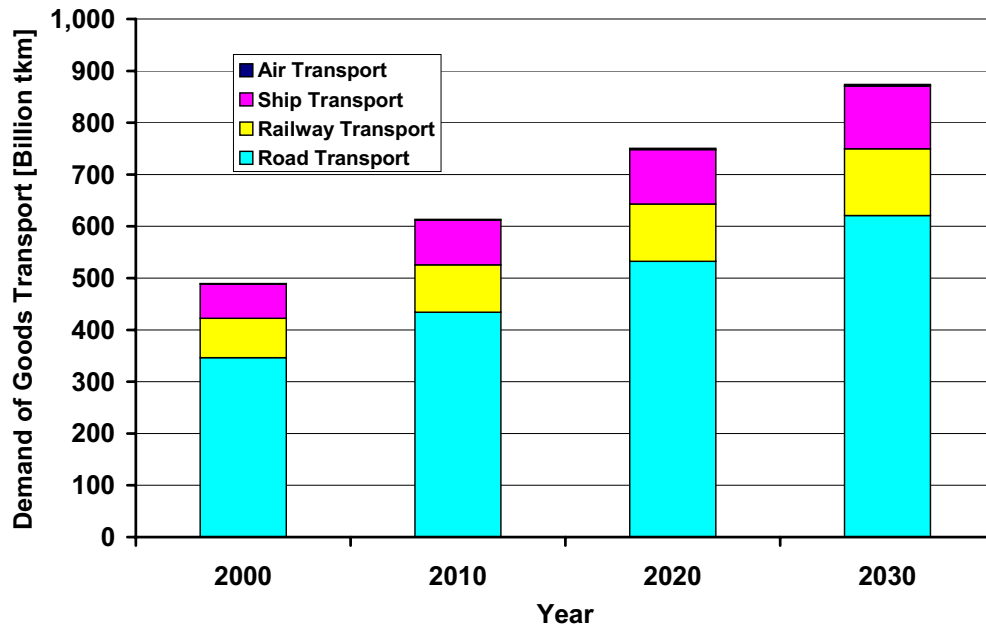


Fig. 4: Assumed development of the goods transport; Basic Scenario

The following figure 5 compares the assumed development of passenger kilometre of the Basic Scenario to actual studies and scenarios of the German transport sector. The trend of the assumed development is similar to other scenarios but with smaller decreasing formation after 2020.

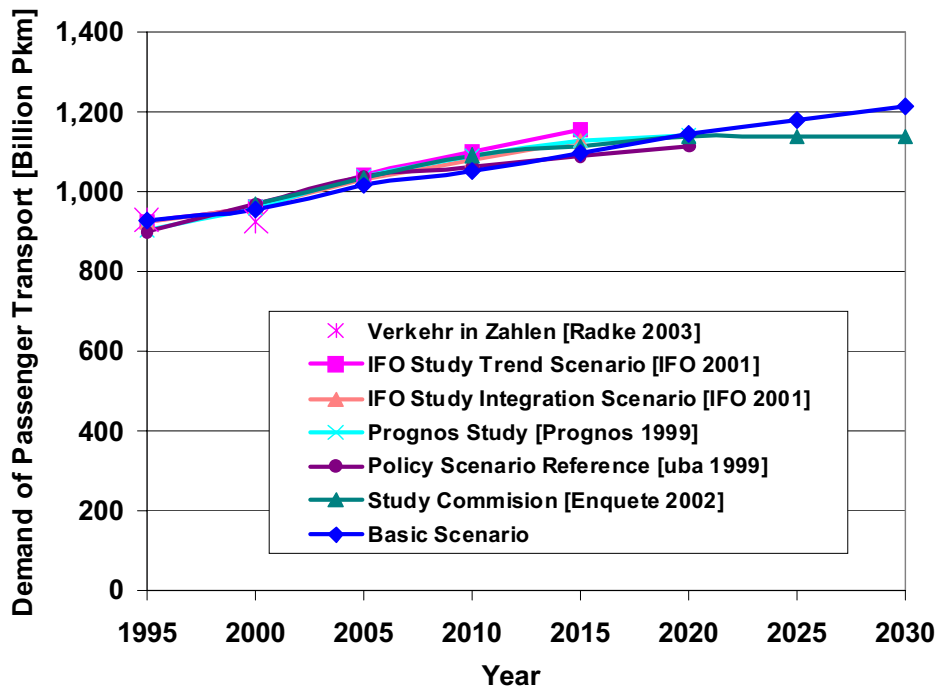
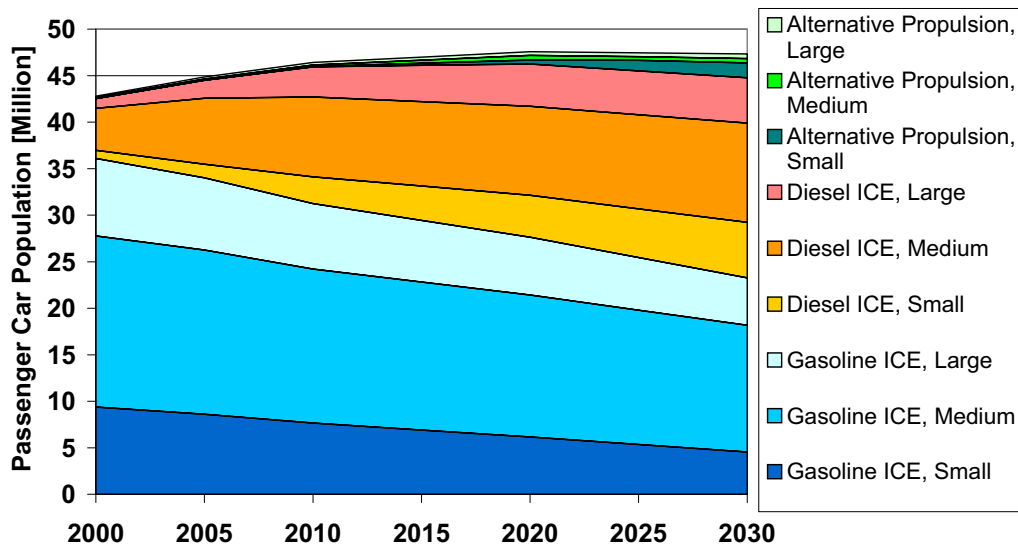


Fig. 5: Comparison of predicted passenger transport of different studies and prognosis

Concerning the assumed development of the passenger car population in Germany the passenger car (PC) density increases from 520 PC per thousand inhabitants in 2000 with a degressive growth rate at the end of the period up to 609 PC per thousand inhabitants. Together with the drop of German inhabitants this assumptions lead after 2020 to a small decrease of vehicle population to 47.3 Million PC in 2030. The composition of vehicle population changes in two ways in future: On one hand it was assumed that there is no further shift to large vehicle classes. Reasons for this trend can be the increasing part of second cars in Germany and ICE downsizing technologies with growing specific power. On the other hand the share of passenger cars driven by diesel combustion engines will increase from 20 % in 2000 up to above 45 % of the total passenger car population in 2030. This assumption is based on the actual development of selling new diesel cars in Germany with a market share up to 50 %.

Figure 6 illustrates the development of the passenger car population based on these assumptions. In addition the passenger car population contains a part of about 5 % alternative propulsion systems in 2030. These are essentially ICE vehicles fuelled by

Rapeseed Methyl Ester (RME), Liquid Petrol Gas (LPG) and Compressed Natural Gas (CNG).



**Fig. 6:** Assumed development of the passenger car population in Germany differentiated according to vehicle classes; Basic Scenario

For the development of the commercial vehicle population (trucks) it was assumed that the number of trucks increases proportionally to the demand of transport. The new driving licence arrangement in Europe limits the possibility to drive commercial vehicles with a passenger car driving license up to a gross load weight of 3.5 t, previously 7.5 t. This change of allowed gross load weight for commercial vehicle leads to a decreasing importance of the weight class from 3.5 t to 7.5 t. Further a shift from truck trailer combinations to (large) articulated vehicles was supposed. This basic assumptions were essential for the national population of commercial vehicles and foreign commercial vehicles participating the German transport system. The chart in figure 7 points out the assumed development of the commercial vehicle population up to the year 2030.

In terms of a business as usual scenario there are no furthermore measures in addition to the existing European emission legislation assumed. Especially no measures to implement soot filters in vehicles area wide were supposed. On a voluntary basis not forced by emission legislation a population share of about 30 % diesel PC with soot filters in the small vehicle class and 16 % in the large vehicle class was assumed. Smaller parts around 10 % were assumed for trucks. In addition a part of efficiency improved vehicles for diesel vehicles between 2 % to 28 % and for gasoline PC between 2 % to 4 % were supposed. The efficiency improved vehicles are characterized by fuel consumption technologies above the normal trend measures. This efficiency increasing technologies can raise the total cost of those cars (e.g. Volkswagen 3 L Lupo). Under these conditions according to the extrapolation of development of future propulsion systems there are already clear reductions of fuel consumptions visible.

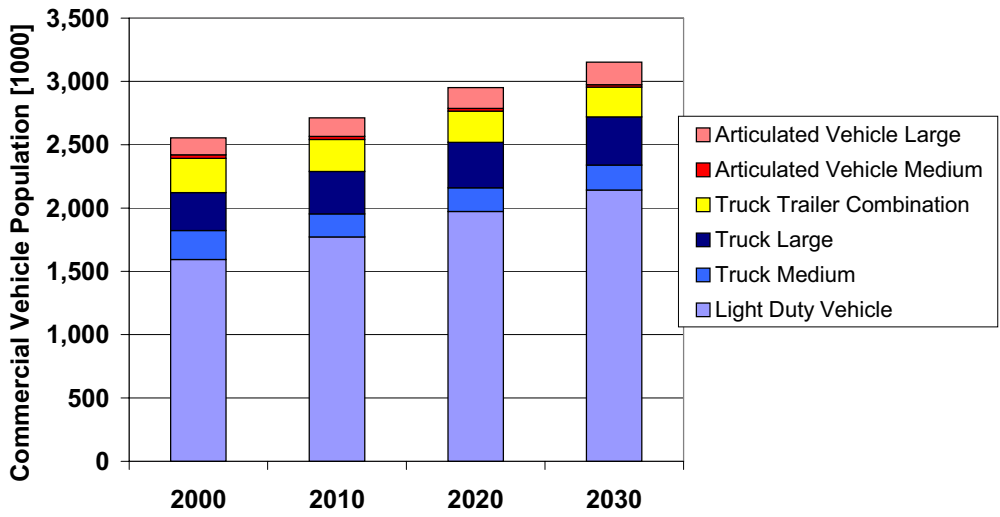


Fig. 7: Assumed development of commercial vehicle population in Germany differentiated according to vehicle types and classes, Basic Scenario

The chart in Figure 8 demonstrates the changes of fuel consumption in comparison to the year 2000 for passenger and goods transport. These fuel consumptions are representative for the population of variously old vehicles and vehicle types.

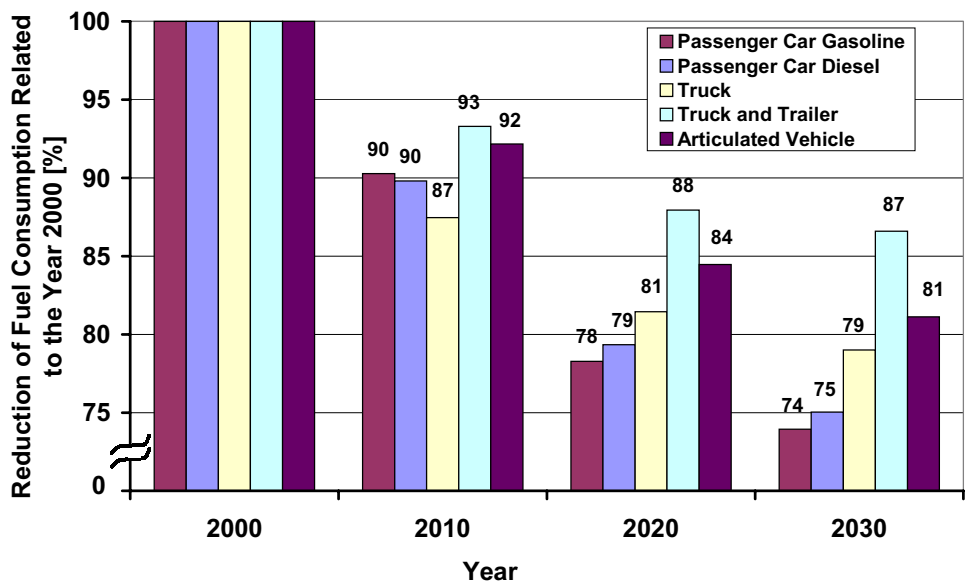
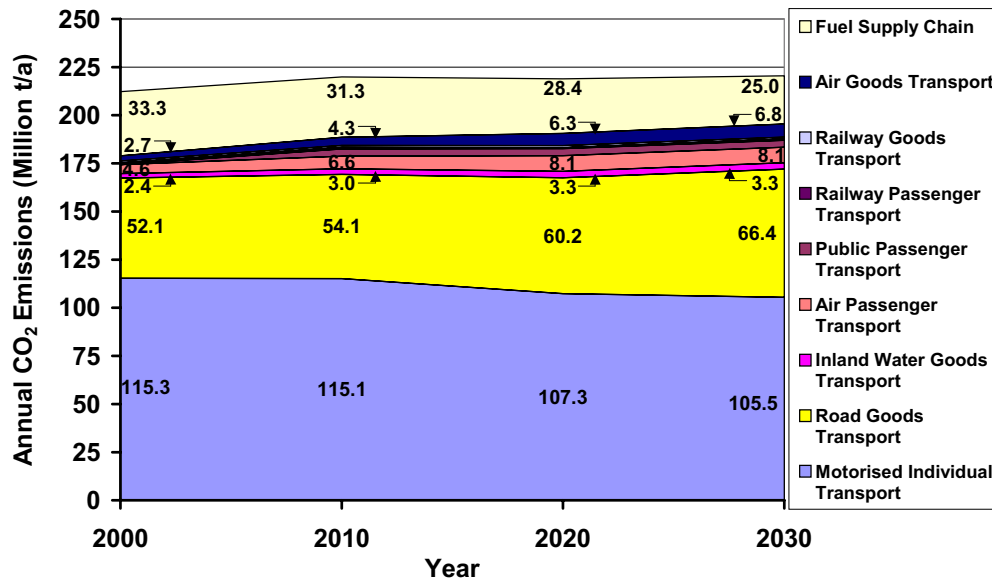


Fig. 8: Assumed reduction of fuel consumption related to the year 2000

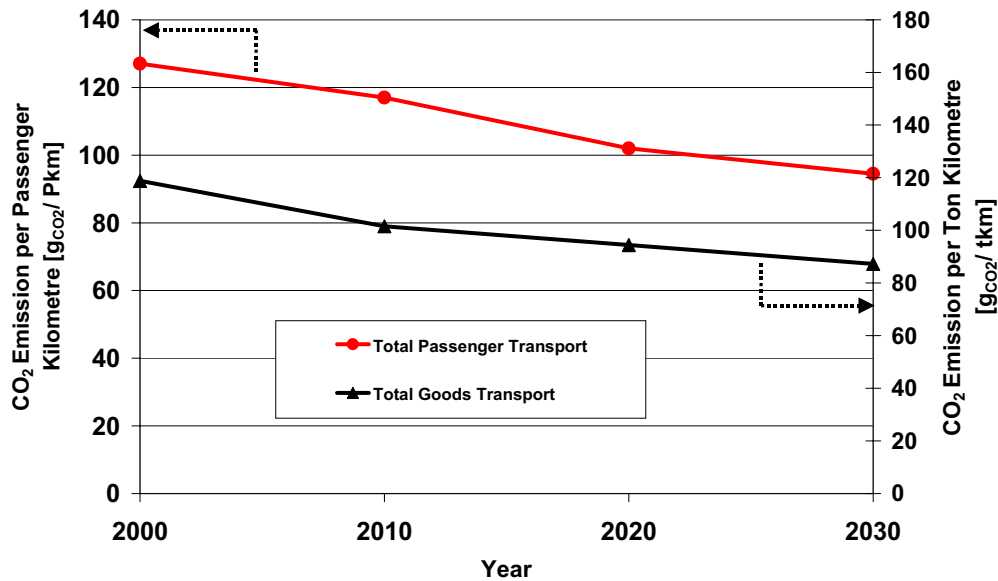
The following figures and remarks indicate an extract of calculated Basic Scenario results based on the already mentioned assumptions. Figure 9 points out the CO<sub>2</sub> emissions of the total transport sector in Germany together with the emissions of the preliminary fuel supply chain. The calculated carbon dioxide emissions are proportional to the demand of energy. In order to keep clearness of the chart the emissions of the fuel supply chain were not allocated to the different means of transport.



**Fig. 9:** Calculated CO<sub>2</sub> emission of vehicle operation differentiated according to means of transport and fuel supply chain, Basic Scenario

The scenario calculations show that the CO<sub>2</sub> emissions of the motorised individual transport clearly decrease (around 10 %) but the emissions of the road goods transport increase around 30 %. These emission trends together lead to a small increase of the total carbon dioxide emissions by more than compensating the reduction effects. In spite of the strong increase of the air passenger transport a small drop of the emissions still arises in the passenger transport sector. However in all means of the goods transport more carbon dioxide is emitted up to the year 2030 so that in total an moderate increase of CO<sub>2</sub> emissions in comparison to 2000 must be expected.

In the passenger and goods transport a decoupling of transport capacity and energy consumption, respectively CO<sub>2</sub> emissions, succeeds (see figure 10). However the transport capacity especially in the goods transport increases so strongly that in spite of these decoupling effects the emission of carbon dioxide does not decrease.

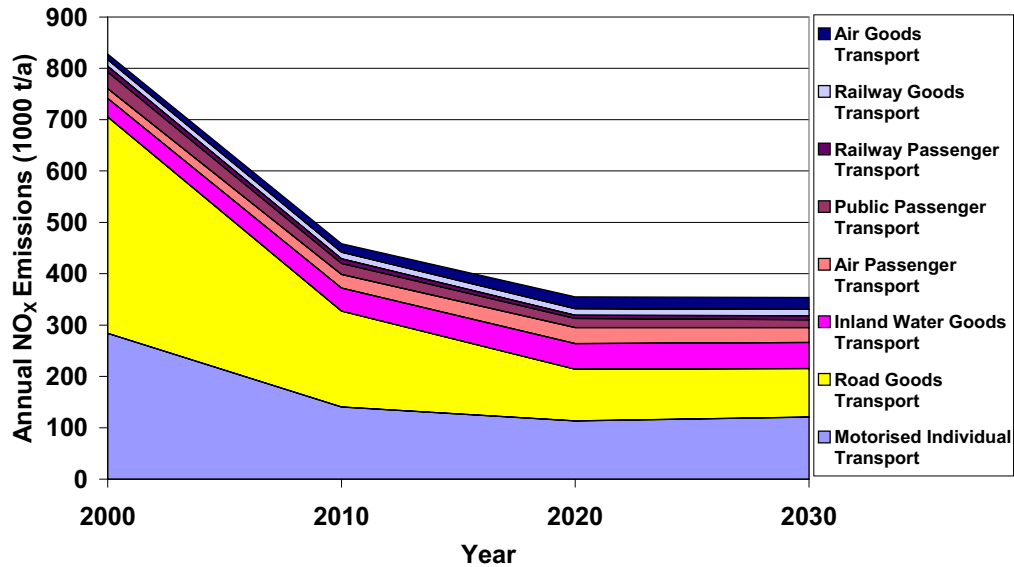


**Fig. 10:** Calculated development of CO<sub>2</sub> emission per passenger respectively ton kilometre of the entire passenger and goods transport (w/o emissions of the fuel supply chain), Basic Scenario

The further development of hazardous emissions in the transport sector limited by emission legislation succeeds in clear reductions: the mitigation of CO emissions reaches about 60 % 2000 to 2030, NMHC emissions will be reduced up to 60 % with increasing trends in the motorised individual transport after 2020, SO<sub>2</sub> emissions decrease about 70 % according to fuel legislation with dropping sulphur contents in gasoline and diesel fuel (after 2005 gasoline and diesel with sulphur content lower than 0.005 weight per cent according to the Auto-Oil-Programme I & II of the European Commission).

The next figures and remarks focus on the situation concerning NO<sub>x</sub> and particle emissions from the transport sector. Figure 11 indicates the trend of NO<sub>x</sub> emissions from vehicle operation differentiated according to means of transport from 2000 up to the year 2030.

The assumed trend results in a reduction around 60 %. This is achieved basically by the drop of emissions in the road transport. The drop of NO<sub>x</sub> emission in the motorised individual transport is characterised by far smaller mitigations than in the goods transport. This is due to the significantly shift from gasoline fuelled passenger cars to diesel cars. A continuation of the emission legislation for passenger cars over the adopted Euro IV level is not assumed because currently this continuation still is in the national and European discussion processes. The NO<sub>x</sub> emission trend of inland water transport is remarkable. In 2000 the shipping transport had a share of about 5 % of the total NO<sub>x</sub> emissions and was rather inconspicuous. But in 2030 the share of inland shipping emissions will be on a level of 15 %. The reason for this trend is the still missing emission legislation for the inland water transport with intensifying limit values for greenhouse and hazardous gases.



**Fig. 11:** Calculated NO<sub>x</sub> vehicle operating emissions differentiated according to means of transport, Basic Scenario

In order to achieve greater reduction potentials of NO<sub>x</sub> emissions it is certainly important to impose emission reduction measures also on shipping transport and to expand existing emission legislation onto this mean of transport.

The emission of particles in the transport sector has also an interesting trend. Figure 12 points out the calculated particle emissions for the assumed technical development.

The share of particle emissions of the inland water transport also becomes more conspicuously from middle of the period. The remarks of the NO<sub>x</sub> emissions are also valid for the trend of particle emissions. Missing emission legislation for water transport has also negative consequences for particle emissions.

The impact of the road passenger transport increases and leads more and more to problematic trends of particle emissions due to the shift from gasoline powered passenger cars to diesel ones. Particle reduction measures like e.g. particle filters were not assumed to be introduced all over the road transport in the calculation. In case that in the period 2010 to 2015 a comprehensively additional launch of particle reduction measures could be reached provoked by legislation or commitments with the vehicle industry, the particle emissions may be decreased in the passenger transport in comparison to the calculated emission values probably around 70 % to 80 % in 2030.

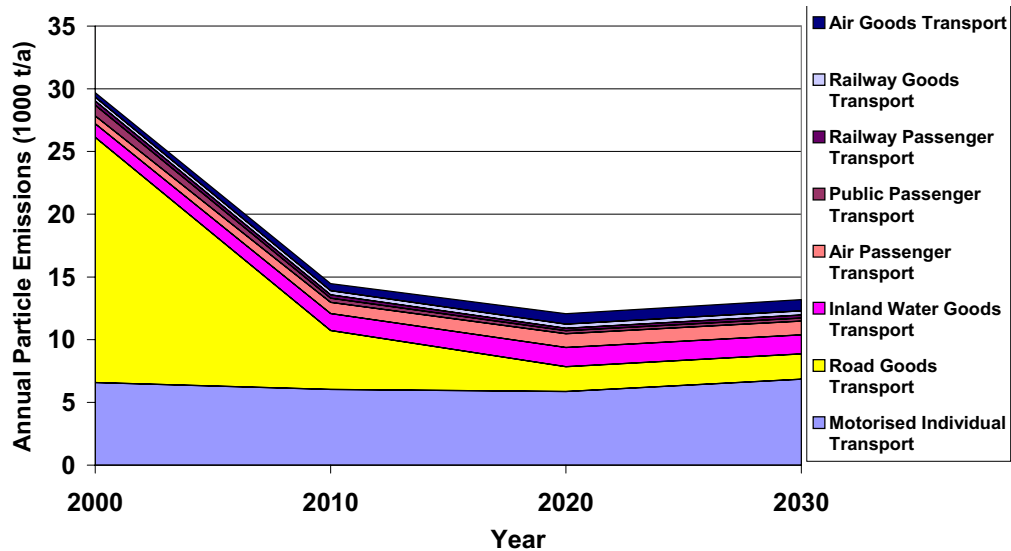


Fig. 12: Calculated particle emissions of vehicle operation differentiated according to means of transport, Basic Scenario

### 3.2 CO<sub>2</sub> reduction scenarios

The application of the transport model together with the scenario technique allows a evaluation of effects caused by different measures concerning the emission situation. In past scenario calculations [IKARUS 1999] it was demonstrated for example that even strong modifications of the Modal Split could reduce carbon dioxide emissions only about maximum 5 % (Frame conditions of the scenario: Shift from motorised individual transport and road goods transport to other means of transport by the extension of public transport capacity around 43 %, railway and bus long-distance transport around 26 %, the pedestrian and bike transport around 24 % respectively the transportation of goods by railway around 24 % and by inland water transport around 8 % ).

Furthermore a study [FZJ 2002] indicates that a possible market introduction of fuel cell passenger vehicles results in a shift of CO<sub>2</sub> emissions from the operation period of the vehicles to the preliminary fuel supply chain. For this scenario it was assumed that due to the currently high specific weights of the propulsion system the fuel cell systems are only suitable for small and medium vehicle classes. With an expected market penetration period of approximately 15 years a share of about 10 % of the passenger car population is replaced in 2020. The attainable calculated reduction of carbon dioxide emissions is under 3 %. This remarks are valid for the assumption that hydrogen will be produced out of fossil energy carriers.

In the reduction scenario of this study the effects of CNG (Compressed Natural Gas) as transport fuel will be investigated. In the assumed CNG Scenario gasoline and diesel vehicles are significantly replaced by natural gas fuelled vehicles. The following reasons lead to the choice of this scenario:

- The CO<sub>2</sub> emission factor of natural gas (55 kg<sub>CO2</sub>/GJ, conditions of complete combustion) is about 25 % lower than that of gasoline (72 kg<sub>CO2</sub>/GJ) and/or diesel (74 kg<sub>CO2</sub>/GJ). Also the efficiency of the fuel supply chain is higher than that of mineral oil products.
- The necessary propulsion technique (including storage systems and filling technologies) is already available for all vehicle classes and a natural gas infrastructure for the German mobile sector is currently in construction.
- The introduction of a compressed natural gas fuelled vehicle fleet, the necessary filling technology and filling stations lead to a smarter shift to compressed hydrogen as fuel whereby the introduction of hydrogen as transport fuel depends on the sustainable and cheap production of hydrogen.

Following aspects were assumed for the scenario calculations:

- After 2005 it was assumed that almost all diesel fuelled buses in the public transport will be replaced by natural gas buses up to 2030.
- By means of a logistic curve a share of 40 % of gasoline passenger cars population and 30 % of the diesel car population will be replaced by CNG fuelled cars from 2005 to 2030. This leads to a share of about 33 % of the total passenger car population in 2030.
- The class of light duty commercial vehicles (national and foreign trucks to 3.5 tons gross load weight) fuelled with gasoline and diesel are also replaced by 10 % CNG vehicles.

The scenario calculations were carried out under same conditions like the Basic Scenario. Figure 13 illustrates the trend of the calculated CO<sub>2</sub> emissions for the CNG Scenario.

The calculated emissions do not fulfil the expectations. Only 8.5 % of CO<sub>2</sub> emissions are reduced in the motorised individual transport, in bus transport only 4.5 % and in road goods transportation very small emission reductions (0.2 %) occur. Only the preliminary fuel supply chain reaches significant carbon dioxide reductions (about 12 %). Due to the effect that other means of transport are not affected by the introduction of natural gas the total CO<sub>2</sub> emissions from the transport sector are only reduced about 4.5 %, respectively about 5 % taking into account the preliminary fuel supply chain.

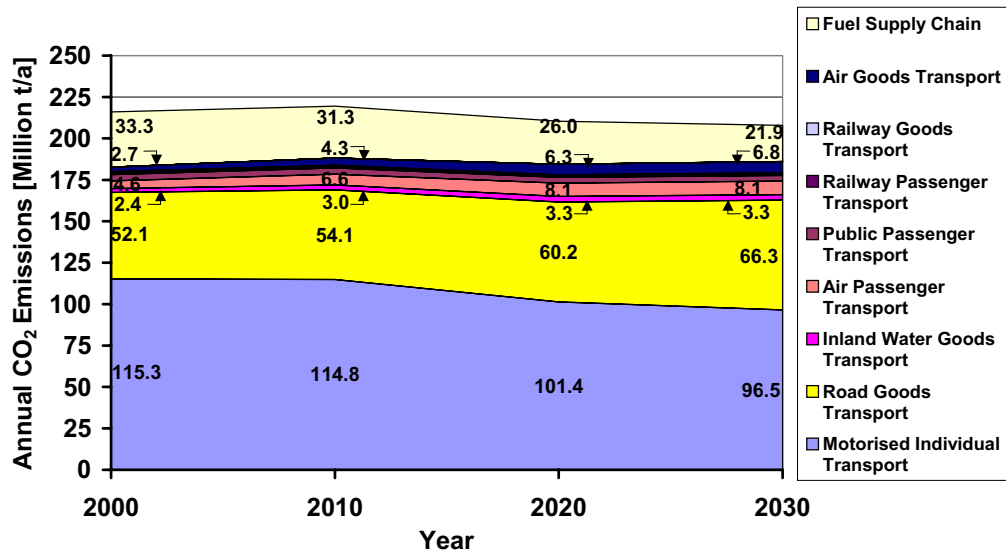


Fig. 13: Calculated CO<sub>2</sub> emission of vehicle operation differentiated according to means of transport and fuel supply chain, CNG Scenario

The comparison of the aggregated PC fuel consumptions explains the small effect (see figure 14). Because of the replacement of modern ICE passenger cars through CNG fuelled passenger cars in the scenario especially for the replacement of new diesel vehicles the CNG cars have higher fuel consumptions between 4 % to 7 % depending on the vehicle class. This additional consumption of CNG vehicles, caused higher propulsion weights and in comparison to the internal combustion process of diesel lower efficiency, partially compensates the lower CO<sub>2</sub> emission factor of the natural gas. The assumed substitution measures were target oriented for a CO<sub>2</sub> reduction scenario because no high efficient heavy duty diesel engines were substituted by natural gas technique.

It could be presumed that a similar introduction strategy of efficiency improved ICE vehicle would have led to similar reduction potentials.

Therefore in a rough calculation for the year 2030 the assumed additional CNG vehicles of the reduction scenario were replaced by the same amount of efficiency improved vehicles. The results of the calculation are illustrated in figure 15 and compared to the carbon dioxide emissions of the Basic and CNG Scenario. The results could be significantly more favourably if the introduction of the efficiency improved technologies is extended to other commercial vehicle classes.

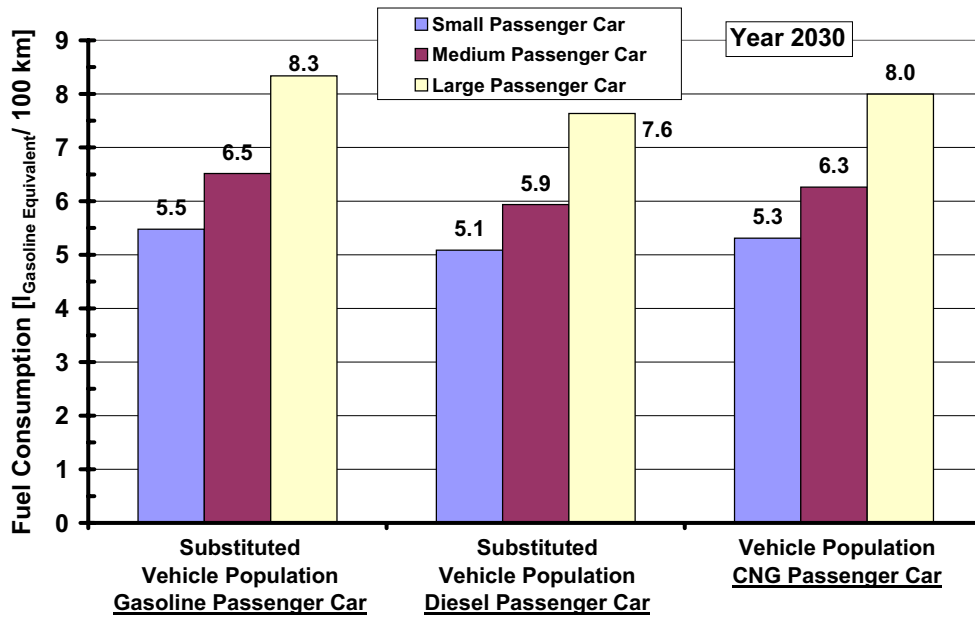


Fig. 14: Comparison of calculated fuel consumptions for the substituted vehicle population in 2030

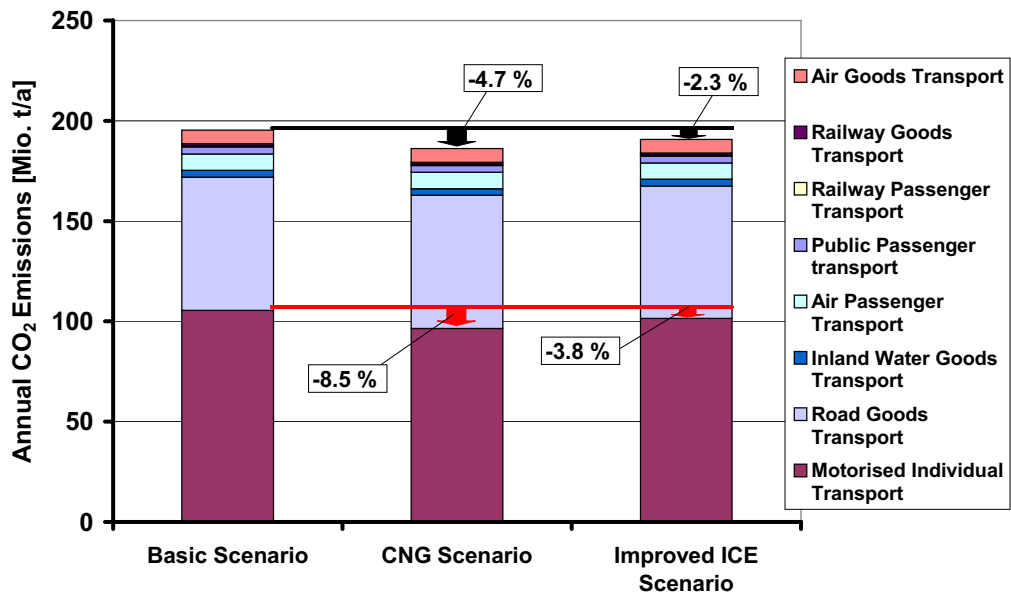


Fig. 15: Comparison of calculated CO<sub>2</sub> emissions in 2030 for the different scenarios

The calculated emission reduction for the efficiency improved vehicle scenario is with approximately 2.3 % half that of the CNG Scenario but the reduction potentials are allocated differently. The reduction potential of the motorised individual transport is about 4.5 percentage points lower in comparison to the CNG Scenario. But in the public transport and road goods transport the emission reduction is about approximately 2 percentage points higher. This is again a hint that only the substitution of gasoline vehicles through CNG fuelled ones leads to real carbon dioxide reductions.

#### 4. Summary und outline

To take care of resources and to obtain mobility for future generation are essential aims of Sustainable Development in the transport sector. The role of politic is to create necessary basic conditions in form of dependable directives. The introduction of carbon reduced and/ or carbon free fuels in transport can be an important choice for achieving national as well as international climate protection aims because transport is one of the essential emission source of greenhouse gases in Europe.

With regard to the presented calculation results and under inclusion of the other studies carried out concerning the introduction of fuel cell vehicles [FZJ 2002] and/ or variation of modal split [IKARUS 1999] it can be concluded that no silver bullet exists for the reduction of CO<sub>2</sub> emission in the transport sector. This conclusion is only valid for the assumption that mobility is not limited in any way. Only with systematic packages of measures emission reductions of 10 % to maybe 15 % with technical and organizational instruments are attainable. Furthermore emission reductions can only be expected on basis of renewable fuels. Measures for the reduction of greenhouse gases and hazardous gases out of transport sector can be summarized to the following points:

- Improvement of efficiency and combustion processes of ICE
- Application of improved non engine measures for exhaust gas treatment e.g. soot filters or catalytic converters especially DeNO<sub>x</sub> catalytic converters
- Increased application of natural gas as fuel in passenger cars and light duty vehicles (in particular substitution of gasoline vehicles)
- Addition of renewable fuels to fossil fuels (diesel and gasoline) in order to increase the share of renewable fuels in the transport sector, see [EU 2003]
- Introduction of hydrocarbons on the basis of carbon-poor or carbon-free energy carriers (e.g. Fischer-Tropsch process in combination with biomass)
- Introduction of fuel cell vehicles with high efficient propulsion systems and simultaneous orientation to an energy sector based on carbon-reduced or carbon-free hydrogen production
- Change of modal split in particular in conurbations areas

The means of transport rail, ship, air and road transport will be embossed in the passenger sector further on by the motorised individual transport. The transportation of goods will be dominated further on by road traffic. The prefaced measures for emis-

sion reductions in the road transport will lead to a shift of hazardous gases proportions to the disadvantage of air and ship transport. The consequence out of this that emission legislation also have to cover these means of transport in order to aim further emission reductions.

## 5 References

### **[Enquete 2002]**

German Cabinet; Study Commission "Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung"; final report; Berlin; Germany; 2002

### **[EU 2003]**

EU Technical Directive 2003/30/EG promotion of the use of bio fuels or other renewable fuels for transport; European Commission; 8.05.2003

### **[FZJ 2002]**

"Brennstoffzellensysteme für mobile Anwendungen"; Biedermann, P; Birnbaum, U.; Grube, Th.; Hake, J.-Fr.; Höhle, B.; Linßen, J; Lokurlo, A.; Menzer, R.; Stolten, D.; Walbeck, M., Energy Technology Volume 19; Forschungszentrum Jülich; Germany; 2002

### **[IFO 2001]**

"Verkehrsprognose 2015 für die Bundesverkehrswegeplanung"; BVU, ifo, ITP, Planco; by order of the German Federal Ministry of Transport, Building and Housing; 2001

### **[IKARUS 1999]**

"Energie- und Emissionsszenarien im Sektor Verkehr"; J. Brosthaus, R. Kober, M. Walbeck, D. Sonnenschein; G. Stein; H-F. Wagner (Hrsg.): Das IKARUS-Projekt: Klimaschutz in Deutschland; Springer-Verlag; Berlin Heidelberg New York; 1999

### **[Prognos 1999]**

"Die längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt"; Prognos/EWI; study by order of the German Federal Ministry of Economics and Labour; Basel; Swiss; 1999

### **[Radke 2003]**

"Verkehr in Zahlen 2001/2002"; German Federal Ministry of Transport, Building and Housing; Deutscher Verkehrsverlag Hamburg; Germany; 2001

### **[UBA 1999]**

"Politiksznarien für den Klimaschutz, Band 5: Szenarien und Maßnahmen zur Minderung von CO<sub>2</sub>-Emissionen in Deutschland bis 2020"; Forschungszentrum Jülich; by order of the German Federal Environmental Agency; Germany; 1999

# Strategy with regard to Fuel-Cell Systems for mobile and stationary applications

B. Hoehlein<sup>\*</sup>; Th. Grube<sup>\*</sup>

## 1 Energy situation

With a growing world population, it is assumed that there will be a greatly increased demand for energy worldwide especially in developing countries. Higher energy prices and a reduction of climate-relevant and local emissions and the associated secondary pollutants brought about by environmental policy will increase the pressure on structural changes for

- improving the local air quality,
- restricting global warming and
- reducing dependence on oil.

An approach towards solving this problem is considered to be an increase in gross national product achieved by applying less and less primary energy and thus of also promoting the application of low-emission and efficient energy conversion systems by the introduction onto the market of low-CO<sub>2</sub> fuels and renewably produced fuels.

Possible Solutions:

- Highly efficient energy conversion systems with fuel cells for vehicles and stationary applications are currently being developed all over the world as a technology which will be able to reduce primary energy demand and emissions of limited and climate-relevant pollutants.
- The high flexibility of fuel-cell systems with respect to the energy carriers used opens up possibilities of changing the energy market in the long term by introducing new fuels.
- In the medium term, but regionally also in the long term, energy carriers other than hydrogen may be appropriate for fuel-cell systems as well. The hydrogen economy will begin in a decentralized manner and grow on the market.

Hydrogen and fuel cells are seen by many as key solutions for the 21<sup>st</sup> century, enabling the clean and efficient production of power and heat from a range of primary

---

<sup>\*</sup> Institute for Materials and Processes in Energy Systems (IWV-3), Forschungszentrum Jülich GmbH

energy sources. The *Vice President of the European Commission, Loyola de Palacio, Commissioner for Energy and Transport, and Philippe Busquin, Commissioner for Research, initiated the High Level Group for Hydrogen and Fuel Cells in October 2002*. The group was invited to formulate a collective vision concerning the contribution that hydrogen and fuel cells could make to the future realization of sustainable energy systems.

A summary report was produced as a communication to the conference “The hydrogen economy – A bridge to sustainable energy” held in Brussels on 16<sup>th</sup> -17<sup>th</sup> June 2003. The terms of reference for the group requested the preparation of a vision report outlining the research, deployment and non-technical actions that would be necessary to move from today’s fossil-based energy economy to a future sustainable hydrogen-oriented economy with fuel cell energy converters<sup>1</sup>.

## **2 Energy carriers**

Many experts expect hydrogen from non-fossil, renewable energy sources to become technically, economically and ecologically important in the next 20 years, although from the present point of view hydrogen still does not play a major part in the energy supply. Wherever hydrogen can be produced in an economically sound and ecologically acceptable manner and supplied to the consumer, it should also be used directly for high-efficiency fuel cells (fleets of vehicles, stationary applications). Other sources of energy must remain under discussion. A future enhanced incorporation of regeneratively produced energy carriers requires sufficiently large potentials, adequate availability along with a competitive cost situation and the creation of new infrastructures. In order to assess the options of future energy supply systems, it will be necessary to determine primary energy demand, CO<sub>2</sub> emission and cost balances from the primary energy carrier at the source or well down to the final energy carrier at the filling station ([LBST 2002], [Grube 2001], [MIT]).

## **3 Energy conversion system: Fuel-Cell Power Trains**

In comparison to internal combustion engines, electrochemical energy converters in combination with electric drives exhibit clear efficiency advantages. The use of fuel cells for power trains permits greater ranges than battery-operated electric vehicles due to the separation of energy converter and energy storage. In addition, fuel cells can also be used as auxiliary power unit for electricity supply on-board conventional vehicles with internal combustion engines.

---

<sup>1</sup> see: <http://europa.eu.int/comm./research/energy>.



#### 4 Well-to-Wheel analyses including FCV and ICEV

For a comparative evaluation, the following **Table 1** shows data for future hydrogen- and methanol-fuelled fuel-cell vehicles on the basis of analyses by Research Centre Juelich [3] in the new European driving cycle comparing them with an assumed gasoline-fuelled passenger car with an internal combustion engine of the future (2005/2010).

		<b>Gasol.</b> (Oil) <b>ICE</b>	<b>Diesel</b> (Oil) <b>ICE</b>	<b>FTD</b> (N.Gas) <b>ICE</b>	<b>C.NG</b> (N.Gas) <b>ICE</b>	<b>C.H<sub>2</sub></b> (N.Gas) <b>FC</b>	<b>IMFC</b> (N.Gas) <b>FC</b>	<b>DMFC</b> (N.Gas) <b>FC</b>	<b>FT-D</b> (N.Gas) <b>FC</b>	<b>Electr.</b> <b>Mix</b> <b>Bat</b>
		<i>Reg.</i>	<i>Reg.</i>	<i>Rem.</i>	<i>Local</i>	<i>Reg.</i>	<i>Rem.</i>	<i>Rem.</i>	<i>Rem.</i>	<i>Reg.</i>
$\eta_{FC}$	[%]	84	92	62	81	64	64	64	62	32
$m_{LDV}$	[kg]	1 064	1 062	1 062	1 064	1 164	1 257	1 202	1 251	k.A.
<b>E<sub>LDV</sub></b>	<b>[MJ/100 km]</b>	<b>153</b>	<b>132</b>	<b>132</b>	<b>145</b>	<b>91</b>	<b>125</b>	<b>111</b>	<b>136</b>	<b>51</b>
$\eta_{LDV}$	[%]	22	25	25	23	39	30	31	27	59
<b>E<sub>FFC</sub></b>	<b>[MJ/100 km]</b>	<b>182</b>	<b>144</b>	<b>213</b>	<b>180</b>	<b>141</b>	<b>194</b>	<b>172</b>	<b>219</b>	<b>160</b>
$\eta_{FFC}$	[%]	18	23	16	19	25	19	20	17	19
<b>CO<sub>2</sub></b>	<b>[kg/100 km]</b>	<b>12.8</b>	<b>10.6</b>	<b>14.5</b>	<b>10.4</b>	<b>8.3</b>	<b>11.8</b>	<b>10.5</b>	<b>15.0</b>	<b>10.0</b>

Additional 2 ... 4 kg<sub>CO2</sub>/100 km for vehicle manufacture and maintenance, ACEA commitment for passenger cars only (2008) and vehicle fleets: 140 g<sub>CO2</sub>/km

Local/Reg./Rem. Local, Regional or Remote (stranded gas) final energy supply (reformer and gas preparation) based on Natural Gas

FTD Fischer-Tropsch Diesel C.H<sub>2</sub> Compressed Hydrogen

IMFC Indirect Methanol Fuel Cell (with reformer) DMFC Direct Methanol Fuel Cell (w/o reformer)

LDV Light Duty Vehicle ICE Internal Combustion Engine Vehicle

FC Fuel Cell Vehicle  $\eta_{FC}$  Efficiency of the fuel cycle

$\eta_{FFC}$  Efficiency of the full fuel cycle (well-to-wheel)  $\eta_{FC}$  Efficiency of the fuel cycle

**Tab. 1:** Well-to-Wheel Comparison of ICEV and FCV [Grube 2001]

The balances include the energy requirements and the emissions of the upstream fuel cycles (well-to-tank) and of the vehicles in the reference driving cycle EURO 4 (tank-to-wheel). In the well-to-wheel evaluation after [Grube 2001] in **Table 1**, directly hydrogen-powered FCVs (C.H<sub>2</sub>) have advantages compared with ICE-LDV in terms of primary energy consumption as well as greenhouse gas emissions. The reference vehicle is an LDV which consumes 5 litres of gasoline per 100 km in the European driving cycle. The advantages are smaller for methanol-fuelled FCVs, but the latter are near-zero emission vehicles (PZEV).

## 5 Energy conversion system: Stationary use of Fuel-Cell systems

The role fuel cells will play in the future will be defined by their economic efficiency and emission regulations. The key uncertainties which could limit the adoption of fuel-cell technology for combined heat and power generation are fuel-cell life and the cost of the fuel-cell system. The start of commercialization of the technology will be facilitated if markets can be identified where fuel-cell systems can be convincingly presented as having unique advantages that might justify higher investments.

The potential mass markets for fuel-cell systems are already provided with a range of technologies for the generation of electricity and heat. These technologies are based on well-established, fully developed and well-proven systems or on newer systems. The types of fuel cells addressed have attained different degrees of progress towards their commercial use [Höhlein 2001], [Höhlein 2000], [SOFC 1999].

Stationary power plants can be used for single houses ( $< 10 \text{ kW}_e$ ), housing estates ( $100\text{-}300 \text{ kW}_e$ ) or for on-site generation plants ( $> 1000 \text{ kW}_e$ ). **Table 2** shows different types of stationary fuel-cell systems of  $100\text{-}300 \text{ kW}_e$  electrical power and their state of development and costs as well as specific costs of conventional CHP plants.

	PEFC	PAFC	MCFC	SOFC
Electric power [ $\text{kW}_e$ ]	250	200	280	100
Electric efficiency ( $\eta_e$ ) [--]	35 %	38 %	48 %	47 %
State of the art	Field test	> 200 plants	Field test	Field test
Specific costs [ $\text{EUR}/\text{kW}_e$ ]	~ 10,000	~ 5,000*	~ 8,000	~ 20,000
Specific Costs, Conventional CHP [ $\text{EUR}/\text{kW}_e$ ]	> 1000 to 500 EUR/kW for < 100 to 1000 $\text{kW}_e$			

**Tab. 2:** Specific costs, state of the art, cost targets for CHP plants with fuel cells

- \* Low cost reduction potentials [VDI nachrichten 22.11.2002]
- \*\* Higher when pressurized and in combination with a gas turbine
- CHP Combined heat and power generation

## 6 Comparison of Fuel-Cell and conventional CHP plants

Electricity generating costs are commonly used as an indicator of the calculation and evaluation of the expected economy of fuel-cell systems compared to conventional systems. The calculation of electricity generating costs is based on the annuity method. In operating stationary power plants, different kinds of payment appear which are dependent on capital, consumption, operation and further payments. Periodically and non-periodically incurred costs with changing values are transformed into periodic constant payments (annuities). The following contributions are involved (see Appendix):

- Capital cost resulting from: investment cost, interest rate and depreciation time
- Natural gas cost resulting from: gas price and operating time of the plants
- Maintenance cost
- Administration and insurance cost

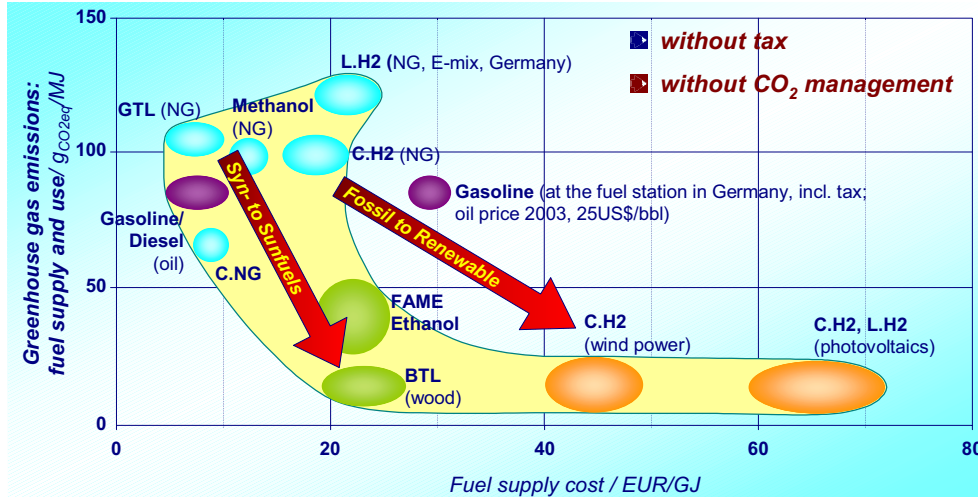
The necessary profitability calculations are dependent on the electricity and heat demand of the customer, the operating and operator models, the local energy carrier situation as well as the system costs. Due to the different electricity and heat shares of the different plant types, comparative calculations are oriented to electricity generating costs and not to investment costs at comparable heat capacity. The following examples in **Table 3** show for the generating costs (considering the new CHP modernization act in Germany, a heat credit of 3 cent/kWh and 2.5 c/kWh natural gas price) that the fuel-cell CHP plants of tomorrow (Case C in **Table 3**) could result in profits comparable to conventional CHP plants at a level of investment costs about twice that of case A. The reason for this is to be found in the different power-to-heat ratios for the same overall efficiency, different maintenance costs and different electricity bonuses for CHP plants without regarding the different CO<sub>2</sub> bonuses. All cases are calculated on the basis of a heat-oriented operation mode of about 200 kW<sub>th</sub> [i.e. 5,000 hours per year full load].

		A: Conventional CHP plant	B: Fuel-cell CHP plant	C: Fuel-cell CHP plant
Power	[kW <sub>th</sub> ]	200	200	200
	[kW <sub>e</sub> ]	127	250	314
Electric efficiency	[--]	35 %	50 %	55 %
Capital investment	[EUR/kW <sub>e</sub> ]	1,000	10,000	2,200
Electricity generation cost (natural gas 2.5 c/kWh)	[c/kWh]	~ 11.7	~ 36.6	~ 11.7
Electricity cost with heat credit (3 c/kWh)	[c/kWh]	~ 7.0	~ 34.2	~ 9.7
Electricity cost with electricity bonus + electricity/heat credit	[c/kWh]	~ - 0.5	~ 23.7	~ - 0.7

**Tab. 3:** Electricity generation costs: FC and conventional CHP( Combined heat and power generation )

## 7 Greenhouse gas emissions and costs of fuel supply

**Figure 2** provides an indication of the relative costs (fuel supply) and greenhouse gas emission levels (fuel supply and use) per megajoule for various fuel chains, including compressed and liquid hydrogen, produced via different routes. Hydrogen costs delivered to the end user will generally be higher than the costs of current fossil fuel options without internalization of external costs.



**Fig. 2:** Specific Greenhouse Gas Emissions Supply and Use as a Function of Vehicle Fuel Supply Costs Based on 1 MJ

BTL	Biomass-to-liquid
C.H2,	Compressed hydrogen
C.NG	Compressed natural gas
E-mix	Electricity mix
FAME	Fatty acid methyl ester
GTL	Gas-to-liquid
L.H2	Liquefied hydrogen
NG	Natural gas

- Non-zero emissions from direct renewable electricity routes result from building and erecting the RES equipment, for which the European mix includes a proportion of fossil fuels and therefore GHG emissions.
- End-use efficiencies will affect the end cost of transport for the consumer. More efficient technologies like fuel cells could allow competitive transport costs with higher fuel costs.
- The above calculations do not include CO<sub>2</sub> savings and related costs that could result from CO<sub>2</sub> sequestration.

Especially hydrogen based on renewable energies will increase fuel costs compared with conventional fuels but at a very low specific CO<sub>2</sub> level. Higher efficiencies of

fuel-cell systems, costs for CO<sub>2</sub> capture and storage or sequestration – necessary for fossil-based hydrogen – as well as bonus points for less specific carbon dioxide emissions and internalization of external costs will modify the figure in terms of EUR/km or EUR/MJ, including fuel supply and use.

## 8 Outlook

Highly efficient energy conversion systems with fuel cells for vehicles and stationary applications are currently being discussed all over the world as a technology which will be able to reduce primary energy demand and emissions of limited and climate-relevant pollutants. A major milestone on the road to market success for all fuel-cell systems – in order to compete with conventional technologies – is the reduction of costs. In this contribution, systems analyses for mobile and stationary applications of fuel-cell systems are presented as well as economic analyses for different fuel-cell systems for stationary applications.

In the well-to-wheel evaluation for mobile fuel-cell applications, directly hydrogen-powered FCVs have advantages compared with ICE-LDV in terms of primary energy consumption as well as greenhouse gas emissions. The reference vehicle is an LDV consuming 5 litres of gasoline per 100 km in the European driving cycle. The advantages are not as great for methanol-fuelled FCVs, but the latter are near-zero emission vehicles (PZEV).

In order to find out whether fuel-cell systems can compete with conventional systems an evaluation of economic efficiency for CHP has to be carried out. A widespread tool for calculating the cost of electricity is the annuity method. The cost of electricity is still very high for fuel-cell systems. Necessary profitability calculations for CHP plants are dependent on the electricity and heat demand of the customer, the operating and operator models, the local energy carrier situation as well as the system costs.

Compared to conventional CHP plants, the future operation of FC-CHP plants may involve higher capital expenditure to achieve comparable profits for identical boundary conditions. The reason for this is to be found in the different power-to-heat ratios for the same overall efficiency, different maintenance costs, and different electricity bonuses for CHP plants not regarding CO<sub>2</sub> bonuses for the reduction of CO<sub>2</sub> emissions.

In spite of a legally stipulated bonus payment for fuel-cell CHP packages in Germany, additional technology support for the first plant series is needed to reduce costs by series production and plant simplification. With respect to a long-term planning and funding horizon additional investment assistance in industrial and state-funded research and development thus appears to be justified.

Hydrogen costs delivered to the end user will generally be higher than the costs of current fossil fuel options without internalization of external costs.

As a whole, the orientation of fuel-cell development is characterized today by the discussion of the “appropriate” fuel (mobile application), the demonstration of the functionality of the technology in application, especially in long-time operation, the

materials optimization required from the present perspective along with a reduction in costs and the feasibility of market penetration (all fuel-cell applications). The start of commercialization of the technology will be facilitated if markets can be identified where fuel-cell systems can be convincingly presented as having unique advantages that might justify higher investments.

## 9 References

### [Höhlein 2002]

Höhlein, B.; *Fuel Cells for Mobile and Stationary Applications - Analysis of Options and Challenges*. World Renewable Energy Congress VII , 29 June - 5 July 2002, Cologne, Germany

### [LBST 2002]

*Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study*. Hart World Fuels Conference – Brussels, 21 May 2002, see also [www.lbst.de](http://www.lbst.de)

### [Grube 2003]

Grube, Th., Höhlein, B., Menzer, R., Stolten, D., *Vergleich von Energieumwandlungsketten – Optionen und Herausforderungen von Brennstoffzellen-Fahrzeugen*. AVL Int. Congress, Graz, 6-7 September 2001

### [MIT]

*On the Road in 2020 – A Life Cycle Analysis of New Automobile Technologies*. Massachusetts Institute of Technology (Cambridge, USA); [www.mit.com/e-lab](http://www.mit.com/e-lab)

### [Höhlein, Nitsch 1998]

*Brennstoffzellenstudie. Ganzheitliche Systemuntersuchung zur Energiewandlung durch Brennstoffzellen*. Project 686, No. 657. Final Report, prepared by Höhlein, B./Nitsch, J./Wagner, U. Forschungsvereinigung Verbrennungskraftmaschinen e.V., Frankfurt am Main, 1998.

### [Höhlein 2001]

*Systemvergleich: Einsatz von Brennstoffzellen in Straßenfahrzeugen*. Studie für Büro für Technikfolgen-Abschätzung, Deutscher Bundestag. Lead author: B. Höhlein, Forschungszentrum Jülich (IWV-3) in Schriften des Forschungszentrums Jülich, Energietechnik / Energy Technology Series, Volume 17, ISSN .1433-5522; see also: "TAB-Arbeitsbericht No. 67, OERTEL/FLEISCHER, TA-Projekt Brennstoffzellen-Technologie Final Report, Büro für Technikfolgenabschätzung des Deutschen Bundestages", [buero@tab.fzk.de](mailto:buero@tab.fzk.de)

### [Höhlein 2000]

Implementing Agreement 026 "Fuel Cells" for International Energy Agency, Annex X: *"Fuel Cell Systems for Transportation"* (1997-1999). Editor. B. Höhlein, Forschungszentrum Jülich, Jülich Germany, in Schriften des Forschungszentrums Jülich, Energietechnik / Energy Technology ,Volume 13, ISSN 1433-5522, ISBN 3-89336-275-4

**[SOFC 1999]**

Simulation der Oxidkeramischen Brennstoffzellen "SOFC" mit nachgeschalteten Gas- und Dampfturbinen-Kombi-Anlagen für verschiedene Brenngase. Fortschritt-Berichte, 6th series: Energietechnik, No. 425, Düsseldorf, 1999.

# LCA and energy technologies

P. Zapp\*

## 1 Introduction

Had the statement of low emissions and a more efficient use of fuel been sufficient to confirm the environmental friendliness of a product or a technology in earlier days, today a more holistic approach is postulated. For instance, during the discussion about the greenhouse effect it became obvious that the treatment of single aspects such as emission, plant or single substance related optimisation is not enough. In consequence a broader approach was established, the Life Cycle Assessment (LCA). Thus, LCA is a tool for the analysis of the environmental burden of a product or a service at all stages in its life cycle, from extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal; in effect from cradle-to-grave.

One advantage of this approach is, that cradle-to-grave analysis avoids shifting problems. It is important not to solve one environmental problem by shifting it to another stage in the product's life cycle. For instance, the production of electric power in a high efficient fuel cell system needs less natural gas than the production in a gas turbine. Nevertheless, the production of the fuel cell system itself consumes much more energy and the lifetime is far less compared to a gas turbine. Only when all these facts are taken into account it can be judged, whether the fuel cell system is truly more environmentally friendly than the gas turbine.

LCA can play a useful role in public and private environmental management in relation to energy technologies. This may involve both an environmental comparison between existing systems and the development of new ones, which also includes comparison of prototypes.

## 2 Life Cycle Assessment – background and motivation

LCA studies the environmental impacts throughout a product's life from raw material acquisition through production, use and disposal. It shows a 30-year history and is harmonised in an international standard as one of several tools to support environmental management on product and company level.

---

\* Programme Group Systems Analysis and Technology Evaluation (STE), Forschungszentrum Jülich GmbH

## 2.1 History

Different actions are understood to be the origin of Life Cycle Thinking. Often, a 1969 study by the Midwest Research Institute in Kansas City on behalf of Coca-Cola is stated as the first official material balance. In this study different packaging systems for Coca-Cola products were compared. Studies considering energy aspects came up in the mid-seventies following the energy crises. One benchmark of energy analysis is the "Handbook of Industrial Energy Analysis" by Boustead and Hancock [Boustead 1979] published in 1979, which deals with methodological questions in energy analysis, but also gives an extensive collection of energy demands for different processes and products. To meet the increasing requests on data, several industries such as the plastic and aluminium industry, set up profile reports to assure consistent data about their products [Boustead 1993, EAA 1997/2000]. The newest and probably most used database for energy technologies is located at the ETH Zurich, Switzerland. In the 1993 first published "Ecoprofiles for Energy Systems" a basis for life cycle assessment of energy generation was provided, which was recently included in the Swiss Center for Life Cycle Inventories [Ecoinvent 2003].

Beside energy systems, packaging and building materials are the most frequently investigated systems. In addition to the taking of material and energy inventories the Swiss environmental agency BUWAL included also possible resulting impacts and the interpretation of the results in their packaging study in 1991 [Habersatter 1991]. As a consequence of the variety of investigated systems and participating practitioners the request for harmonisation became obvious. Under the umbrella of the Society for Environmental Toxicology and Chemistry (SETAC) a discussion forum for science, industry and policy in Europe, North America and nowadays also in Asia was implemented, which yielded in the establishment of the international standard series EN ISO 14040 ff "Environmental management – Life cycle assessment". The first standard ISO 14040, Principles and framework [ISO 1997], was published in 1997, followed by ISO 14041, Goal and scope definition and inventory analysis [ISO 1998], in 1998 and the ensuing impact assessment [ISO 2000] and interpretation [ISO 2000a] in 2000. However, in contrast to other standards, where for instance detailed descriptions of procedures are given, the LCA standards leave the freedom to use different methods, to choose system boundaries and scopes. Regulated are only the transparent use of a method and the precise description of the final decisions.

## 2.2 Definition and methodological framework

In ISO 14040 LCA is defined as "a technique for assessing the environmental aspects and potentials impacts associated with a product, by:

- Compiling an inventory of relevant inputs and outputs of a product system;
- Evaluating the potential environmental impacts associated with those inputs and outputs;
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."

Figure 1 depicts the rough classification of LCA in the four phases of goal and scope definition, inventory, impact assessment and interpretation and their interrelations.

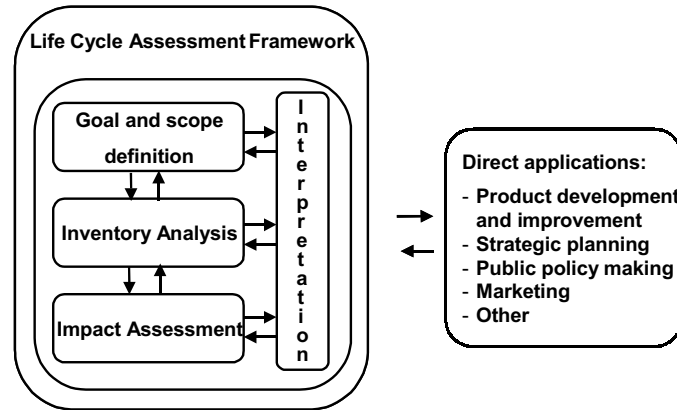


Fig. 1: Phases of an LCA according to ISO 14040 [ISO 1997]

The first phase is the goal and scope definition. Contents of the goal definition are the description of the intended application, the reason for carrying out the study and the intended audience, i.e. to whom the results are intended to be communicated. The scope definition includes the description of the investigated system, the functional unit, the system boundaries and the considered impact categories.

The *inventory* analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the investigated product system. Beside the main process route auxiliary products, transports and energy supply can be considered. In most cases the inventory is the most complex and time-consuming element of the LCA.

The inventory constitutes the input to the *impact assessment*. In this third phase the significance of potential environmental impacts associated with the inputs and outputs of the investigated system are evaluated, through the assignment of inventory data to impact categories, the modelling within these categories and a possible aggregation of the results.

During the *interpretation* phase the results of the inventory and the impact assessment are combined consistent with the defined goal and scope in order to reach conclusions and recommendations.

As mentioned before, the ISO standard leaves room for interpretation and value choices. The Dutch Institute of Environmental Science in Leiden, NL (CML) has released a detailed "operational guide" to the ISO standards, to support step-by-step LCA [Guinée 2002].

2.3 Positioning of LCA in environmental management systems

LCA is one of many instruments to analyse and support decisions in environmental management, where impacts on the environment are quantified. However, LCA is not always the appropriate tool to answer every question in every situation. Therefore, before an LCA will be started, it has to be made sure that LCA is the right instrument.

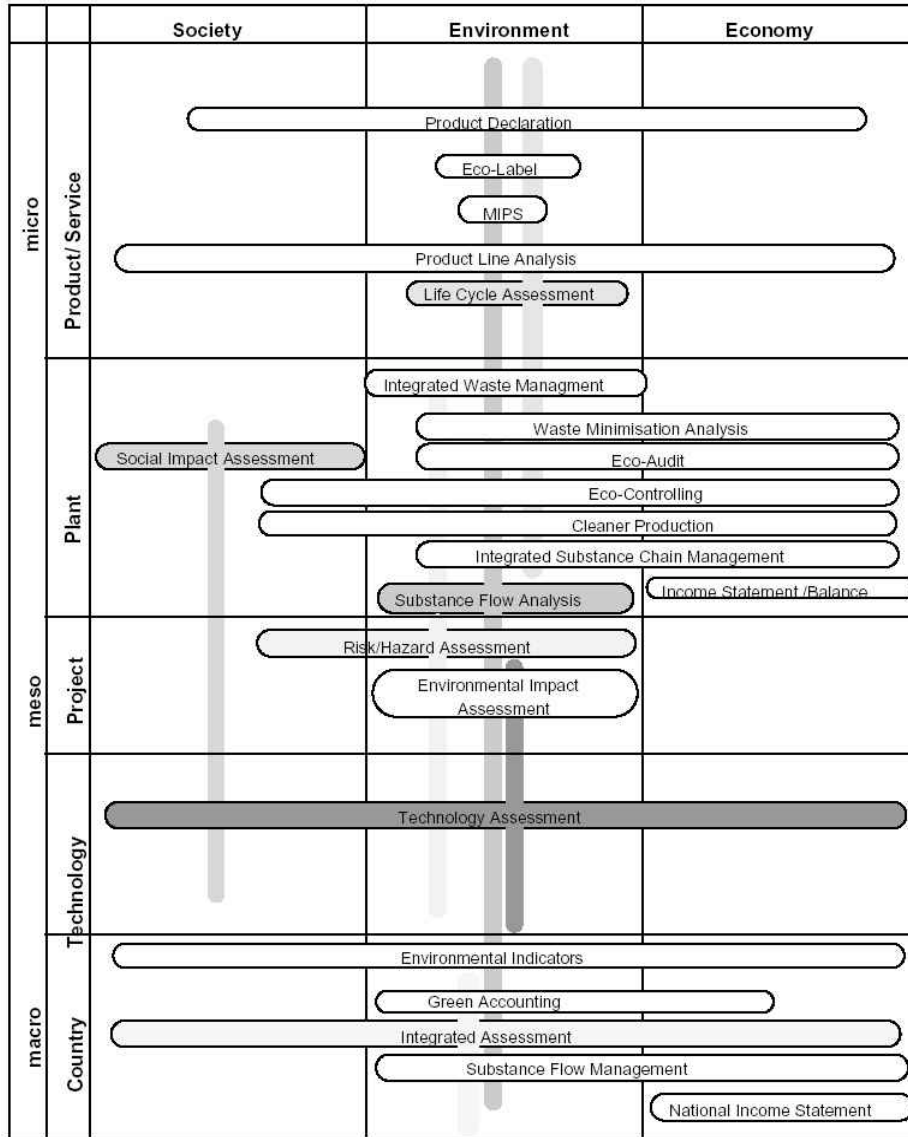


Fig. 2: Structure of decision supporting instruments in environmental management according to Hofstetter 1998 [Hofstetter 1998] (the vertical pillars illustrate covered analysis levels and can be attached to the different instruments by their colour)

In Figure 2 different important decision supporting instruments are structured according to the economic level of the object (micro to macro) and the dimension of sustainability (society, environment, economy) [Hofstetter 1998]. LCA is an instrument to analyse the environmental dimension on the micro level, i.e. products, services and to some extent also plants. When additional relevant life cycle related impacts of a product on economy or society shall be investigated a Product Line Analysis is a better tool.

#### 2.4 *Limits of LCAs*

LCA provides information about environmental aspects connected with the use of a product or a service. Still, decision-making processes demand additional information about ecological, technical and social aspects. The strength of the broad scope of analysing the complete life cycle can only be achieved at the expense of simplifying other aspects. Therefore, LCA cannot replace the decision making process itself but supports it.

Although LCA aims to be scientific-based, it involves a number of technical assumptions and value choices. An important aim is therefore, to make these assumptions and choices as transparent as possible. To optimise the decision support it is helpful to match the value choices of the decision maker.

A more practical limitation can often be found in the availability of data. Even though databases are being developed, in practice data are frequently obsolete, incomparable or of unknown quality. Again, a full and transparent documentation helps to evaluate the results.

Nevertheless, the increasing use of LCA and the ongoing scientific discussions emphasise the acceptance of LCA as an environmental management tool.

### **3 Procedure of LCA in energy systems analysis**

The following chapter describes again the four phases of LCA, this time in more detail and with special regard to energy systems analysis. It is based on the ISO standard. Since the standard represents only the consensus recent developments and additional aspects are also included in this paper.

#### 3.1 *Goal and scope definition*

The goal and scope definition is the phase in which the initial choices which determine the working plan of the entire LCA are made. The first step involves stating and justifying the goal of the LCA study, explaining the aim and specifying the intended use of the results, the initiator, the practitioner, the stakeholders and the intended user of the results. The scope definition establishes the main characteristics of the study, precise description of the investigated product, temporal, spatial and technological coverage, methodological choices and the overall sophistication of the study.

### 3.1.1 Functional unit and reference flows

The definition of the functional unit is the core step of every LCA. The functional unit quantifies the performance of a product system for use as a reference unit in a life cycle assessment study [ISO 1997]. It therefore describes how many of the functions of a product are to be considered in the study and will be used as basis for selecting one or more alternative product systems. The system may have a number of possible functions but the selected ones for the study are depending on the goals and scope.

Looking at energy systems for example, it has to be defined if electrical power production exclusively shall be considered or combined heat and power production shall be investigated. This determines the energy systems, which provide the product(s) and can therefore be compared.

Alternative product systems can be declared functionally equivalent and reference flows will be determined for these systems, which must be measurable. For instance, one could define the functional unit of a service as the drying of 100 hands. Systems, which can provide this service, are textile or paper towels or an air hand dryer. The reference flows for the systems are m<sup>2</sup> textile or paper towel and m<sup>3</sup> hot air flow. If an additional requirement is the functionality in an isolated area without power supply, the air hand drier cannot be included in the comparison.

It is important that the definition of the functional unit includes quality aspects of the product to ensure the equality and therefore comparability of two product systems. For instance, if different heating systems shall be compared on basis of 1 kWh delivered final energy, also specifications about temperature level of the heating circle, flow requirements and the maximum output are important. For electricity supply a differentiation of base or peak load can be of interest.

### 3.1.2 Description of the product system and system boundaries

The next step after the definition of the functional unit is the description of the investigated system, which meets these criteria. As data quantity and requirements as well as the discussion of the results increases with complexity of the system, the aim must be a minimum representation of the system, which is necessary to serve the goal and scope.

The system boundaries determine which processes shall be included within the LCA. The LCA distinguishes three types of boundaries:

- The boundary between the product system and the environment;
- The boundary between processes that are relevant and irrelevant to the product system;
- The boundary between the product system under consideration and other product systems.

Looking at electricity production for instance, it must be defined whether the transmission of electricity to the local end user, with its additional losses, is included or the system boundary is drawn at the power plant. Another system boundary must be set describing the spatial coverage of the system, i.e. country mix, UCPTE mix or local supplier, which then defines the share of energy carriers.

Especially for electrical energy systems, but also in many other applications, the time relation is important. As, for example, the share of energy carriers in national grids in Europe is recorded on a yearly base and changes can be seen it is necessary to specify the accounted year. Also considered import and export structures vary over time.

The results of an LCA are therefore only valid for the defined year and system. A transferability of the results to other years or systems must be checked carefully regarding the system boundaries.

### 3.1.3 Choice of impact categories

Main subject of an LCA is the analysis of impacts on the environment. In the goal and scope definition it must be decided which environmental problem is considered relevant for this investigation. Normally, a full LCA covering all recommended impact categories (described in Chapter 3.3.1) is performed, but some investigations allow a reduction of considered aspects. In the analysis of the environmental impact of a product with regard to the Kyoto Protocol for example, it is mandatory to look at the impact category of climate change but not at e.g. acidification or others. This reduces the expenses of the performed LCA and therefore time and costs.

### 3.1.4 Quality aspects

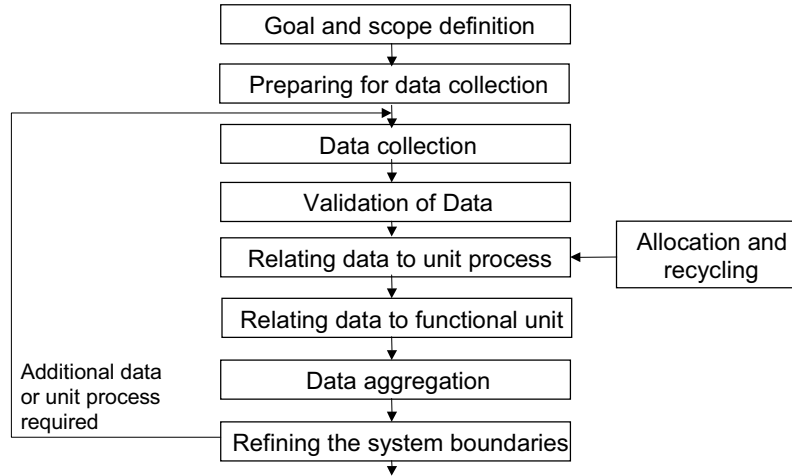
Descriptions of data quality are important to understand the reliability of the study and properly interpret the outcome of the study. Data requirements for the study must be defined regarding precision of the data, completeness, representativeness, consistency and reproducibility. Even if the quality of individual data sets is high, however, such data can still yield erroneous results when used to answer questions on which they have no bearing. It can be distinguished between so-called "foreground data", which are case-specific primary data and so-called "background data", e.g. power supply, which can be gathered from more general sources.

The quality assurance can be an internal procedure, but an external, independent panel of peers can also perform it. According to the standard latter is required when a comparative assertion is disclosed to the public.

## 3.2 *Inventory analysis*

Core element of every LCA is the inventory phase. Within the inventory the data related to the investigated system are gathered. It is, in fact, the most objective phase of an LCA and describes the investigated system by its inputs from and outputs to the environment quantified and calculated in a model. The main outcome is an inventory table of the results, which is then either used to carry out the impact assessment or interpreted in itself according to the goal and scope. Studies, leaving the impact assessment out are called Life Cycle Inventories (LCI) and can be found for many products. The earlier stated ecoprofiles of energy systems of the ETH Zurich is one typical example of an LCI.

The operational steps in the inventory analysis according to ISO 14041 standard are outlined in figure 3. Its main steps are the preparation of data collection followed by the iterative process of data collection, aggregation and validation of the obtained results, which can yield in new data collection and calculation regarding the goal and scope of the study.

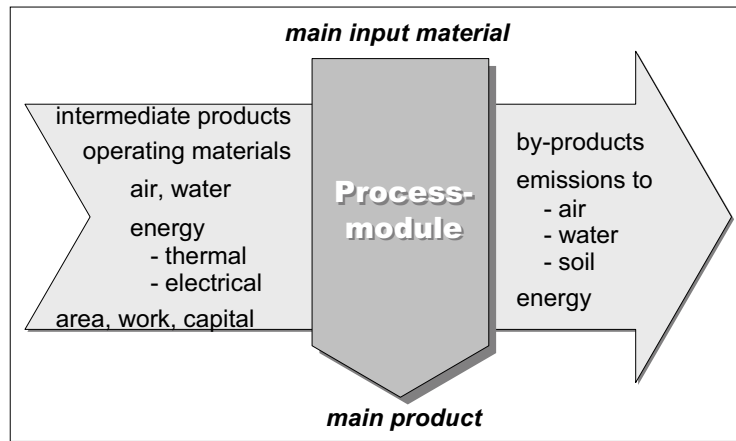


**Fig. 3:** Simplified procedures for inventory analysis according to ISO 14041 [ISO 1997]

### 3.2.1 Preparation for data collection

The descriptive definition of the investigated system during goal and scope definition is concretised in the inventory phase by setting up a so-called flow diagram, in which the investigated system is subdivided into smaller units, the modules. The flow diagram provides an outline of all major processes to be modelled, including their relationship. The use of the product is the central element; starting from here the processes ramify “upstream” to the different resources used and “downstream” to the different ways of recycling or waste management involved. Flow diagrams can be done at different levels of complexity according the goal and scope of the study, the most complete being a diagram in terms of unit processes.

The smallest portion of a product system for which data are collected when performing an life cycle assessment is called a unit process. Figure 4 specifies the main input and output categories, which must be considered in a unit process and for which data must be collected. The different unit modules are then combined to the flow diagram.



**Fig. 4:** Input and output categories of a unit process

### 3.2.2 Data collection

Often, data collection is the most challenging issue of an LCA. Existing data are either obsolete, variable or secret. A thorough knowledge about each unit process is necessary to set up the data. The procedure used for data collection varies for each unit process. LCA practitioners often do not and cannot have the insight in all processes of the complex system. Therefore, close cooperation of LCA practitioners, process operators and scientists is essential.

As time is often a limiting factor, it is important to prepare questions and data sheets, which consider the means of the partners. Hence, information and data have to be further processed, so that they can be included in a process description. For instance, LCA data are organised around the related reference flow. Process data provided by companies are often given in terms input or output per time, e.g. x tonnes CO<sub>2</sub> per year.

To avoid double counting or gaps, the description of each unit process shall be recorded. The more information to data provider is given, the more comparable data can be gathered. Setting up unit processes or connecting the unit processes using different data sources the data must be validated and if necessary other sources consulted. Similarly, missing data should be identified and a decision made how to handle the data gaps. The time necessary for data collection is often underestimated.

### 3.2.3 Allocation and recycling

In practice, few industrial processes yield a single output or are based on a linearity of raw material inputs and outputs. In fact, most industrial processes yield more than one product, and they recycle intermediate or discarded products as raw materials. This leads to the problem, how to adequately allocate the materials and energy flows as well as associated environmental releases to the different products. Although this problem is considered in the ISO standard, it still causes discussion within the LCA community, what appropriateness means. The ISO 14041 standard provides a three tier procedure how to handle allocation:

Step 1: Whenever possible, allocation should be avoided by:

- a) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes,
- b) expanding the product system to include the additional functions related to the co-products taking into account the data requirements.

Step 2: Where allocation cannot be avoided, the system inputs and outputs should be partitioned in a way, which reflects the underlying physical relationship between them; e.g. mass, energy, density relation.

Step 3: Where physical relationship alone cannot be established or used as basis for allocation the inputs should be allocated in a way, which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

When companies producing different product in one plant publish emission figures in environmental reports of this location, for instance, avoidance through division into sub-processes might be possible. Additional information about processes is necessary. If some emissions only occur due to the production of one product, this emission can then be allocated exclusively to this product while the other products are free of this emission. Nevertheless, this additional information is often not accessible and allocation cannot be avoided.

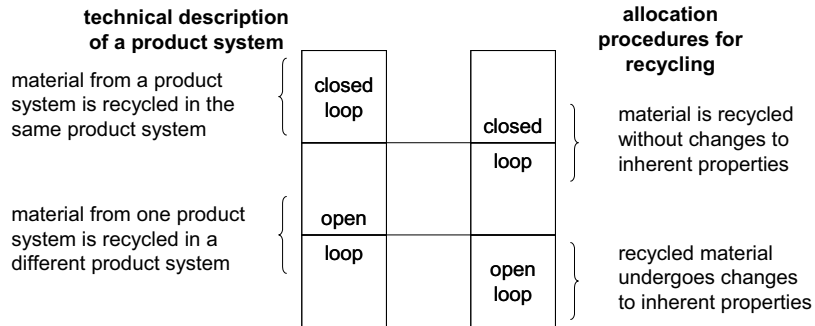
The most often used allocation method is still the consideration of physical relationship and thereof the mass relation. For transportation this is the appropriate method if the limiting factor is the mass, e.g. transport of heavy goods. Is the limiting factor for the cargo the space, as it is in packaging systems, density is the more appropriate function. For combined heat and power production, with its energies of different values, exergy might be the best relation.

Lately, the third step, the economic allocation becomes more and more important. During the production of copper from primary ore, a small amount of precious metals is produced. An allocation regarding mass would leave most of the burden to the copper product. But some of the copper producers are only able to do so because of the prices they achieve by selling the precious metals. Hence, the economic relation is the suitable allocation method. Objections against this third step of allocation are due to the fact that prices are time dependent and therefore reproducibility is not given. Nevertheless, if the gold price for example would break down, some producers might have to stop their production and allocation is pointless anyway.

The aforementioned allocation principles and procedures also apply for reuse and recycling situations. However, these situations require additional elaboration for the following reasons:

- Reuse and recycling may imply that the inputs and outputs associated with unit processes are to be shared by more than one product system;
- Reuse and recycling may change the inherent properties of materials in subsequent use;
- Specific care is needed for system boundaries definition regarding recovery processes.

In LCA it is distinguished between closed-looped and open-looped recycling. It must be differentiated between a technical description of a product system and allocation procedures for recycling. Figure 5 illustrates the conceptual differences of the two procedures according to the ISO 14041 standard.



**Fig. 5:** Distinction between a technical description of a product system and allocation procedures for recycling according to ISO 14041 [ISO 1997]

Clear definition of when to use which allocation in LCA for multifunctional systems as well as for reuse and recycling is not being given and subjective choices influence the decision and, of course, the result. In table 1 different allocation factors are given for a CHP system considering energy, exergy and price relations [Frischknecht 2000].

	energy	exergy	price
heat	0.64	0.25	0.38
el. power	0.35	0.75	0.62

**Tab. 1:** Allocation factors for heat and electrical power production of a CHP process considering different relationships [Frischknecht 2000]

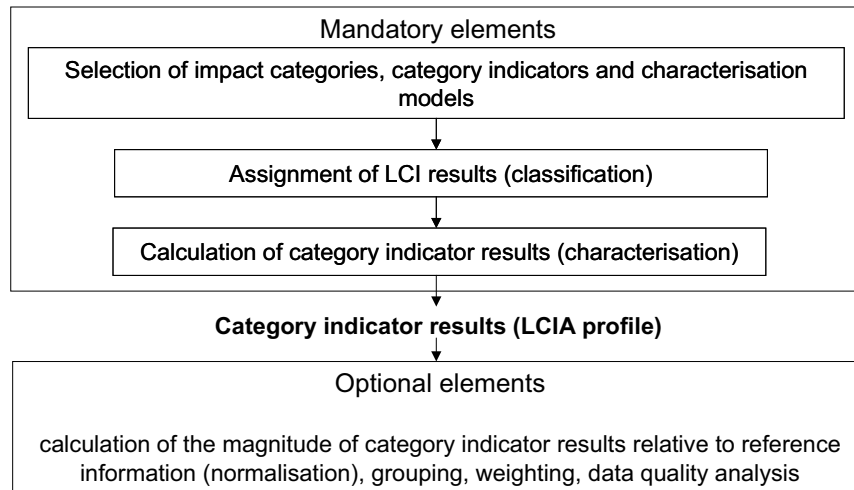
It can be seen, that the factors vary widely and while exergy and price factors show the same valuation, with el. power having the higher factor, the allocation considering energy has it in an opposite way. This will also have an impact on the final results and therefore on the drawn conclusion.

Allocation for reuse and recycling shows the problem of legislation differences in a worldwide system. While waste in one country has to be recycled it can be dumped in other regions. These discussions are not LCA specific. All the more clear and transparent documentation is necessary, where the subjective choice is explained and the impacts of choosing one or the other allocation method is shown.

### 3.3 Impact assessment

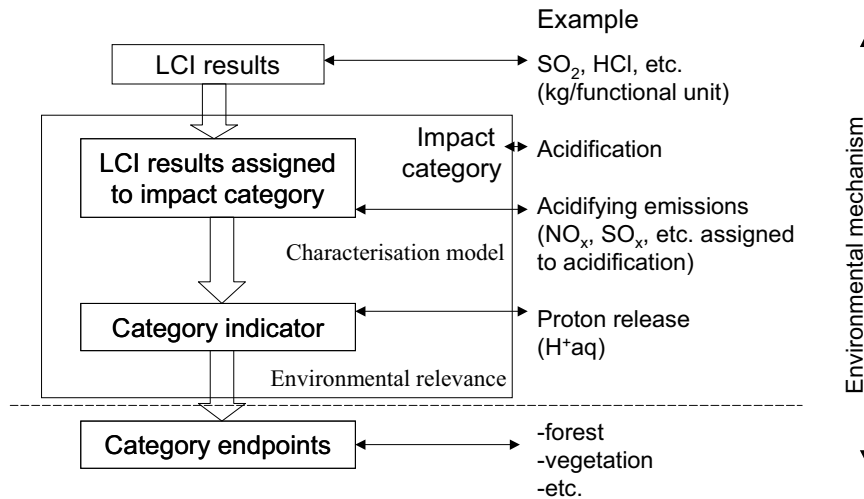
In the Life Cycle Impact Assessment (LCIA) the comprehensive set of results of the inventory is condensed for better communication and/or decision support. Therefore,

the data are further processed and interpreted in terms of environmental impacts and societal preferences. To identify possible environmental impacts a list of impact categories is defined, and models for relating the environmental interventions of the inputs and outputs are selected. The actual modelling results are calculated in the characterisation step. In figure 6 these three mandatory elements of the impact assessment together with the optional elements of normalisation, grouping and weighing are indicated. The latter two are used to include societal preferences of the various impact categories.



**Fig. 6:** Elements of the LCIA phase according to ISO 14042 [ISO 2000]

In LCIA studies normally no research of environmental impact mechanism is performed, but rather existing models are selected to express the interventions. Therefore, the ISO standard also describes procedures rather than specific methodologies or models. In the impact assessment the data of the inventory are translated to contributions to selected impact categories, such as climate change, acidification, ozone depletion, etc. The contributions are calculated using characterisation models, in which relevant environmental processes are modelled to so-called category endpoints. For example, the climate change impact category represents emissions of greenhouse gases (LCI results) using infrared radiative forcing as the category indicator. Figure 7 summarises the overall framework of LCIA, showing the relationship between LCI results, impact categories, category indicators and category endpoints, all illustrating these concepts with reference to the impact category "Acidification".



**Fig. 7:** Conceptual framework for defining category indicators according to ISO 14042 [ISO 2000]

### 3.3.1 Selection of impact categories

To facilitate the work of LCIA practitioners a SETAC working group has elaborated a default list of impact categories, thereby distinguishing between baseline, study-specific and other impact categories. Table 2 list the impact categories. Nevertheless a selection from this list can be made according to the goal and scope of the study.

Baseline	depletion of abiotic resources; impacts of land use/land competition; climate change; stratospheric ozone depletion; human toxicity; ecotoxicity: freshwater aquatic., marine aquatic., terrestrial.; photo-oxidant formation; acidification; eutrophication
Study-specific	impacts of land use: loss of life support function, loss of biodiversity; ecotoxicity: freshwater sediment, marine sediment; impacts of ionising radiation, odour: malodorous air; noise; waste heat; casualties
Other	depletion of biotic resources; desiccation; odour: malodorous water

**Tab. 2:** Default list of impact categories and subcategories

The baseline impact categories are included in almost all full LCA studies. For each impact category a characterisation method was elaborated, although for some categories, e.g. ecotoxicity, the discussion is still going on which model is most appropriate.

### 3.3.2 The impact category climate change

As an example for the characterisation method the climate change impact category is chosen:

Climate change is defined as the impact of human emissions on the radiative forcing of the atmosphere, causing the temperature at the earth's surface to rise. This is popularly referred to as the "greenhouse effect". The areas of protection are human health, the natural environment and the man-made environment.

Radiative forcing by (anthropogenic) emissions is the most appropriate midpoint for the impact category. For modelling purpose the closely related global warming effect is used as an indicator.

The international Panel on Climate Change, IPCC, has developed a model to show the global warming potential (GWP). GWP is normalised with regard on mass unit of carbon dioxide CO<sub>2</sub>. Different time horizons are considered (20, 100, 500 years).

Table 3 shows some greenhouse gases and their global warming potential according to the three time horizons.

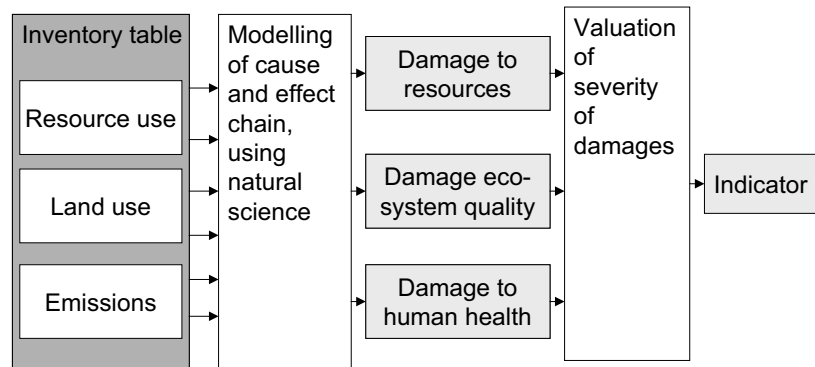
Compound	GWP 20	GWP 100	GWP 500
CO <sub>2</sub>	1	1	1
CH <sub>4</sub>	64	24	7.5
N <sub>2</sub> O	330	360	190
SF <sub>6</sub>	15100	22200	32400
Chloroform (CHCl <sub>3</sub> )	55	16	5
Tetrafluoromethane	3900	5700	8900

**Tab. 3:** GWP of selected emissions

### 3.3.3 Mandatory LCIA elements

The list of impact categories is still long and many decision makers demand a "clearer" picture of the results. Sometimes a normalisation is helpful to classify the results by relating the obtained results to reference information, e.g. CO<sub>2</sub> of the investigated product system in relation to the total CO<sub>2</sub> emissions of a country, over a given period of time. Thus does not reduce the amount of indicators but relates the results to other systems.

A decrease of indicators can be reached by grouping and weighting. The most recent studies where the reduction of indicators is reached by assigning the impact categories to damage pattern are the Dutch Ecoindicator 99 [Goedkoop 2000] and the Swedish Environmental Priority Strategy system (EPS) [Steen 1999], where the indicators are consolidated according to issues of concern, e.g. resources, human health, etc. Figure 8 describes roughly the concept of the Ecoindicator 99.



**Fig. 8:** Concept of the Ecoindicator 99

This reduction of indicators is subject of lively discussion, as many practitioners criticise the missing transparency of the models. On the other hand, it cannot be concluded that a complex list of indicators gives a clearer picture. Nevertheless, the reduction to one indicator does not reflect the manifold information possibilities.

### 3.4 Interpretation

In the interpretation phase the results (of either LCI or full LCA) and all choices and assumptions made during the analysis are evaluated in terms of soundness and robustness. Final, overall conclusions are drawn and recommendations are given considering the goal and scope of the study.

The evaluation of the results is done by consistency and completeness checks. The objective of consistency check is to determine whether the assumptions, methods, models and data are consistent with the goal and scope of the study. The completeness check ensures that all relevant information and data needed for the interpretation are available and complete. In a sensitivity and uncertainty analysis the influence on the results of variations in process data, model choices and other variables are assessed in order to determine the robustness of the results.

In the last step of the interpretation phase, conclusions are drawn and recommendations are made to the intended audience of the study, based on the information gathered, for instance as to product choices or improvements.

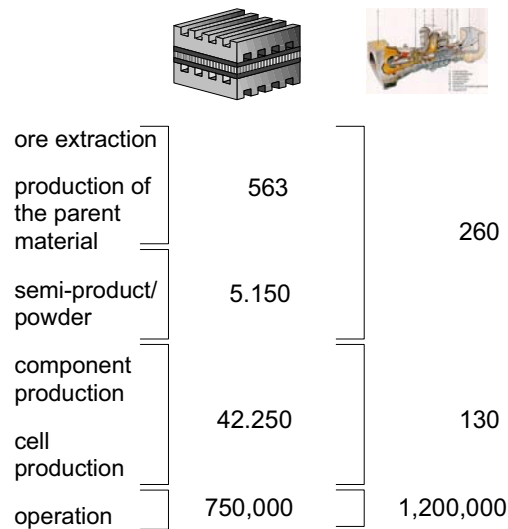
## 4 Examples

Many studies concerning energy technologies or energy intensive materials are available. Below, exemplarily results of two studies of the Forschungszentrum Jülich are given. In the first study a material and energy balance of a Solid Oxide Fuel Cell (SOFC) system was compared to that of a gas turbine. A second study had the energy intensive material Aluminium as subject of the investigation.

#### 4.1 Solid Oxide Fuel Cells

The development of the SOFC in the Forschungszentrum Jülich was assisted by a material and energy analysis [Zapp 1998]. Goal of the study was the comparison of a technology, which was in an early stage of development and the competing state of the art technology. The functional unit of the two systems is the production of 1 kWh electricity. Therefore, the fuel cell system has not only to include the fuel cell itself, but also auxiliary components such as reformer, steam generator, etc. For the gas turbine system the compressor, combustion chamber and generator are considered.

In figure 9 the different cumulated energy demands according to the different lifetime steps of production and operation are indicated. As it can be seen, the energy demand for the production of the fuel cell is much higher (factor > 100) than necessary for the well-established gas turbine system. Nevertheless, the operation phase, where natural gas is the energy carrier for both systems, the fuel cell needs far less energy due to the higher efficiency.



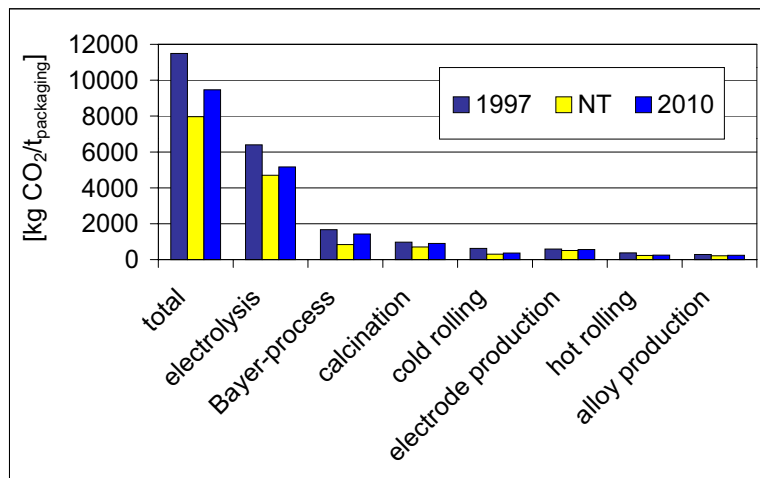
**Fig. 9:** Cumulated energy demand for the production and operation of a fuel cell compared to a gas turbine system [Steen 1999]

Along the entire life cycle the fuel cell needs less energy. All the same, there is still a high optimisation potential during the production of the fuel cell system. The calculation result can also be used to set up goals for the research and development of the new technology. The figures for the fuel cell system are obtained for the target system with a lifetime of 40,000 h and an efficiency of 0.6%. It can be shown, that a lesser efficiency of 0.5% leads to an inversion of the ranking.

#### 4.2 The energy intensive material aluminium

To show the existing potentials for an efficient use of resources in complex production systems such as the German aluminium packaging system a process chain model from ore extraction to the production of semi finishes including imports and exports was developed. Differentiating between the maximum and predicted technical potential the impacts of the implementation of modern technical concepts on resource use and emissions are quantified. Based on a scenario approach the 1997 basis is compared with a calculation considering full replacement by newest technologies available today and a further one with regard to reduced replacement in the year 2010, taking financial and market aspects into account.

As an example, in figure 10 the CO<sub>2</sub> emissions of the total system for all three cases and for each process step respectively are summarised. It is obvious, that the electrolysis process, with its high energy demand has the highest CO<sub>2</sub> emissions, followed by the Bayer-process.



**Fig. 10:** CO<sub>2</sub> emissions of the scenario calculations per tonne of packaging material

As expected, the NT case using exclusively newest technology has the lowest CO<sub>2</sub> emissions for all processes. The technical reduction potential of the electrolyses process is higher than the absolute value of most other processes. An intensified effort in the improvement of that section will therefore lead to the highest CO<sub>2</sub> reduction.

These were only two examples where LCA methods were used to support decision making. In many other applications concerning energy technology systems LCI information or full LCA are used as a tool.

## 5 Current availability of LCI databases worldwide

A recent study of the Life Cycle Initiative has summarised the current availability of publicly available databases [UNEPTIE 2003]. Table 4 lists the countries with databases according to their development status.

	<b>Complete</b>	<b>Ongoing, with data gathering underway</b>	<b>Planned or underway, but data gathering yet not underway</b>
National and multi-government	Italy, Switzerland	Australia, Canada, Chinese Taipei, Japan, Korea, Sweden	USA
Consultants and research institutes	Denmark (EDIP), Sweden (CPM)	Austria, Denmark, France, Germany, Sweden, Switzerland, UK, USA	
Industrial	IISI, EAA, APME, NiDi, FEFCO		
Academic/ decentralised*		Belgium, China, Chile, Estonia, Finland, India, Norway, The Netherlands, Portugal, Poland, South Africa, Spain, Vietnam	Argentina, Malaysia, Thailand

**Tab. 4:** Matrix of LCI databases by country and project status adapted from [UNEPTIE 2003] (\* *Counties may have some degree of information sharing but no co-ordinated database*)

In the Asia Pacific region, a need to develop a public database has been identified. In 2000 Japan has launched a project with Korea, Chinese Taipei, Malaysia and Thailand to exchange information and develop LCI data in cooperation. In Australia, a number of research institutes, consultants and industry associations have developed LCI databases, which are not all publicly available.

In the North American region, Canada has nearly finalised a national database. Although in the USA several institutes and consultants are long active in the LCA field only recently a national project has been launched.

The European LCI community is by far the most active but also the most diverse due to the many countries and many actors (industry, research, public authorities) involved. Most of the data bases developed are only available through one of many LCA software programs. Denmark, Sweden, Switzerland and Italy have so far been able to set up a national database. In other countries, such as Germany or the UK national project have been launched, but due to many different interests, the harmonisation process is very slow. Still, a lot of fundamental research and conceptual improvements are coming from countries such as The Netherlands, Switzerland, UK and Germany.

## 6 References

### **[Boustead 1979]**

Boustead, I.; Hancock, G.F. (1979): Handbook of Industrial Energy Analysis. Ellis Horwood Ltd., John Wiley & Sons, New York/Chichester/Brisbane/Toronto

### **[Boustead 1993]**

Boustead, I. (1993): Eco-Balance, Methodology for commodity thermoplastics. Technical paper for the Association of Plastic Manufacturers in Europe (APME), Brussels

### **[EAA 1997/2000]**

European Aluminium Association (EAA) (1997/2000): Environmental Profile report for the European Aluminium Industry. EAA, Brussels

### **[Ecoinvent 2003]**

www.ecoinvent.ch (2003)

### **[Habersatter 1991]**

Habersatter, K. (1991): Ökobilanzen von Packstoffen (LCA of packagings). Schweizerisches Bundesamt für Umwelt, Wald und Landschaft, Bern

### **[ISO 1997]**

ISO 14040 (1997): Environmental management – Life cycle assessment – Principles and frameworks

### **[ISO 1998]**

ISO 14041 (1998): Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis

### **[ISO 2000]**

ISO 14042 (2000): Environmental management – Life cycle assessment – Life cycle impact assessment

### **[ISO 2000a]**

ISO 14043 (2000): Environmental management – Life cycle assessment – Life cycle interpretation

### **[Guinée 2002]**

Guinée, J.B. (2002): Handbook on life cycle assessment - Operational guide to the ISO standards. Kluwer academic publisher, Dordrecht, Niederlande

### **[Hofstetter 1998]**

Hofstetter, P. (1998): Perspectives in Life Cycle Assessment; A structured approach to combine models of the technosphere, ecosphere and valuesphere. Kluwer academic publisher, Boston/Dordrecht/London

### **[Frischknecht 2000]**

Frischknecht, R. (2000): Allocation in Life Cycle Inventory Analysis for joint production. In: Int. J. LCA 5 (2), pp. 85-95.

**[Goedkoop 2000]**

Goedkoop, M.; Spriensma, R. (2000): The Eco-Indicator 99 a damage oriented method for life cycle impact assessment. Methodology report. Pre Consultants B.V., Amersfoort, NL

**[Steen 1999]**

Steen, B. (1999): A systematic approach to environmental priority strategies in product development (EPS). Version 2000 – general system characteristics. CPM report 1999:4, Chalmers University of Technology, Gothenburg, Sweden

**[Zapp 1998]**

Zapp, P. (1998): Ganzheitliche Material- und Energieflussanalyse von SOFC Hochtemperaturbrennstoffzellen (material and energy analysis of SOFC high temperature fuel cells). Jül-3497, Forschungszentrum Jülich

**[Zapp 2001]**

Zapp, P.; Rombach, G.; Kuckshinrichs, W. (2001): Technological Development in Aluminium Production - Contributions to Environmental Changes. Proceedings of the EMC 2001 Conference, Friedrichshafen, Volume 3, pp. 83 - 98

**[UNEPTIE 2003]**

[http://www.uneptie.org/pc/sustain/lcinitiative/lci\\_program.htm](http://www.uneptie.org/pc/sustain/lcinitiative/lci_program.htm) (status Oct.2003)

1. **Fusion Theory**  
Proceedings of the Seventh European Fusion Theory Conference  
edited by A. Rogister (1998); X, 306 pages  
ISBN: 3-89336-219-3
  
2. **Radioactive Waste Products 1997**  
Proceedings of the 3rd International Seminar on Radioactive Waste Products  
held in Würzburg (Germany) from 23 to 26 June 1997  
edited by R. Odoj, J. Baier, P. Brennecke et al. (1998), XXIV, 506 pages  
ISBN: 3-89336-225-8
  
3. **Energieforschung 1998**  
Vorlesungsmanuskripte des 4. Ferienkurs „Energieforschung“  
vom 20. bis 26. September 1998 im Congressentrum Rolduc und  
im Forschungszentrum Jülich  
herausgegeben von J.-Fr. Hake, W. Kuckshinrichs, K. Kugeler u. a. (1998),  
500 Seiten  
ISBN: 3-89336-226-6
  
4. **Materials for Advances Power Engineering 1998**  
Abstracts of the 6th Liège Conference  
edited by J. Lecomte-Beckers, F. Schubert, P. J. Ennis (1998), 184 pages  
ISBN: 3-89336-227-4
  
5. **Materials for Advances Power Engineering 1998**  
Proceedings of the 6th Liège Conference  
edited by J. Lecomte-Beckers, F. Schubert, P. J. Ennis (1998),  
Part I XXIV, 646, X pages; Part II XXIV, 567, X pages; Part III XXIV, 623, X  
pages  
ISBN: 3-89336-228-2
  
6. **Schule und Energie**  
1. Seminar Energiesparen, Solarenergie, Windenergie. Jülich, 03. und  
04.06.1998  
herausgegeben von P. Mann, W. Welz, D. Brandt, B. Holz (1998), 112 Seiten  
ISBN: 3-89336-231-2

7. **Energieforschung**  
Vorlesungsmanuskripte des 3. Ferienkurses „Energieforschung“  
vom 22. bis 30. September 1997 im Forschungszentrum Jülich  
herausgegeben von J.-Fr. Hake, W. Kuckshinrichs, K. Kugeler u. a. (1997),  
505 Seiten  
ISBN: 3-89336-211-8
  
8. **Liberalisierung des Energiemarktes**  
Vortragsmanuskripte des 5. Ferienkurs „Energieforschung“  
vom 27. September bis 1. Oktober 1999 im Congressentrum Rolduc und  
im Forschungszentrum Jülich  
herausgegeben von J.-Fr. Hake, A. Kraft, K. Kugeler u. a. (1999), 350 Seiten  
ISBN: 3-89336-248-7
  
9. **Models and Criteria for Prediction of Deflagration-to-Detonation Transition (DDT) in Hydrogen-Air-Steam-Systems under Severe Accident Conditions**  
edited by R. Klein, W. Rehm (2000), 178 pages  
ISBN: 3-89336-258-4
  
10. **High Temperature Materials Chemistry**  
Abstracts of the 10<sup>th</sup> International IUPAC Conference, April 10 - 14 2000, Jülich  
edited by K. Hilpert, F. W. Froben, L. Singheiser (2000), 292 pages  
ISBN: 3-89336-259-2
  
11. **Investigation of the Effectiveness of Innovative Passive Safety Systems for Boiling Water Reactors**  
edited by E. F. Hicken, K. Verfondern (2000), X, 287 pages  
ISBN: 3-89336-263-0
  
12. **Zukunft unserer Energieversorgung**  
Vortragsmanuskripte des 6. Ferienkurs „Energieforschung“  
vom 18. September bis 22. September 2000 im Congressentrum Rolduc und  
im Forschungszentrum Jülich  
herausgegeben von J.-Fr. Hake, S. Vögele, K. Kugeler u. a. (2000),  
IV, 298 Seiten  
ISBN: 3-89336-268-1

13. **Implementing Agreement 026**  
For a programme of research, development and demonstration on advances fuel cells  
**Fuel Cell Systems for Transportation**  
Annex X. Final Report 1997 - 1999  
edited by B. Höhlein; compiled by P. Biedermann (2000), 206 pages  
ISBN: 3-89336-275-4
  
14. **Vorgespannte Guß-Druckbehälter (VGD) als berstsichere Druckbehälter für innovative Anwendungen in der Kerntechnik**  
Prestressed Cast Iron Pressure Vessels as Burst-Proof Pressure Vessels for Innovative Nuclear Applications  
von W. Fröhling, D. Bounin, W. Steinwarz u. a. (2000) XIII, 223 Seiten  
ISBN: 3-89336-276-2
  
15. **High Temperature Materials Chemistry**  
Proceedings of the 10<sup>th</sup> International IUPAC Conference  
held from 10 to 14 April 2000 at the Forschungszentrum Jülich, Germany  
Part I and II  
edited by K. Hilpert, F. W. Froben, L. Singheiser (2000), xvi, 778, VII pages  
ISBN: 3-89336-259-2
  
16. **Technische Auslegungskriterien und Kostendeterminanten von SOFC- und PEMFC-Systemen in ausgewählten Wohn- und Hotelobjekten**  
von S. König (2001), XII, 194 Seiten  
ISBN: 3-89336-284-3
  
17. **Systemvergleich: Einsatz von Brennstoffzellen in Straßenfahrzeugen**  
von P. Biedermann, K. U. Birnbaum, Th. Grube u. a. (2001), 185 Seiten  
ISBN: 3-89336-285-1
  
18. **Energie und Mobilität**  
Vorlesungsmanuskripte des 7. Ferienkurs „Energieforschung“  
vom 24. September bis 28. September 2001 im Congressentrum Rolduc und im Forschungszentrum Jülich  
herausgegeben von J.-Fr. Hake, J. Linßen, W. Pfaffenberger u. a. (2001),  
205 Seiten  
ISBN: 3-89336-291-6
  
19. **Brennstoffzellensysteme für mobile Anwendungen**  
von P. Biedermann, K. U. Birnbaum, Th. Grube u. a. (2002)  
PDF-Datei auf CD  
ISBN: 3-89336-310-6

20. **Materials for Advances Power Engineering 2002**  
Abstracts of the 7th Liège Conference  
edited by J. Lecomte-Beckers, M. Carton, F. Schubert, P. J. Ennis (2002),  
c. 200 pages  
ISBN: 3-89336-311-4
  
21. **Materials for Advances Power Engineering 2002**  
Proceedings of the 7th Liège Conference  
Part I, II and III  
edited by J. Lecomte-Beckers, M. Carton, F. Schubert, P. J. Ennis (2002),  
XXIV, 1814, XII pages  
ISBN: 3-89336-312-2
  
22. **Erneuerbare Energien: Ein Weg zu einer Nachhaltigen Entwicklung?**  
Vorlesungsmanuskripte des 8. Ferienkurs „Energieforschung“  
vom 23. bis 27. September 2002 in der Jakob-Kaiser-Stiftung, Königswinter  
herausgegeben von J.-Fr. Hake, R. Eich, W. Pfaffenberger u. a. (2002),  
IV, 230 Seiten  
ISBN: 3-89336-313-0
  
23. **Einsparpotenziale bei der Energieversorgung von Wohngebäuden durch  
Informationstechnologien**  
von A. Kraft (2002), XII, 213 Seiten  
ISBN: 3-89336-315-7
  
24. **Energieforschung in Deutschland**  
Aktueller Entwicklungsstand und Potentiale ausgewählter nichtnuklearer  
Energietechniken  
herausgegeben von M. Sachse, S. Semke u. a. (2002), II, 158 Seiten,  
zahlreiche farb. Abb.  
ISBN: 3-89336-317-3
  
25. **Lebensdaueranalysen von Kraftwerken der deutschen Elektrizitäts-  
wirtschaft**  
von A. Nollen (2003), ca. 190 Seiten  
ISBN: 3-89336-322-X
  
26. **Technical Session: Fuel Cell Systems of the World Renewable Energy  
Congress VII**  
Proceedings  
edited by D. Stolten and B. Emonts (2003), VI, 248 pages  
ISBN: 3-89336-332-7

27. **Radioactive Waste Products 2002 (RADWAP 2002)**  
Proceedings  
edited by R. Odoj, J. Baier, P. Brennecke and K. Kühn (2003), VI, 420 pages  
ISBN: 3-89336-335-1
  
28. **Methanol als Energieträger**  
von B. Höhle, T. Grube, P. Biedermann u. a. (2003), XI, 109 Seiten  
ISBN: 3-89336-338-6
  
29. **Hochselektive Extraktionssysteme auf Basis der Dithiophosphinsäuren:  
Experimentelle und theoretische Untersuchungen zur Actinoiden(III)-  
Abtrennung**  
von S. A. H. Nabet (2004), VI, 198 Seiten  
ISBN: 389336-351-3
  
30. **Benchmarking-Methodik für Komponenten in Polymerelektrolyt-Brenn-  
stoffzellen**  
von Matthias Gebert (2004), 194 Seiten  
ISBN: 3-89336-355-6
  
31. **Katalytische und elektrochemische Eigenschaften von eisen- und kobalt-  
haltigen Perowskiten als Kathoden für die oxidkeramische Brennstoffzelle  
(SOFC)**  
von Andreas Mai (2004), 100 Seiten  
ISBN: 3-89336-356-4
  
32. **Energy Systems Analysis for Political Decision-Making**  
edited by J.-Fr. Hake, W. Kuckshinrichs, R. Eich (2004), 180 pages  
ISBN: 3-89336-365-3

## Systems Analysis and Technology Evaluation at the Research Centre Jülich

Many of the issues at the centre of public attention can only be dealt with by an interdisciplinary systems analysis. Scientific, economic and ecological subsystems which interact with each other often have to be investigated simultaneously. The Programme Group Systems Analysis and Technology Evaluation (STE) takes up this approach and concentrates its work on issues concerning the long-term orientation of the energy economy, on selected economically or ecologically relevant material flows in the technosphere and geosphere as well as on electronic information processing and communications and the changes in society brought about by these technologies. In these fields, STE analyses the consequences of technical developments and provides scientific aids to decision-making for politics and industry. This work is based on the further methodological development of systems analysis tools and their application as well as cooperation between scientists from different disciplines.

Forschungszentrum Jülich  
*in der Helmholtz-Gemeinschaft*



**Band / Volume 32**  
**ISBN 3-89336-365-3**

**Energietechnik**  
**Energy Technology**