

IEA-ETSAP TIMES models in Denmark

Preliminary Edition, March 2011 —



Risø-R-Report

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Abstract (max. 2000 char.):

This report presents the project “Danish participation in IEA-ETSAP, Annex XI, 2008-2010”, which continued the Danish participation in ETSAP under Annex XI “JOint STudies for New And Mitigated Energy Systems (JOSTNAMES): Climate friendly, Secure and Productive Energy Systems”. The main activity has been semi-annual workshops focusing on presentations of model analyses and use of the ETSAP tools (the MARKAL/TIMES family of models). Contributions to these workshops have been based on various collaborative projects within the EU research programmes and the Danish Centre for Environment, Energy and Health (CEEH). In addition, the DTU Climate Centre at Risø, which was founded in the autumn of 2008, has taken part in the ETSAP workshops, and used the ETSAP model tools for projects, papers, and presentations, as well as for a Ph.D. project.

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Abbreviations

BAU	Business as usual
CCGT	combined cycle gas turbine
CCS	Carbon Capture and Storage
CEEH	Center for Energy, Environment and Health (Denmark)
CHP	combined heat and power
CO ₂	carbon dioxide
DTU	Technical University of Denmark
EIA	Energy Information Administration (US)
EFOM	Energy Flow Optimisation Model
EFDA	European Fusion Development Agreement
EMF	Energy Modelling Forum (Stanford)
EPRI	Electric Power Research Institute
ETL	Endogenous Technology Learning
ETP	Energy Technology Perspectives (IEA)
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
GEUS	Geological Survey of Denmark and Greenland
GHG	Greenhouse gasses
GIS	geographical information systems
Gt	Gigatonne
GW	Gigawatt
GWh	Gigawatt hours
IEA	International Energy Agency
IER	Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart
IEW	International Energy Workshop
IGCC	Internal Gasification Combined Cycle power plant
IIASA	International Institute for Applied Systems Analysis (Laxenburg Austria)
IPCC	Intergovernmental Panel on Climate Change
kt	Kilotonne
kW	Kilowatt
kWh	kilowatt hours
LHV	Lower heat value
MARKAL	Market Allocation (optimisation model developed by the IEA)
Mt	Megatonne
Mtoe	million ton of oil equivalent
MW	Megawatt
MWe	megawatt, electric
MWh	megawatt hours
NEEDS	New Energy Externalities Developments for Sustainability
NEET	Networks of Expertise in Energy Technology
NGCC	Natural Gas Combined Cycle power plant
Nord Pool	The Nordic Power Exchange
SAGE	System to Analyze Global Energy
PC	Pulverised coal-fired power plant
PET	Pan European TIMES (model)
PJ	Petajoule 10 ¹⁵ Joule
ppm	Parts per million
RES	renewable energy sources
RFF	Resources for the Future
RoW	Rest of World)
RTD	Research and Technology Development (EU Programmes)
SO ₂	sulphur dioxide
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated Markal EFOM System
TJ	Terajoule 10 ¹² Joule
toe	ton of oil equivalent
TWh	terawatt hours 10 ¹² Wh
VEDA	Versatile Data Analyst
USDoE	United States Department of Energy
VTT	Technical Research Centre of Finland
WEO	World Energy Outlook (IEA)

Preface

An important part of the cooperation within the IEA (International Energy Agency) is organised through national contributions to "Implementing Agreements" on energy technology and energy analyses. One of them is ETSAP (Energy Technology Systems Analysis Programme), started in 1976. Denmark has signed the agreement and contributed to some early annexes.

This document is the final report of the project "Danish participation in IEA-ETSAP, Annex XI, 2008-2010" under the Danish Energy Technology Development and Demonstration Programme (EUDP) 2008.

A new project, "Danish participation in IEA-ETSAP, Annex XII, 2011-2013" was granted under the EUDP for the autumn call 2010.

The current report from the Annex XI project is a status report updating the report Risø-R-1656 "Using the IEA ETSAP modelling tools for Denmark" from December 2008. It is a preliminary edition of Risø-R-1774, which will be published later in 2011 after presentation of some of the contents at the Risø International Conference in May and the next ETSAP workshop at Stanford, California in July. ETSAP also expects to publish its final report for Annex XI during this workshop.

The use of the ETSAP tools is linked to many other projects focusing on model application worldwide. This includes the organisations and institutions gathering in the annual International Energy Workshops (IEW), which are held back-to-back with one of the ETSAP semi-annual workshops. In recent years the ETSAP modelling tools have contributed to several projects under the various European research programmes.

Poul Erik Grohnheit, Senior Scientist is responsible for this preliminary report. Kenneth Karlsson, Senior Scientist and Helene Ystanes Føyn, Research Assistant, DTU Climate Centre have contributed to parts of Chapter 6.

Risø DTU, March 2011

Poul Erik Grohnheit

<http://www.iea-etsap.org/web/index.asp>

1 Introduction

This report summarises the activities under ETSAP Annex XI and related projects, emphasising the development of modelling tools that will be useful for modelling the Danish energy system. It is also a status report for the development of a model for Denmark, focusing on the tools and features that allow comparison with other countries and, particularly, to evaluate assumptions and results in international models covering Denmark.

Thus, the aim is to describe the large amount of available information on the ETSAP modelling tools from a Danish national perspective.

1.1 CEEH – Centre of Energy Environment and Health

The Centre for Energy, Environment and Health (CEEH) is funded by the Danish Council for Strategic Research, and run over 5 years from January 2007. CEEH is a collaboration between scientists from different research fields, with the mission to develop a system to support planning of future energy systems in Denmark, where both direct and indirect costs related to environment, climate and health are considered. The centre will work with a number of different realistic scenarios for the quantity and type of the future energy production and associated emissions. These objectives are similar to those of the NEEDS project, which means that the centre can benefit significantly from participating in ETSAP model activities.

- The main outcome of the centre is an integrated regional model chain consisting of air pollution models, models for optimisation of energy systems and including components for air pollution chemistry and dispersion down to urban and sub-urban scales, and model components of the impacts on public health and the external environment.
- The system will be designed to minimize the grand costs of Danish energy system. Boundary conditions will be obtained from a global and regional energy system model and from a global air pollution model.
- To create global energy and emission scenarios, supplying boundary conditions to the regional and local models, we focus on the MARKAL family of models and relevant projects (such as NEEDS).

The scientific work of the centre will be the basis for 6 PhD projects. Some of these are focusing on atmospheric, air pollution and energy demand modelling at the Danish Meteorological Institute, the National Environmental research Institute and Risø DTU. Starting 2008 Erika Zvingilaite is working on the energy demand modelling with focus on local externalities. The project is motivated by a need for a better modelling of the energy demand in energy system models. The main objective of the PhD project is to develop an energy demand model covering Denmark; Norway; Sweden; Finland; and Germany. The model should describe all final energy demands in all the countries and all sectors. This work will in particular benefit from participation in some of the ETSAP workshops as well as collaboration ETSAP partners.

1.2 DTU Climate Centre

The DTU Climate Centre (DKC) was established as a research programme at Risø DTU in 2008. The Centre works with research related to climate change, including energy

systems modelling and policy analysis. In relation to ETSAP, DKC focuses on the global energy-optimisation TIAM – the TIMES Integrated Assessment Model. In particular, the centre works with on methodological issues and empirical assessments of the costs of international climate change policies, on the modelling of intermittent energy like wind, and on issues related to biomass and CCS.

Starting 2010 Olexandr Balyk is looking at the role of renewable energy sources in different regions of the World under Climate Change mitigation policy regimes. As a part of his PhD he is planning to improve the way intermittent energy sources, especially wind, are modelled in TIAM in order to better capture their variability and temporal availability. The title is “Improved Representation of Renewable Energy Sources in Integrated Assessment Modelling of Energy and Climate Change Policies”

1.3 Report Contents

Chapter 2 describes the history and development of ETSAP, and the current activities, emphasising the Danish contributions to the semi-annual workshops under Annex XI, and the topics that have particular interest for development and use of energy models in Denmark.

Chapter 3 summarises the ongoing international studies using the ETSAP tools, in particular European studies with Danish participation (the European projects NEEDS and RES2020) and other studies which may be useful for current and future research and development projects in Denmark.

Chapter 4 describes the principles of the ETSAP tools, which belongs to the type of technology-rich ‘bottom-up’ flow optimisation energy models, emphasising the issues of data sources, user interface, model development and organisation, mathematical tools and key parameters.

Chapter 5 describes recent applications of the Pan-European model, which was developed under the NEEDS project under the EU 6th Framework Programme. This includes results from the EU RES2020 under Intelligent Energy Europe and “Storage Utsira” under the EU network FRECO ERANET.

Chapter 6 summarises results from the selected studies using the ETSAP global models (EFDA-TIMES and TIAM).

Finally, *Chapter 7* describes selected topics for future work.

2 The IEA Implementing Agreement ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA). It was first established in 1976. In 2009 the IEA Energy Technology Collaboration Division officially notified the Chair of the ETSAP Executive Committee that the Implementing Agreement has been extended for a period of five years from July 2009 to 30 June 2014.

2.1 IEA Implementing Agreements

ETSAP is one of some 40 Implementing Agreements (IA) under the IEA. Most IAs focus on specific technologies, while a few IAs are crosscutting, focusing on the development and dissemination of technology data. Denmark contributes to about half of the IAs.

Table 2.1. Current IEA Implementing Agreements

Advanced Fuel Cells
Advanced Materials for Transportation
Advanced Motor Fuels
Bioenergy
Buildings and Community Systems (ECBCS)
Clean Coal Sciences
Climate Technology Initiative (CTI)
Co-operation on Tokamak Programmes
Demand-Side Management
District Heating and Cooling, including the Integration of Combined Heat and Power
Efficient Electrical End-Use Equipment
Electricity Networks Analysis, Research & Development (ENARD)
Emissions Reduction in Combustion
Energy Storage
Energy Technology Data Exchange (ETDE)
Energy Technology Systems Analysis Programme (ETSAP)
Enhanced Oil Recovery
Environmental, Safety and Economic Aspects of Fusion Power
Fluidized Bed Conversion
Fusion Materials
Geothermal
Greenhouse Gas
Heat Pumping Technologies
High-Temperature Superconductivity (HTS) on the Electric Power Sector
Hybrid and Electric Vehicles
Hydrogen
Hydropower
IEA Clean Coal Centre
Industrial Energy-Related Technologies and Systems
Multiphase Flow Sciences
Nuclear Technology of Fusion Reactors
Ocean Energy Systems
Photovoltaic Power Systems
Plasma Wall Interaction in TEXTOR

Renewable Energy Technology Deployment
 Reversed Field Pinches
 Solar Heating and Cooling
 SolarPACES
 Spherical Tori
 Stellarator-Heliotron Concept
 Wind Energy Systems

Source: www.iea.org/Textbase/techno/ia.asp (accessed 29 March 2011),.

2.2 ETSAP's history

The activities of the ETSAP Implementing Agreement are organised within annexes, normally running over three years. They are financed from national contributions to the annexes. Denmark signed the Implementing Agreement and took part in some early annexes, but was inactive for some 20 years before participating in Annex X from 2005.

In 2010 the active participating countries were Belgium, Canada, EU, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, the Netherlands, Norway, Russia, Spain, Sweden, Switzerland, United Kingdom and United States.

ETSAP is governed by the Executive Committee, which meets during the semi-annual workshop. The current Chair is Hertsel Labib, Natural Resources Canada, and the Operating Agent is GianCarlo Tosato, ASATREM srl., Italy. The Desk Officer in the IEA Secretariat from 2006 was Peter Taylor and since November 2009 Uwe Remme.

Table 2.2. ETSAP Annexes

	1976-77	Analysis of existing tools for evaluating R&D strategies
	1978-80	MARKAL Model generator development
Annex I	1981-83	Energy Technology Systems Analysis Project
Annex II	1984-86	Information Exchange Project
Annex III	1987-89	International Forum on Energy Environment Studies
Annex IV	1990-92	Greenhouse Gases And National Energy Options: Technologies & Costs for Reducing GHG Emissions
Annex V	1993-95	New Directions in energy modelling - <i>Top-Down/Bottom-Up</i>
Annex VI	1996-98	Dealing with uncertainty together - <i>Learning curves</i>
Annex VII	1999-02	Contributing to the Kyoto Protocol
Annex VIII	2002-05	Exploring Energy Technology Perspectives: Learning Strategies for Technological Development toward Sustainable Futures
Annex IX	2003-05	Energy Models Users' Group, 2003 -- <i>The MARKAL family of models</i>
Annex X	2005-07	Global Energy Systems and Common Analyses: Climate friendly, Secure and Productive Energy Systems,
Annex XI	2008-10	JOint STudies for New And Mitigated Energy Systems (JOSTNAMES): Climate friendly, Secure and Productive Energy Systems.
Annex XII	2011-13	Policy Analysis Tools for Global Sustainability (PAT-SUS): E4 systems tools and joint studies

The focus of the early Annexes was model development and technology descriptions. The focus shifted to environment – in particular emissions to the air from energy conversion and energy consumption. During the 1980s SO₂ and NO_x emissions were of primary interest, but from about 1990 nearly all the annexes have referred to Greenhouse Gasses. The focus of the Annexes during the last 15 years has been expansion of the classical model approach of energy flow optimisation modelling and combination with

other approaches, e.g. macroeconomic ‘top-down’ modelling, technology learning and stochastic modelling. The key study object is climate change and technologies for mitigation

Working with models requires continuity and consistency. Many participants in the ETSAP community have long-long-term experience with this type of modelling. During the same time, key data for modelling have been institutionalised as official statistics, in particular data for energy flows and emission. Also capacity data for electricity generation is well described in the statistics, while other data for technologies are much less available.

Table 2.3. ETSAP semi annual workshops since 2005

Annex	Time and location	ETSAP Topic	Joint workshop
X	Oxford, UK, November 2005	Models and studies	Oxford, November 2005 with Workshop on Modelling Future Energy Technology Cost and Technology Choice, organised by UKERC, in collaboration with ETSAP, PSI, DTI and AEAT
X	Cape Town, South Africa, June 2006	IEA G8 Plan of Work in response to the Gleneagles Communiqué	25th International Energy Workshop, organized by IIASA, EMF (Stanford), the IEA and the Energy Research Centre of the University of Cape Town.
X	Stuttgart, Germany, November 2006	Training on VEDA-TIMES, TIMES integrated assessment model (TIAM)	Jointly with NEEDS. Development of national and global models using the TIMES model and the interface VEDA.
X	Stanford, California, June 2007	Models and studies	Annual Meeting of the International Energy Workshop 2007, EMF, IEA, and RFF
X	Brasilia, Brazil, November 2007	Introduction to IEA/ETSAP tools for energy systems analyses	Brazil – IEA/NEET Workshop
XI	Paris, France, June 2008	ETSAP, IEW extension, / ETSAP Regular WS	Annual Meeting of the International Energy Workshop 2008 EMF, IEA, and RFF
XI	Nice, France, November 2008	ETSAP regular sessions	Workshop on 'Carbon and Prospective'
XI	Venice, Italy, June 2009	ETSAP Regular Workshop	International Energy Workshop 2009
XI	Delhi, India, January 2010		Joint TERI – ETSAP Workshop Energy Modelling Tools & Techniques to address Sustainable Development & Climate Change
XI	Stockholm, Sweden, June 2010	The use of the global multi-regional ETSAP-TIAM model via Data Base	International Energy Workshop 2010
XI	Cork, Ireland, November 2010	Regular ETSAP Workshop	Joint UCC – ETSAP Seminar Energy Systems Modelling Addressing Energy Security and Climate Change

2.3 ETSAP workshops

The semi-annual workshops are open for participation and contributions from modelers throughout the world. Normally they are two days events that are held back-to-back with the annual International Energy Workshops (IEW), or meetings of national modelling

communities, or project meetings within international modelling projects, in particular European projects under the framework programmes and Intelligent Energy Europe.

The aim of these workshops is to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modelling developments. Table 2.3 summarises the topics of the workshops since 2005 under the Annexes VIII, IX and X and XI.

Detailed information of the workshops and the ETSAP tools can be found on the ETSAP website www.iea-etsap.org.

Table 2.4. Selected Danish contributions in previous ETSAP workshops.

<p>Macro-economic modelling approaches (Cape Town June 2006)</p> <p>A European Model on Municipal Waste. <i>Alejandro Villanueva, Mette Skovgaard, Marko Vrgoc, Frits Møller Andersen, Helge V. Larsen, Stéphane Isoard, European Topic Centre on Resource and Waste Management, Risø, European Environment Agency.</i></p> <p>Wind (Stuttgart, November 2006)</p> <p>Wind power in technology-rich energy system optimisation models, <i>Poul Erik Grohnheit, Peter Meibom, Rüdiger Barth, Derk Swider, Risø, IER, University of Stuttgart.</i></p> <p>Methodology and preliminary results (Stanford June 2007)</p> <p>Using data from ETSAP models in a hemispheric pollution model, <i>Marie-Louise Siggaard-Andersen, Kenneth Karlsson, Poul Erik Grohnheit.</i></p> <p>IEW Paris, July 2008: Contributions on Waste and biomass, etc. Use of GIS</p> <p>Waste-to-energy technologies in TIMES models, <i>Poul Erik Grohnheit, Kenneth Karlsson, and Marie Münster.</i></p> <p>IEW Venice, June 2009</p> <p>Modelling of heating sector in Denmark with focus on local externalities, <i>Erika Zvingilaite</i></p> <p>Energy Modelling Tools & Techniques to address Sustainable Development & Climate Change (New Delhi, January 2010)</p> <p>A Global Renewable Energy System - A Modelling Exercise in ETSAP/TIAM, <i>Tullik Helene Ystanes Føyn, Olexandr Balyk.</i></p> <p>Wind Power Potentials in Global Energy Models, <i>Kenneth Karlsson.</i></p> <p>Tax Incidence from Environmental Taxation, <i>Henrik Klinge Jacobsen, Poul Erik Grohnheit.</i></p> <p>International Energy Workshop (Stockholm, June 2010)</p> <p>GHG mitigation targets and potentials in large emerging economies, <i>Tullik Helene Ystanes Føyn, Kenneth Karlsson, Olexandr Balyk, Kirsten Halsnæs.</i></p> <p>A comparative assessment of national CCS strategies for Northwest Europe and the cost-effectiveness of storing CO₂ at the Utsira formation, <i>Andrea Ramirez, Ric Hoefnagels, Machteld van den Broek, Neil Strachan, Audun Fidje, Pernille Seljom, Markus Blesl, Tom Kober, Poul Erik Grohnheit</i></p> <p>The possible role of fusion power in a future sustainable global energy system using the EFDA TIMES global energy model, <i>Cabal Helena, Lechón Y., Hamacher T., Muehlich P., Hartmann T., Eherer C., Ciorba U., Gracceva F., Ward D., Han W., Biberacher M., Grohnheit P.E., Pina A., EFDA</i></p> <p>Regular ETSAP workshop (Cork, November 2010)</p> <p>Modelling CCS, Nuclear Fusion, and large-scale District Heating in EFDA-TIMES and TIAM, <i>Poul Erik Grohnheit.</i></p>

2.4 Programme for ETSAP Annex XI

The title of Annex XI, running from 2008-2010 is “JOint STudies for New And Mitigated Energy Systems (JOSTNAMES)” with the subtitle “Climate friendly, Secure and Productive Energy Systems”.

The programme for the Annex was adopted on the ETSAP Executive Committee Meeting in November 2007. It contains four main objectives:

- Research and Development focusing on advancing the state-of-the-art with respect to energy systems analyses and integrated energy / economic / environmental /engineering modelling.
- Co-ordinated Analyses using the methodologies for global and/or regional energy systems studies
- Capacity building aiming at maintaining and improving capabilities for energy systems analyses and the use of ETSAP tools.
- Tools maintenance as the minimum objective of this Annex to maintain and update ETSAP model generators (MARKAL, TIMES) and users’ interfaces (ANSWER, VEDA), and to organize two semi-annual workshops every year.

2.5 Programme for ETSAP Annex XII

The list of objectives for Annex XII is divided into (a) Coordinated Analysis Tools, (b) Research and Development, (c) Capacity building, and (d) Maintenance of the base tools.

The objectives for Coordinated Analysis Tools are Developing, improving and making available to the members and the IEA:

1. TIMES models, and
2. the Energy Technology Data Source (E-TechDS).

In the proposal for the new project ”Danish participation in IEA-ETSAP, Annex XII, 2011-2013” which was granted under the EUDP for the autumn call 2010 special interest was devoted to the following items from the list of topics in the programme for Annex XII,

- associate CGE properties to MARKAL-TIMES models, either with the extension of the tools or the association to an existing economy wide model, in order to assess the full economic implications (in particular jobs and GDP) of an energy revolution
- increase the myopic foresight capabilities of the tools;
- improve the stability analyses of the equilibria with respect to key input parameters, the pre-run elaboration of demand-supply curves, the post-optimal analyses tools, including pre-run and post-run diagnostics on technologies that are not chosen;
- experiment with the inclusion in MARKAL-TIMES model of agriculture, which competes with energy through bio-fuels and GHG emissions.

2.6 Training in ETSAP Tools

During the autumn of 2008 three courses on training in ETSAP tools were held in Astana, Kazakhstan, London, UK, and Nice, France in December – back-to-back with the semi-annual workshop. Similar courses were held before or after the following

workshops In June 2010 the training course was held at Risø DTU before the workshops in Stockholm.

2.7 ETSAP Annexes final reports

The report from ETSAP, Annex X “Global Energy Systems” and Common Analyses was presented at the workshop in Paris, July 2008, consisting of two volumes “Highlights and Summary” and the full report. The report illustrates fifty or more models, studies and analyses carried out with ETSAP tools. In the presentation two global model development undertakings were particularly emphasised. These are the global applications associated with the publication of the IEA Energy Technology Perspective (ETP) in 2006 and 2008, and the assessment of possible routes to climate stabilization using ETSAP TIMES Integrated Assessment Model (TIAM).

These activities were continued under Annex XI, and a similar final report will be due for presentation at Stanford, California, June 2011.

3 Modelling issues for the ETSAP tools

This chapter summarises the ongoing international studies using the ETSAP tools, in particular European studies with Danish participation (the European projects NEEDS and RES2020) and other studies which may be useful for current and future research and development projects in Denmark.

3.1 The global TIAM model

The ETSAP-TIAM (TIMES Integrated Assessment Model) is a detailed, technology-rich global TIMES model. The structure and data came from the MARKAL-based SAGE model that was developed by the US Dept of Energy's Energy Information Administration¹ (www.eia.doe.gov). SAGE is also the origin for the VEDA database user interface, which is now used for NEEDS and RES2020 TIMES.

The world is divided into 15 regions (in the new version of TIAM modified to 16 regions) as shown in Figure 3.1. The time horizon is 2100, which is needed for long-term climate mitigation policies.

The main structure of the energy system is similar to the structure of the NEEDS-TIMES model, but with less emphasis on the technological details in the downstream sectors (transport, industry, residential, commercial and agriculture) and more focus on the energy resources in the Upstream sector (Supply sector in NEEDS-TIMES), in which the global regions are divided into OPEC and non-OPEC countries.

The results of ETSAP-TIAM studies have wide diffusion among the groups that assess climate mitigation policies through EMF and IPCC.

In the summary of the ETSAP Annex X report an analysis examining Hedging Strategies for Climate Stabilisation is presented to illustrate the application of the model. This is one of the aspects of the climate change studies of The Energy Modeling Forum (EMF). EMF is a long standing international forum based at Stanford University, which brings together the leading global energy modellers to look at the pressing energy and environmental issues.

Six long range temperature change targets from 2.1 to 3.3°C were analysed [Reference increase 4.6°C; smallest achievable increase 1.9°C at very high cost.] Targets 2.1°C and 2.3°C are difficult and very expensive to attain, while 3.3°C is quite easy.

The development of TIAM and climate change studies were important topics for presentations at the ETSAP semi-annual workshops and the joint workshops with the International Energy Workshop under ETSAP Annex X.

The further development of TIAM has been a key task of the ETSAP Annex XI programme. This includes an effort for improving the extraction-recalibration facilities of countries in ETSAP-TIAM.

A typical conclusion from studies using TIAM is that a reduction of 80-95% in GHG emissions would require many countries' energy systems to become net CO₂-free in the second part of the century. This means that energy conversion should either not rely on

¹ SAGE was used by the EIA for their International Energy Outlook from 2002 to 2008.

fossil fuels at all, or should include carbon capture and storage (CCS); preferably by equipping biomass-fired power plants with CCS (Labriet et al. 2010; Loulou et al. 2009).



Figure 3.1. TIAM: New 16 region version.

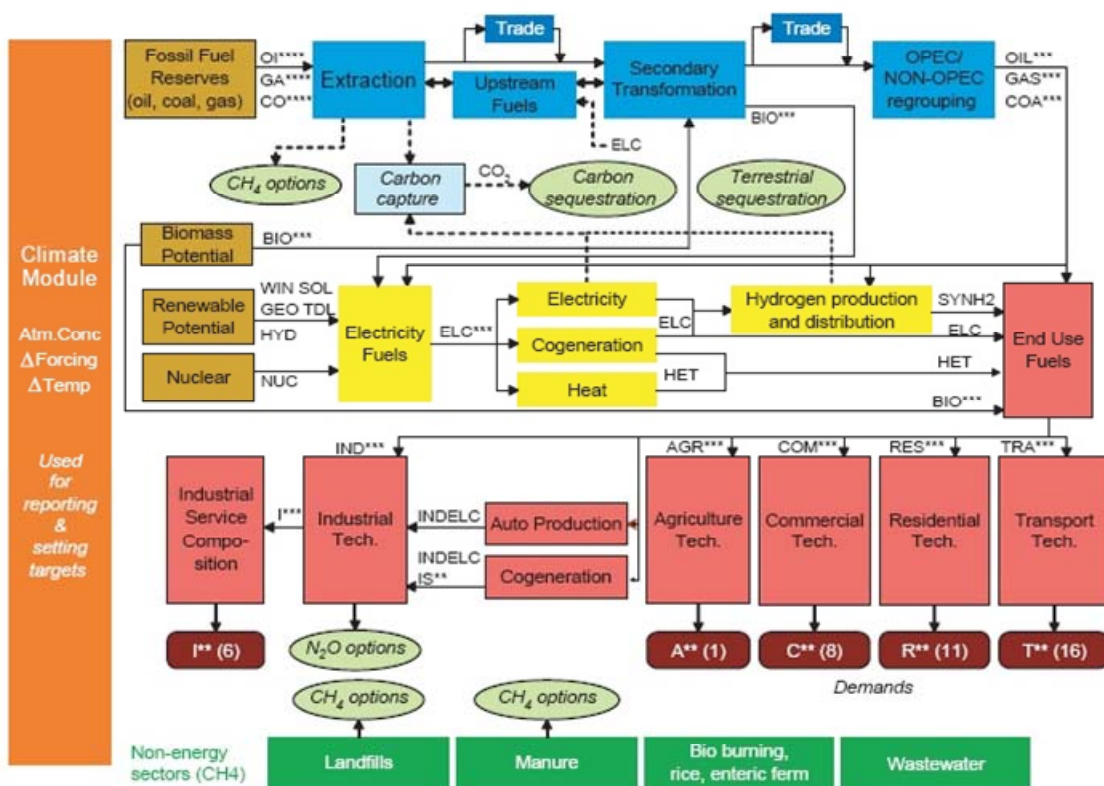


Figure 3.2. TIAM: Energy network structure.

Scenarios for the EU27 countries plus Norway, Switzerland and Iceland (EU27+3), which are covered by the Pan European TIMES model, were examined using the global energy system model TIAM-World. The EU27+3 countries form one of 16 regions in the model (Loulou and Labriet 2008; Loulou 2008).

TIAM-World has many capabilities which normally fall outside the scope of energy system models, such as mining and trading in fuels, and modelling fuel prices. It also includes climate equations to calculate GHG concentrations in the atmosphere and the oceans, the consequential changes in radiative forcing, and hence changes in global mean temperature (Loulou and Labriet 2008; Loulou 2008).

3.2 The EFDA-TIMES model on fusion energy

As a part of the research under the European Fusion Development Agreement (EFDA) there is a small programme on Socio-Economic Research on Fusion (SERF).

The first version of the EFDA-TIMES Modelling Framework was developed for EFDA by an external consortium of experts and delivered in 2004. The motivation for this development was that fusion power practically not considered in existing long-term energy scenarios and that the earlier energy scenario studies within EFDA only considered Western Europe or used a basic single-region global model.

The structure and data of the first EFDA-TIMES model were similar to the SAGE and TIAM models and the further development has benefited on the synergy with the development of the VEDA user interface software.

3.3 Pan European TIMES model

The Pan European TIMES model that was developed as a part of the EU research projects NEEDS (www.needs-project.org/) and RES2020 (www.res2020.eu/) now covers more than 30 countries. These projects are now finished, and results from the RES2020 project are available online. Further applications of the model are now being developed under various projects, e.g. REACCESS, PLANETS (www.feem-project.net/planets), and “Storage Utsira” on carbon capture and storage in the five countries around the North Sea.

3.4 CCS modelling

In contrast to fusion carbon capture and storage (CCS) is becoming an increasingly important technology before 2050. CCS is the key technology that is considered by the Implementing Agreement IEA Greenhouse Gas R&D Programme, and it is one of the most important technologies that is considered by the IEA Clean Coal Centre. Data for CCS have been improved as a part of the development of the NEEDS Pan-European model, and the technology plays a key role in achieving the targets for emission reduction in the policy scenarios in the first published results of the model.

3.5 Technology database for global and regional models

While the model used in the Energy Technology Perspectives consider a limited number of technologies that are described in details, a full-scale national model considers a large number of technologies for optimisation of investment and future operation. Each technology is described by a relatively small number of parameters (efficiency, availability, investment and operation costs, emission factors, etc.). Obviously, the values of these parameters and the consistency among competing technologies is essential for the results of the optimisation

Endogenous technology learning is not used for models with a large number of technologies. Instead, the feature for technology vintages is used, which may be based on results from studies using learning curves.

At the beginning of its activity ETSAP has produced three volumes of energy technology databases:

- Technology Review Report, KFA, October 1978; BNL, December 1979;
- Energy Technology Data Handbook, vol. 1 and 2, KFA STE nr. 18-19;
- Energy Technology Characterization, KFA STE nr. 30, 1982.

The compilation of a new energy technology database within ETSAP has been proposed several times since, but not implemented before Annex XI.

Early in 2011 24 ‘briefs’ were available from ETSAP’s homepage, <http://www.iea-etsap.org/web/E-TechDS.asp>

3.6 Modelling issues in Denmark

In 1980 Denmark – as represented by the newly established Ministry of Energy – signed the ETSAP Implementing Agreement and took part in Annex I “Energy Technology Systems Analysis Project”, under which the Energy Technology Data Handbook, mentioned above, was developed.

The key issue for modelling in Denmark in the 1980s were the build up of infrastructure for natural gas and expansion of district heating systems for combined heat and power. These models must be based on site-specific analysis in a high geographical resolution with little room for technology optimisation.

3.6.1 Macroeconomic models and satellites

The continuous model development and model use in Denmark has followed these lines. A macroeconomic tradition was established in the 1970s for economic policy analysis by the Aggregated Danish Annual Model (ADAM). This model has been developed and expanded continuously. Originally limited to short and medium term analysis based on the Keynesian macroeconomic theory, the model now also covers longer term analyses with more emphasis on neo-classical economic theory. Several satellite models have been developed to ADAM. The first development in the 1980s focused on energy used in manufacturing industry, called INDUS. Later the Energy and eMission Model for ADAM (EMMA) was developed for econometric-based forecasts of final energy consumption in most sectors. This model is continuously being used for energy demand forecasts for the next 20 years by the Danish Energy Agency and the Danish system operator for electricity and gas, Energinet.dk.

3.6.2 Accounting energy models

Covering DES, BRUS, RAMSES, EnergyPLAN and STREAM.

The key model used for the overall energy planning in the 1980 was a simple accounting model for all sectors with a merit-order/load duration curve function for the power sector with CHP with time-horizon 2000. This model was expanded for the subsequent energy planning publications during the 1980s,

From 1988 a more detailed model, RAMSES, was developed within the Danish Energy Agency. RAMSES Version 6 from 2006 is a techno-economic model for electricity and heat in several regions with merit-order optimisation on an hourly basis. Most detailed

for West and East Denmark, less detailed for Finland, Sweden and Norway. Investment in new capacity is exogenous. The main output is regional electricity prices, electricity and heat production, fuel requirement fuel and emissions (www.ens.dk/sw68206.asp - in Danish).

3.6.3 Technology optimisation

From 1999 the development of a new optimisation model for analyses of the electricity and CHP sector in the Baltic Sea Region, financed by the Danish Energy Research Programme and the participating institutions. The model has since then consistently been developed and applied in various contexts, also outside the original focus area. The Balmorel model is coded in GAMS. The Balmorel GAMS code is 'Open Source', which may be downloaded from the project website, www.balmorel.com with a complete set of reference data.

In contrast to Denmark, the MARKAL model that was implemented for the Nordic countries under ETSAP Annex I in the early 1980s became a widely used modelling tool in Sweden and Norway, while the EFOM model later became very much used in Finland with emphasis on large energy consuming industries, in particular the pulp and paper industry.

A MARKAL model was developed for Denmark by the Norwegian Institute for Energy Technology (IFE) and reported in Krogh 1998. The large Swedish NORDLEDEN Project with participation by electricity companies and research institutes in Sweden, Norway and Finland included also Denmark in the optimisation using the MARKAL-NORDIC model (ETSAP News, Vol. 8, No. 5, June 2005).

Finally, as mentioned above, all five Nordic countries are included in NEEDS-TIMES and RES2020 with direct participation by teams from Sweden (Chalmers), Finland (VTT-TEKES) and Denmark (Risø DTU).

3.6.4 Technology catalogues

The development and maintenance of technology data has been a continuous activity in Denmark since the early 1980s, focusing on electricity and heat generation technologies and sometimes also on end-use technologies. A series of technology catalogues have been developed by Danish consultancy firms with some five years intervals. The latest issued was published in English by the Danish Energy Agency and Energinet.dk in June 2010, "Technology Data for Energy Plants".

3.6.5 Wind power

Modelling an energy system with a significant contribution by wind power has become a key task for modelling the electricity system task in Denmark, because nearly one-fourth of the electricity consumption in Western Denmark is generated by wind on an annual basis.

Aggregate parameters developed from models like WILMAR will be needed to address wind power in models with endogenous investment. This issue have been considered within the TIMES model for the RES2020 project, but no satisfactory solution have has yet been found.

4 Flow optimisation energy models

The ETSAP model tools belong to the type of technology-rich bottom-up optimisation models. The energy system is described by a network of energy flow, which is optimised using a mathematical algorithm.

4.1 Main principles

The basic elements of the ETSAP model tools are summarised in Figure 4.1. The key elements of a *Reference Energy System* are illustrated in the diagram. The *processes* (energy technologies) transform upstream *commodities* (energy carriers, materials or emissions) to downstream commodities.

Flow optimisation models

Variables:

Flows
Capacity investments

Objective function - options:

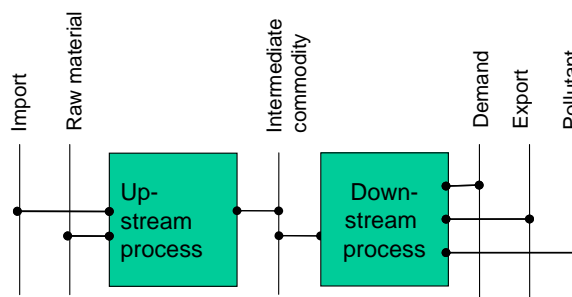
Min. total system costs
Max. contribution margin/utility

Constraints:

Demands
Commodity balances
Flow-capacity
Non-negative variables

Multi-period options

Myopic - period by period
Full foresight -
Discounted objective function



Basic parameters:

Initial capacities
Efficiencies
Prices

Optional parameters:

Price elasticities
Emission factors
Discount rate

Model systems:

Excel solver
EFOM
MESSAGE
MARKAL/TIMES
Balmorel

Figure 4.1. Flow optimisation models in principle

The relations between upstream and downstream energy carriers are normally given by *efficiencies*, typically less than 1, while the relations between pollutants and energy input are given by *emission factors*. The system is driven by *demand forecasts* using a mathematical algorithm, typically linear programming. The reference energy system within a region is described by the initial capacities of existing technologies. These capacities will be reduced over the years and replaced by *new technologies* that are added to the system. The system must comply with a set of technical constraints, such as *commodity balances* between output and input for all processes, *flow-capacity* constraints requiring the necessary available capacity for the flows of commodities.

The variables – normally *non-negative* – to be calculated by the *optimisation* are commodity *flows* and capacity investment for processes representing new technologies. The objective function to be optimised depends on the type of the model.

In the classical and most simple model it is minimising *total system cost* necessary to meet the exogenous demand forecast. Key parameters in the objective function are *prices*

for the most upstream commodities, typically primary fuels, and investment and operating cost of processes.

The demand for energy may be an endogenous variable to be determined by the optimisation. This will change the objective function to maximisation of the *contribution market*, gross profit, or maximum utility, which may be quantified as the sum of consumers' and producers' benefits in a market equilibrium mode.

If the demand for energy is dependent on the price of delivered energy, *price elasticities* are used to determine the demand function.

In multi-period models the optimisation may be calculated period-by-period, so the result of one period will be initial capacities for the next period (myopic). Alternatively, the optimisation may cover the whole period within the time horizon (*full foresight*). In this case future costs and revenues will be *discounted*.

4.2 TIMES software

The EFOM and classical MARKAL models, which are the basis for the TIMES model, were simple cost minimisation models driven by exogenous demands. In contrast to these models, TIMES is far more flexible, in particular concerning the seasonal and diurnal break-downs of the year, which were limited to four or six time slices in the old model, but fully flexible in TIMES.

Elastic demands were introduced in early versions of TIMES, and TIMES has gradually developed to include most of the features of the MARKAL Family of models.

Table 4.1. TIMES updates with new functionality.

Version	Month	Function
1.3.1	1/2005	Added prototype climate module.
1.4.4	10/2005	Introduced Damage Functions.
1.5.0	11/2005	Added Macro module to TIMES and introduced Stochastic TIMES (used for the climate module)
2.0.0	01/2006	Documentation note
2.1.8	11/2006	Enhancements in Climate Module
2.4.0	10/2007	Implemented support for using GAMS savepoint / loadpoint facility. Added switch for input parameters only.
2.5.0	11/2007	Implemented Tradeoff Analysis Facility under stochastic model.
2.5.7	03/2008	Support for three alternative objective function variants completed.
2.8.0	08/2008	First Implementation of Time-Stepped TIMES (limited foresight).
2.9.0	11/2008	Compatibility problems with running MACRO fixed
2.9.9ii	03/2010	New features: Extending the climate equations beyond end-of-horizon, bounds on objective function component variables, elastic supply cost curves.
3.0.5	08/2010	Reporting of lumpsum investment and commissioned capacity.
3.0.6	08/2010	Added a currency conversion utility (experimentat)
3.1.0	12/2010	Full review of all objective formulations with small additional improvements

The recent versions of MARKAL and all versions of TIMES are written in the General Algebraic Modelling Language (GAMS), which is used to formulate problems that is solve by a variety of mathematical solvers. The basic user interface for GAMS is simple text files. However, for larger GAMS models a user shell written in Excel or Access is required.

GAMS is developed and sold by GAMS Development Corporation (www.gams.com). The software comes with a text editor GAMS-IDE, which is mainly for model development. The TIMES source code consists of more than 200 files, which contains formulas, but no data. Any TIMES model consists of a large amount of data that are organised as described in Figure 4.1.

ETSAP supports the development of two different user shells for both MARKAL and TIMES, ANSWER developed by Ken Noble, Noble Soft, Australia and VEDA developed by Amit Kanudia, KanORS, Canada/India. These user shells are propriety software, which are available mainly for participants in collaborative projects using MARKAL or TIMES, or licensed to other users.

The TIMES code will be updated automatically together with VEDA from the KanORS website using the Web Installer, which normally runs very smoothly. In addition to the updates with new functionalities as shown in Table 4.1, there have been frequent updates with minor bug fixes and enhancements.

The source codes for The MARKAL and TIMES model generators are available free of charge, upon providing a signed copy of the ETSAP Letter of Agreement.

In 2005 an extensive and comprehensive documentation for TIMES was published as a part of Annex VIII/IX, consisting of three main volumes:

- Part I: TIMES Concepts And Theory,
- Part II: Reference Manual
- Part III: GAMS Implementation

This documentation is freely available for the ETSAP website, together with documentation of updates and extensions to the core feature of TIMES, see. www.iea-etsap.org/web/Documentation.asp

- Version 2.1. Information note. June 2006.
- Version 3.1. Information note. October2010. New Features in TIMES v2.1–v3.1
- The Dual Solution of a TIMES Model: its interpretation and price formation equations. Draft, July 2009.
- Climate: TIMES Climate Module. November 2010 abridged version.
- Control Switches: TIMES Version 2.5 User Note. User Control Switches in TIMES. Revised September 2008
- Cost Bounding: TIMES Version 2.5 User Note. Specifying Cost Bounds in TIMES. February 2007
- Damage: TIMES Version 2.0 User Note: TIMES Damage functions. November 2005
- Elastic Demands – Shaping: TIMES Version 2.5 User Note Shaping of Demand Elasticities in TIMES. February 2008.

- Elastic supply cost curves in TIMES, January 2010.
- Interpolation Settings. Inter/Extrapolation of Input Parameters in TIMES. December 2007.
- Load Point: GAMS Savepoint and Loadpoint in TIMES, September 2007
- Macro: Documentation of the TIMES-MACRO model (Draft). February 2006
- Objective Function Variants: TIMES Version 2.8 User Note. TIMES Objective Function Formulations. August 2008.
- Stochastic: TIMES Version 2.5 User Note. Stochastic Programming and Tradeoff Analysis in TIMES. Revised November 2007
- New parameters for TIMES under TIMESVDA. April 2005, Updated October 2010..

Several of these updates and extensions were developed within the projects using the model) e.g. NEEDS, RES2020, REACCESS) and linked to the improvements of the front-end of the VEDA user shell. Others are improvement of the mathematical formulation of the model with variants of the objective function.

Table 4.2. Contents of GAMS text files used to run TIMES.

Run file

Initialisation

```
SET ALL_TS/ANNUAL seasons seasons-diurnal /
[* Generate.gdx files for input only - (optional):
$SET INTEXT_ONLY YES
$SET PREP_ANS YES]
$BATINCLUDE base.dd
$BATINCLUDE b-newtechs.dd
$BATINCLUDE demproj.dd
$BATINCLUDE fuel_price.dd
$BATINCLUDE uc_sector.dd
$BATINCLUDE uc_policy.dd
$BATINCLUDE syssettings.dd
SET MILESTONYR /2000,2005,2010,2015,2020,2025,2030,2040,2050/;
$SET RUN_NAME 'DKw20h'
```

.dd files

SET

/elements/

/combined elements from previously defined sets/

PARAMETER

Parameter name

combined elements from previously defined sets – value

Vtrun.cmd

Call GAMS folder DKw20h.RUM IDIR=folder GDX=DKw20h

GDX2VEDA DKw20h TIMES GAMS code folder\times2veda.vdd DKw20h

Two type of GAMS text files are used to run the TIMES model, The “Run” file calls the TIMES model generator and includes a number of data files that specifies the reference energy system (*base.dd*), new technologies (*b-newtechs.dd*) and several files for scenario specifications, consisting of demand projections (*demproj.dd*), fuel price forecasts (e.g. *fuel_price.dd*), various user-specified constraints (e.g. *uc_sector.dd*) for the different sectors of the reference energy system or policy scenarios, plus some more general system parameters (*syssettings.dd*) and milestone years used for optimisation and reporting.

For each run of the model a single run file and several *-dd* files are used, which contains all additional data used in the model. The system is started by a commend file, which runs in a command window showing the progress of the model execution.

The time needed to run a single-country model in is normally 1-5 minutes, but very dependent of the particular choice of scenarios. The time needed for multi-regional models increase progressively with the number of regions. The time needed for these models, e.g. the Pan-European model in a single optimisation or the TIAM 15-regions model is also very dependent on the optimisation software.

4.2.1 Input parameter documentation

The switch for input only – shown in square brackets in Table 4.2 - was introduced im TIMES version 2.40. This feature enables a comprehensive documentation of all input. And comparison of different versions.

4.3 The VEDA-TIMES user shell

“The VErstitle Data Analyst (VEDA) supports both MARKAL and TIMES. VEDA consists of two independent but closely related software, VEDA Front-End (VEDA-FE), managing input data and starting model runs, and VEDA-Back-End (VEDA-BE) used to analyze the results of the model runs. VEDA was developed to support the increased complexity associated with developing and applying large multi-region models.

Table 4.3. ETSAP models using VEDA

Model	Programme	Regions	Horizon	Foresight	Focus
NEEDS-TIMES	EU FP6 NEEDS	29 European countries (+Pan- European)	2050	Perfect	All energy, Climate module, LCA, externalities.
Pan European- TIMES	Intelligent Energy Europe	Up to 36 European countries	2020- 2050	Perfect	Many
TIMES-EE (- EG)	IER-Stuttgart, (EUSUSTEL, etc.)	EU15 ++	2030	Perfect	Electricity, (gas)
SAGE (MARKAL)	US-DOE, Energy Information Administratio n.	Global 15 regions	2050	Myopic	SAGE: System for Analysis of Global Energy markets
EFDA-TIMES	EFDA	Global 15 regions	2100	Perfect	Fusion + alternatives
TIAM - TIMES Integrated Assessment Model	ETSAP, and many othersl	Global 15 / 16 regions	2100	Various	Technology, energy trade, link with GEM-E3, climate module, carbon sequestration

A major effort within ETSAP Annexes X and XI has been the further development of the VEDA user shell, which was done as a task within the projects for the development of NEEDS-TIMES, EFDA-TIMES and TIAM. A smooth procedure for update of VEDA as well as the TIMES model generator was developed and has been used by all modellers within these projects.

4.4 Discount rates

The NEEDS Pan-European model assumes a general discount rate at 4 % p.a. This is very low compared to the requirements by private investors, but similar to the discount rates used for traditional energy planning studies for a regulated market.

The choice of discount rate for long-term models is difficult from a theoretical point of view. It may also have significant practical impact on the results, because higher discount rates will discourage capital-intensive technologies, such as nuclear and renewables.

In addition, TIMES has a feature for technology-and regional specific discount rates, which is extensive used in both TIAM and EFDA-TIMES. However, the theoretical arguments for these discount rates is seldom fully described and their practical impact on the technology choice is unclear. This issue has been studied for the EFDA-TIMES model recently, but no conclusion or recommendation was reached.

5 Results from the Pan-European model

This chapter summarises the assumptions and results for studies using national models developed within the framework of the Pan-European model, originally developed under the EU-NEEDS (New Energy Externalities Developments for Sustainability). Kick-off meeting of Research Stream 2a: “Energy systems modelling and internalisation strategies, including scenarios building” 2004-2008.

Section 5.1 gives an overall presentation of the Danish energy sector that was prepared for the Storage Utsira project on CCS. Section 5.2 presents selected results from the FENCO-ERANET project ‘Storage Utsira’. Section 5.3 presents the first reference case by the Pan-European model that was used for scenarios until 2050. Section 5.4 describes the subsequent development of the Pan European model with results from the RES2020 project.

Section 5.5 focuses on the selection of data for modelling bioenergy production, while Section 5.6 considers the implementation of these data into the Pan European TIMES model.

5.1 The Danish energy sector

Since the mid 1970s the total primary energy consumption in Denmark has been about 800 PJ with annual variation that has been due mainly to variations in electricity trade with the hydro-based regions in Norway and Sweden. In the same period there has been a continuous development from about 90% imported oil to a more diversified supply of coal, oil gas and renewables.

Currently, Denmark is the only country within the EU that is a net exporter of oil and gas. Denmark’s primary energy production of oil and gas from the North Sea has continued to increase steadily from 1980 to 2005. However, the production has peaked about 2005 and will decrease in the coming years due to depletion of the resources in the North Sea.

The natural gas infrastructure was built up during the 1980s and 1990s with transmission lines for export to Sweden and Germany and seasonal storages. The gas distribution network covers most of the country with supply to power stations, district heating plants, industries and individual homes in areas less suitable for district heating. The district heating infrastructure covers all the more densely populated urban areas, including small towns and villages. Base load heat in nearly all district heating networks is supplied CHP plants, ranging from less than 1 MW gas motors to large-scale power plants). Waste incineration for CHP or heat-only is used as base-load in all urban areas using about 95% of the available urban waste. From about 1980 all new power stations have systematically been located to supply district heating systems with co-generated heat.

Wind power has grown constantly during the 1990s and covers about 20% of the electricity demand in the years 2004-2008 on an annual basis.

5.1.1 Development of electricity and heat supply

Figure 5.1 shows the development of the Danish electricity generation during the last three decades. The two main characteristics are the fluctuation in international electricity trade and a steady increase in generation from large-scale and small-scale CHP and – more recently – also from wind. The electricity generation from CHP is linked to the

infrastructure and demand for district heating, while the fluctuation in international electricity trade depends on the natural variations in precipitation – and, thus, hydro power generation in Norway and Sweden. In the very dry years 1996 and 2003 the electricity generation and export from Denmark was large, and in the wet years 1989, 1990, 2005 and 2008 the electricity import to Denmark was large.

TWh

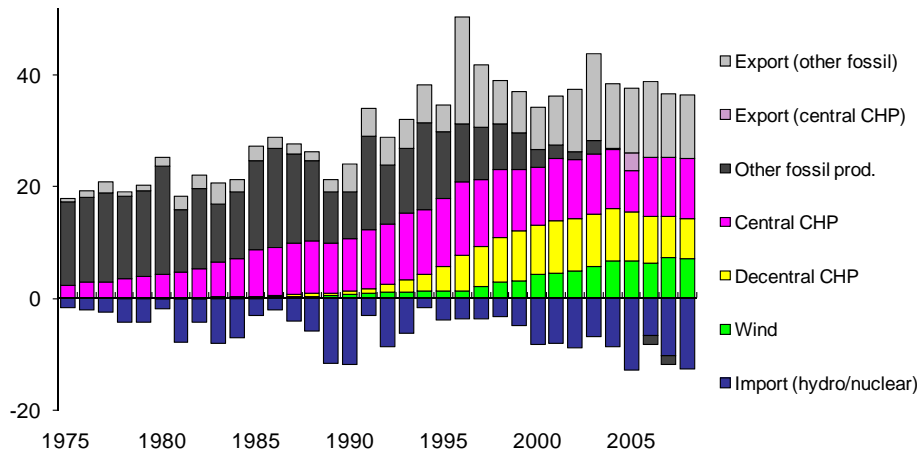


Figure 5.1. Electricity production and import, Denmark 1975-2008

Source: Danish Energy Association, Statistics and own calculations.

After 1980 all new power stations have been located systematically to supply district heating systems with co-generated heat. In the 1980s nearly all new capacity was medium-sized extraction-condensing units for large-scale CHP; in the 1990s a significant share was small-scale gas-fired CHP units for the smaller district heating systems in towns and villages. Wind power has grown constantly during the 1990s and has been nearly 20% of the electricity demand on an annual basis for several years before 2009.

The most suitable technology for CCS is modern extraction-condensing power plants, located for supply of the large urban district heating systems in Copenhagen, Odense, Aarhus, Aalborg, Esbjerg and the conglomeration of towns around the Little Belt bridges with the interconnected district heating transmission network TVIS, see Table 5.1.

The Copenhagen network is supplied mainly from two power stations, Amager and Avedøre and three waste incineration plants, one located at the Amager power station and two at separate sites. In addition, there are several gas or oil fired peak load units. The same structure is found in the other large systems. In addition to the power stations the very few large industrial plants are located in these areas: Cement in Aalborg, refineries in Fredericia (TVIS) and Kalundborg. The large heat supply for the small town of Kalundborg is explained by the ‘industrial symbiosis’ of the large coal-fired power plant, the refinery and several industrial plants, where waste from one plant is used as input for others.

The largest coal harbour in northern Europe is located at Enstedværket near Aabenraa with barge transport to other coal-fired power stations. At Stigsnæsværket, there is another harbour with large capacity for coal import, but its electricity generation is mainly for export in dry years, such as 1996, 2003 and 2006. The large capacity at Kyndbyværket is very important for peak load, but the annual production has been small during the last decades, even in dry years.

Table 5.1. Electricity and heat generation and capacities connected to interconnected district heating grids in Denmark

	Capacity,	Electricity, GWh		Heat, PJ	Emission, Mt CO ₂		
	MW	2005	2008	2005	2005	2008	GEUS
Copenhagen (Amager, Avedøre, etc.)	1479	5180	4972	24.1	4.2	4.1	5.93
Aarhus (Studstrupværket)	712	2239	2873	9.0	1.8	2.3	2.83
Odense (Fynsværket)	640	1828	2024	8.1	1.5	1.6	2.00
Aalborg (Nordjyllandsværket)	692	2281	2363	3.5	1.9	1.9	4.88
TVIS (Skærbækværket)	392	1176	1075	3.4	1.0	0.9	0.99
Esbjerg (Esbjergværket)	378	1731	1352	2.6	1.4	1.1	1.90
Kalundborg (Asnæsværket)	1057	2561	2537	2.1	2.1	2.1	3.54
Aabenraa (Enstedværket)	625	1105	2611	0.2	0.9	2.1	2.60
Stignæsværket	409	631	582	0.0	0.5	0.5	0.97
Kyndbyværket	734	48	42		0.0	0.0	0.07
Decentral CHP areas	2437	9186	7556	22.7	4.4	3.6	3.00
Total thermal generation	9555	27966	27988	75.8			
Wind (incl.hydro)	3146	6637	6954				
Total	12701	34603	34942	75.8	20	20	28.71

Future large power units with CCS as well as retrofit of existing units will be located at the stations connected to the large district heating networks,

More than hundred smaller CHP units, ranging from 100 MW combined cycle gas turbines to gas motors less than 1 MW are connected to smaller CHP areas. These units are fuelled mainly by natural gas, but the number of units fuelled by various types of biomass is increasing. In the future development of district heating many of these areas will be expanded by interconnection of smaller district heating systems or connection to the large systems, most important in the densely populated region north of Copenhagen. This will increase the heat markets connected to power stations suitable for CCS.

More energy efficient buildings in the future will reduce the demand for heat from the existing district heating networks. However, the share of district heating is planned systematically increased on the expense of natural gas, electric heating and individual oil burners. The most important alternative to district heating in future energy efficient buildings will be heat pumps.

In the next decades the share of wind power will gradually increase from 20 % to more than 50 %. A wide range of measures will be required to respond to load variations from wind. This includes heat storages for flexible supply of electricity and heat, electric boilers and heat pumps for use of cheap surplus electricity, electric cars with managed charge of batteries and possible further electric storages, and increased transmission capacity for international trade.

The electricity spot markets, e.g. Nord Pool covering the Nordic countries, are essential for managing electricity loads, when there is a large capacity of wind power. From 2005 a three-level feed-in tariff for decentral CHP was replaced by a premium to the day-ahead, hourly spot market price (13 € per MWh). The day-ahead and intra-day markets is continuously being developed to address the issues of the technology development. From October 2009 a negative minimum price was introduced at the Nord Pool spot market.

Annual aggregated electricity prices from the spot market will be important for future decisions on the investment in CCS facilities.

5.1.2 Biomass

Wind energy and biomass are the most significant renewable energy sources in Denmark, while the contributions of hydro power, solar and geothermal are negligible.

The total contribution of biomass in 2000 was 70 PJ or 8% of the primary energy requirement. The increase in the use of biomass since 1980 has been a part of the national energy policy. The contribution of biomass has further increased to 100 PJ in 2005.

Incineration of urban waste has a long tradition in the district heating sector, mainly for base-load heat supply, and most urban waste is used for energy.

The use of straw for energy purpose has been developed during the 1990s, mainly with the development of decentralised CHP, and this development has continued after 2000. This includes both combustion facilities for straw at CHP and district heating plants of different sizes as well as the infrastructure for recovery, storage and transport. By 2005 18 PJ or one-third of the available straw resources was used for energy purposes.

Wood chips and wood waste is also used in the district heating sector. Wood pellets have become a convenient replacement of oil for individual boilers, and a significant part of the consumption of wood pellets is imported.

The development of biogas has been much weaker, mainly due to technical and logistical difficulties. In 2005, there was a small production of biodiesel, which was exported.

5.1.3 Large energy consuming industries

There are very few large energy consuming industries in Denmark that are suitable to consider as explicit technologies in the Pan European model.

There is a single cement plant at Aalborg in North Jutland, located close to the Nordjyllandsværket power station and the potential CO₂ storage at the Vedsted formation.

A steel work using electric arc furnace for melting scraped steel for recycling has worked irregularly for several years with shifting ownership. The food, chemical and pharmaceutical industries does not contain processes that are identifiable for the Pan European model.

5.1.4 Industrial CHP

The capacity of Industrial CHP has been gradually increasing over the last decades adding small units. The total capacity has been around 0.6 GW. Generation by industrial autoproducers have been within the range of 2.2 and 3.3. TWh since 2000. The production apparently follows the pattern of the marginal condensing production and the prices on the Nord Pool spot market.

5.1.5 Refineries

Three refineries were built in Denmark around 1960 and two of them – in Kalundborg and Fredericia – are still in operation. Since the late 1990s the output of oil products from the Danish refineries has been similar to the Danish consumption, except for diesel and residual fuel oil, while Denmark has become a net exporter of crude oil,

5.2 Storage Utsira

This section describes selected results from the project “Analysis of potentials and costs of storage of CO₂ in the Utsira aquifer in the North Sea – StorageUtsira” within FENCO-ERA,

5.2.1 Project summary

This subsection contains the project final report for the Danish contribution to “Storage Utsira” submitted to ForskEL 17 May 2010

Introduction

The project is aimed at funding the Danish participation in the project “Analysis of potentials and costs of storage of CO₂ in the Utsira aquifer in the North Sea – StorageUtsira” within FENCO-ERA, which is an EU network for national R&D activities in 13 countries in the field of fossil energy conversion and CO₂ capture and storage.

The StorageUtsira project has studied the possibilities of CO₂ storage into the Utsira formation and analysed carbon capture, transport and storage of CO₂ from countries in the North Sea region into the formation. The following partners have been involved in the project:

- Institute for Energy Technology, NO (coordinator)
- University College London, UK
- Utrecht University, NL
- University of Stuttgart, DE
- Risø DTU, DK

The project have used the Pan European TIMES (PET) model and national MARKAL/TIMES models for the United Kingdom, the Netherlands, Germany, Denmark and Norway. Input data to the national models and a common regional model, covering all five countries were harmonised including cost and performance of fossil fuel based power plants. Analyses were carried out on both national level and regional (North European) level, and the model results were compared to study the advantages of a common European CO₂ infrastructure in contrast with national infrastructures.

The potential capacity to store CO₂ in the Utsira formation is very large. Thus, it is expected that the Utsira formation could be used as a CO₂ reservoir for at least 20-30 years for several European countries. Therefore, the possibility of storing CO₂ at Utsira needs to be assessed taking into account national CO₂ reduction targets, temporal, and spatial aspects (e.g. availability and location of local sinks and CO₂ sources over time).

Data sources

The main source for estimates on storage capacities was the database developed within the GETSCO and GeoCapacity projects. Data and maps for storage potentials and point sources in Denmark were received from GEUS. These estimates are subject to significant uncertainty, which follows from a set of conservative estimates in the final report from GeoCapacity. For Denmark the conservative estimate is about one-fifth of the theoretical potential.

Final results and Conclusions

The future role of the Norwegian Utsira formation as a storage location for CO₂ from North European countries depend on the actual properties of the formation, mitigation strategies, future energy costs, development of CCS technologies, public acceptance and political barriers.

The main limitation for the Utsira formation is the maximum annual injection rate for CO₂. This is a stronger limitation than the total storage capacity. The literature show simulating results of CO₂ injection up to 150 Mt per year in Utsira distributed over many wells and water production from the formation is necessary to reduce the pressure build up. Under stringent mitigation targets the requirement of annual CO₂ capture can exceed 150 Mt per year in the North European countries. To obtain a better understanding of the limitation of the Utsira formation as a possible storage location for North European CO₂, further research on the injection rate capacity is required.

The European CO₂ reduction commitment is vital for the implementation of CCS technologies towards 2050 and the importance of CO₂ storage in the Utsira formation. All national models (United Kingdom, the Netherlands, Germany, Norway and Denmark) have considerable differences in the CCS implementation dependent on the emission reduction targets. National models have been analysed with both 20% and 80% emission reduction on the EU27+ in 2050. For example in Germany the amount of CO₂ captured in 2050 is 22 Mt/y with a 20 % emission reduction and 238 Mt/y with an 80 % emission reduction.

When comparing the modelling results from national and regional level, we find that modelling with different geographic scale have an impact on the results. This is a result of different input, e.g. the regional model cover international aviation and the national models only cover domestic aviation. The national models have also a higher level of detail on demand changes, technologies, taxes and policies, thus generates a range of difference in sectors, resources and measures to meet CO₂ targets.

With a tight climate target storage of CO₂ in the Utsira formation can be a cost effective option for North Europe. With an 80 % emission reduction target in 2050 up to 1.4 Gt CO₂ will be captured annually in EU27+ in 2050 and the use of costly storages and long transport distances will be necessary. Under this condition the Utsira formation can be competitive and it represents a valuable CO₂ storage option. According to the European model results CO₂ transport to Utsira from outside Norway comes mainly from the UK (60 to 75 Mt/y in and 2050) and from the Netherlands (20 to 50 Mt/y in 2040 and 2050).

The United Kingdom profits from the comparably short transport distance to Utsira and the Netherlands utilise the Utsira formation due to limited domestic low cost storages. In Germany and Denmark the availability of domestic onshore saline aquifers determines the competitiveness of CO₂ storage in Utsira. If these aquifers are not usable, Utsira gains a competitive storage option.

The price development of oil, natural gas and coal influences the role of CCS in the energy system. At a stringent emission target CCS is inter alia in competition with renewable and nuclear technology. Higher fossil fuel prices are in favour of the renewable technologies and lower energy prices is favour for the CCS technologies. Model results from the United Kingdom show that there is a competition between nuclear power and CCS technologies. When the energy prices increase, the power production from coal-based CCS decrease and the nuclear power increase. Thus, the future role of the Utsira formation can depend on the political acceptance of future nuclear power in Europe. The utilisation of CCS technologies in a country will also be influenced by the national electricity supply options and the opportunity for cross-boundary CO₂ transport.

For the CO₂ transport to Utsira three different network layouts have been analysed. The analysis showed that electricity generation structure of the neighbouring countries of the

North Sea is not influenced by the type of network but rather by climate policies. Different CO₂ infrastructure layouts for the North Sea region primarily affect the transported quantities of CO₂ from the Netherlands to Utsira. The different infrastructures options have little impact on the CO₂ storage from the other North Sea countries.

The deployment of a trans-boundary CO₂ offshore pipeline will require an active participation and commitment from the national governments. It is a relative new topic and many organisational aspects are still unclear. A CO₂ transportation network needs governmental support, suitable domestic and international legislation and a financial plan.

Main conclusions for Denmark

So far, there has been very little interest in CCS in Denmark. The technology is not a part of public policy, and the Government has not expressed any official standpoint on the use of CCS in Denmark. On the other hand, both the electricity industry and geologists from the Geological Survey of Denmark and Greenland (GEUS) have been active in international research on both capture and storage.

A very significant additional constraint for CCS in Denmark is the planned development of wind power, which currently covers some 20 % of the annual electricity demand, but is planned to increase to 50 % of the annual electricity demand by 2025. This will further reduce the need for base-load thermal electricity generation.

For the model analysis in the StorageUtsira project it means that the potential for CCS is becoming increasingly constrained. To model these constraints, it means that the Pan European TIMES model, which has a structure that is harmonised to meet the requirements for 30 European countries, must be calibrated in further details for give a proper representation of the constrained potential for Denmark.

It is unlikely that Denmark will need the CO₂ storage capacity in Utsira within the time-horizon of the study. However, in co-operation with other countries around the North Sea the Danish potential for carbon storage may contribute to the build up of the long-distance CO₂ transport infrastructure.

Dissemination and further model development

The partners have submitted contributions to conferences to be held during 2010 in the fields of CCS, energy modelling and energy economics.

The Danish country report and the common final report will be distributed to Danish institutions that have been active within the FENCO ERA network.

A Danish version of the Pan European TIMES model, which was developed as a part of this project and previous EU-projects will be used by the DTU Climate Centre, and data and results from the model will be made available for other energy models for Denmark and North Europe, e.g. Balmorel.

5.2.2 CCS activities in Denmark

So far there has been very little interest in CCS in Denmark. The technology is not a part of public policy, and the Government has not expressed any official standpoint on the use of CCS in Denmark. On the other hand, both the electricity industry and geologists from the Geological Survey of Denmark and Greenland (GEUS) have been active in international research on both capture and storage.

Table 5.2. Danish participation in European projects on CCS.

Project	Participant	Contribution
CASTOR	Geological Survey of Denmark and Greenland (GEUS) Elsam/Energi E2	Test plant at the power plant at Esbjerg
GETSCO	Geological Survey of Denmark and Greenland (GEUS) Danish Oil and Natural Gas (DONG)	GEUS project co-ordinator
GeoCapacity	Geological Survey of Denmark and Greenland (GEUS)	GEUS project co-ordinator

National storage capacity

The CO₂ storage capacity onshore and near shore in Denmark is very large, some 16,000 mill. ton CO₂, while the offshore capacity in depleted oil and gas fields in the Danish section of the North Sea is much smaller, only 828 mill. ton CO₂. (Oil fields 176 Mt and gas fields 652 Mt) These estimates are from the GESTCO project on the European potential for CO₂ storage, which was initiated by GEUS in 1999. GEUS was project leader of both GESTCO (completed in 2003) and the following GeoCapacity project (2002-2006) under the EU 6th Framework Programme with participation from most European countries. The latter project also contains a “conservative estimate of storage capacities, which is much lower. For Denmark this estimate is 2600 mill. ton in Aquifers and 200 mill. ton in hydrocarbon fields (GeoCapacity 2009a, Kober and Blesl, 2010b).

The estimate of the onshore storage capacity was based on a study focusing on 11 individual storage structures mainly in Jutland.

Table 5.3. Main data for 11 identified locations of CO₂ storages in Denmark

Structure	Area (m ²)	Thickness (m)	Net/gross ratio	Porosity (%)	CO ₂ density (t/ m ³)	Storage efficiency factor (%)	Total estimated CO ₂ storage Capacity (Mt)
Hanstholm	603356598	230	0.40	20	0.620	40	2753
Gassum	241668369	130	0.32	25	0.627	40	630
Havnsoe	166442658	150	0.67	22	0.629	40	926
Horsens	317699055	94	0.26	25	0.630	40	489
Paarup	121316443	130	0.23	10	0.625	40	91
Roedby	55303608	256	0.18	24	0.620	40	152
Stenlille	8217927	130	0.76	25	0.631	40	51
Thisted	648970712	756	0.60	15	0.625	40	11039
Toender	52621027	203	0.17	20	0.626	40	91
Vedsted	31041316	139	0.74	20	0.633	40	162
Voldum	235015556	128	0.38	10	0.630	40	288
Total estimated CO₂ storage capacity in deep saline aquifers (Mt)							16672

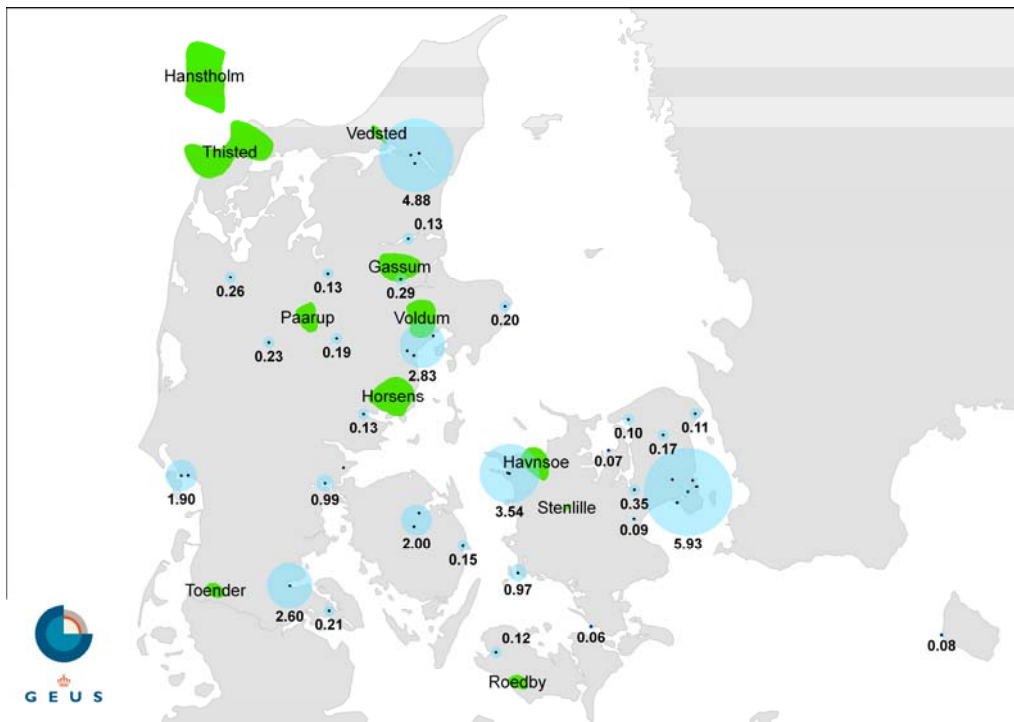
Source: GEUS.

5.2.3 Research in CCS

There is a long tradition in Denmark for development and implementation of coal combustion technology for electricity – electricity-only as well as cogeneration with heat. The condensing – electricity-only efficiency of the 300-500 MW extraction-condensing units increased during the last decades from less than 40 % to 47 % at Nordjyllandsværket. The use of seawater cooling instead of cooling towers added some 1.5 %-points to the efficiency. The Danish power companies have played a major role in the AD700² project on the development of further efficient coal-fired power stations.

² Project supported by the EU, see AD700.dk. The Advanced (“700°C”) PF Power Plant project aims at the development of pulverised coal-fired plants with live steam temperatures of 700°C.

Other important technologies have been urban waste incineration and large-scale combustion of straw.



Source: GEUS.

Figure 5.2. Potential CO₂ storages and point sources in Denmark

Specifically on carbon capture, DONG Energy has taken part in the CASTOR project, which included a pilot plant at Esbjergværket in Denmark aiming at testing the reliability and efficiency of the post-combustion capture process. The test facility was finished in 2006, and four 1000 hours test campaigns were carried out the following year.

The total CO₂ emission from Denmark in year 2000, which is the starting year of the model study was 52.5 mill ton. Annual variations are significant, because electricity export from coal combustion varies with hydropower production in Norway and Sweden.

CASTOR pilot plant

A test plant was established at the power plant at Esbjerg – owned by DONG Energy within the CASTOR project under the EU 6th Framework Programme in the period 2004-2008. This project was aimed at developing new CO₂ post-combustion separation processes suited to the problems of capture of CO₂ at low concentrations in large volumes of gases at low pressure. The processes were tested in a pilot unit capable of treating from 1 to 2 tons of CO₂ per hour, from real fumes. At that time it was the largest installation in the world. The pilot plant is a modern CHP coal-fired plant operated by ELSAM (now DONG Energy), which also supplies the district heating system at Esbjerg, located near the Danish North Sea oil and gas fields.

Vedsted formation

In Vedsted, some 30 km from Nordjyllandsværket, Vattenfall started collecting new seismic data in September 2008 as a part of a full-scale project for capture, transport and

storage to be available from 2013. The potential CO₂ storage in a geological formation at a depth of 1-2 km under ground³.

In connection with this, block 3 at the Nordjyllandsværket facility is currently being fitted with a full-scale plant for capturing carbon dioxide using post-combustion technology. However, in the Autumn 2009 it was decided to postpone this project.

5.2.4 CO₂ transport and storage

The method used for estimating transport cost of CO₂ was developed for the Netherlands (Hoefnagels and Ramirez, 2010) and used by all partners in the Storage Utsira project. The transport cost depends on capacity (scale), distance and terrain factors. The latter encapsulates the geographical and human land use that impact pipeline siting and construction. For example peaty soils, social/legal aspects, dense populated areas and numerous art works and waterways makes on-shore pipeline in the densely populated countries to be expensive.

Model of pipeline costs

To estimate the diameter of the CO₂ pipeline as a function of mass flow, the Ecofys model as presented by McCollum and Ogden. (*Details (omitted)*)

CO₂ storage costs

A similar analytical process for CO₂ storage has been taken, with engineering derived data aggregated in the UK model, and checked against the detailed reservoir database in the Dutch model. For CO₂ storage quantities, key parameters are the minimum storage size (4 MtCO₂ for hydrocarbon fields and 2 MtCO₂ for aquifers), the thickness of the reservoir (>10 m), the depth to the top of the reservoir (≥800m), the exclusion of overpressures areas and the seal composition (salt, anhydrite, shale or claystone). For CO₂ storage costs, key parameters are the drilling costs, the site development costs (e.g., exploration costs for aquifer are higher than those of hydrocarbon fields with prior geological data), well fixed costs, and surface facilities (e.g., hydrocarbon fields have old platforms that can be re-used). For Denmark, however, only the standardised cost parameters from the Pan European model are used.

CO₂ transportation costs for Denmark

Table 5.4 shows a set of techno-economic assumptions for the calculation of CO₂ pipeline transportation cost and shows result for pipeline lengths and CO₂ mass flows that may be used in Denmark for transport of CO₂ between the point sources connected to large and small district heating systems and the domestic onshore and near-shore CO₂ storages. For example 5 Mt mass flow from the power stations in Copenhagen with 100 km to the nearest storage or 250 km to Esbjerg or Hanstholm. Branch pipes from 50-100 MW CCGT units in mid-sized towns are represented by 0.5 Mt mass flow and the distance 50 km. Transport from Danish sources to Utsira is not considered here (see Section 0).

As described above, Section 0, the main point sources on Zealand are the two large power plants in Copenhagen. The nearest storage possibility is Havnsø, nearly 100 km away. A pipeline should have the dimension 0.42 m and the annual capacity 5 Mt CO₂. Some smaller point sources may be connected to the main pipeline or directly to the storages at Havnsø or Stenlille.

³ From Vattenfall Annual report 2008, <http://report.vattenfall.com/annualreport2008/Menu/CCS>:

For modelling purpose we can assume 2 pipes of 50 km. However, there is no cost estimate for pipes of smaller dimensions.

Table 5.4. Techno-economic assumptions for CO₂ pipeline and booster station.

Pipeline			
Constant factor	C	1600	€/m ²
Discount rate		10%	
Lifetime		40	years
Fixed charge factor (FCF)		10%	
O&M pipeline		2.50%	of capital
Capacity factor		80%	
Booster station			
Investment		11	M€
Fixed O&M		5%	of investment
Electricity price		0.06	€/kWh
Variable O&M		0.114	€/ton CO ₂

Table 5.5. Calculation of CO₂ transport cost

<i>Input variables</i>						
Mass flow CO ₂	5	3	5	2	0.5	Mton/yr
Mass flow CO ₂	159	95	159	63	16	kg CO ₂ /sec
Length	250	150	100	50	50	km
Booster station	150	150	150	150	150	km
Terrain factor	1	1	1	1	1	
<i>Results</i>						
Diameter pipeline	0.50	0.37	0.42	0.25	0.14	m
Investment costs pipeline	201	89	67	20	12	M€
Investment cost booster station	11	11	0	0	0	M€
Fixed O&M cost pipeline	5.02	2.22	1.67	0.50	0.29	M€
Fixed O&M cost booster station	0.55	0.55	0.00	0.00	0.00	M€
Investment cost	5.4	4.2	1.7	1.3	3.0	€/ton CO ₂
Fixed O&M	0.1	0.1	0.0	0.0	0.1	€/ton CO ₂
Variable O&M	0.1	0.1	0.0	0.0	0.0	€/ton CO ₂
Total	5.7	4.5	1.8	1.3	3.0	€/ton CO ₂

Table 5.6. Regions for CCS modelling in Denmark

	Source: GEUS Annual Capacity emissions Mt CO ₂ Mt CO ₂		Pipeline length				No. of units			Pipeline capacity 50/100/250 kr			Pipeline dimension	
	Large CHP	Small CHP	Large CHP	Small CHP	Large CHP	Small CHP	Large CHP	Small CHP	Sum	Large CHP	Small CHP			
Zealand, 100 km	1131	11.59	100	50	1	2	5	3	11	0.42				
Funen, 100 km	0	2.15	100	50	1	3	3		3					
Jutland, 50 km	1463	14.97	50	50	5	3	3	3	24					
Hanstholm/Thisted	13792	0	250	50	1	28	20		20	0.87				
Total	16386	28.71												

Source: GEUS

	Max. Heat, PJ			Electricity capacity, GW				Heat Capacity, GW						
	Large CHP	Small CHP	Small CHP	Central power stations	Waste incineratio n	Decentral power stations	Total	District heating boilers	Central power stations	Waste incineratio n	Decentral power stations	Total		
Zealand, 100 km	26.4	6.6	6.6	4.71	0.15	0.35	5.20	2.05	4.48	0.67	0.76	7.96		
Funen, 100 km	8.3	3.1	3.1	0.91	0.07	0.07	1.05	0.77	1.10	0.15	0.16	2.18		
Jutland, 50 km	19.4	14.0	14.0	3.99	0.19	0.80	4.98	1.90	3.05	0.58	2.09	7.62		
Hanstholm/Thisted														
Total	54.0	23.7	23.7	9.61	0.41	1.21	11.23	4.72	8.63	1.40	3.00	17.75		

Source: Danish Energy Agency. Punktkilder. Download 13-11-2007

5.2.5 CCS Policy in Denmark

Until recently, CCS has not been considered as a part of the long-term Danish energy policy. However, in the publication from January 2007 “A visionary Danish energy policy 2025” it was stated: “Trials are at present being made on storing CO₂. If technological development indicates that this can be done cost effectively and without harm to the environment, the consequences for energy policy must be examined in greater detail. Naturally, this still lies some years in the future.”

Phase-out of coal

For more than ten years the government’s official standpoint has been complete phase out of coal rather than support of CCS. In the same period the technology and infrastructure for biomass combustion has been further developed. This includes incineration of nearly all combustible municipal waste in some 30 waste incineration plants supplying base-load heat to the large district heating systems as well as an increasing amount of electricity. In addition straw has become a significant fuel for several small-scale and a few large-scale CHP units. This opens for a vision of negative CO₂ emission, when combining biomass combustion and CCS.

A very significant additional constraint for CCS in Denmark is the planned development of wind power, which currently covers some 20 % of the annual electricity demand, but is planned to increase to more than twice as much. This will further reduce the need for base-load thermal electricity generation

For the model analysis in the Storage Utsira project it means that the potential for CCS is becoming increasingly constrained. To model these constraints, it means that the Pan European TIMES model, which has a structure that is harmonised to meet the requirements for 30 European countries, must be calibrated in further details for give a proper representation of the constrained potential for Denmark.

Official standpoint with respect to CCS

Autumn 2009, the homepage of the Ministry of Climate and energy only contains this short message with reference to Directive 2009/31/EC: “The climate and energy package

supports CCS technology, which offers the potential to reduce CO₂ emissions through storage of CO₂ underground”⁴The Danish Energy Agency has a short description of CCS in Danish and a shorter in English,⁵

On the other hand, it is the Government’s long-term vision that Denmark shall become 100 % independent of fossil energy. This may not necessarily include the use of CCS. However, in 2009 the Danish Energy Association published a long-term vision for a future CO₂ neutral energy system in Denmark by 2050, “Power to the people” (Dansk Energi, 2009) This vision is based on three main pillars:

- Energy efficiency
- Renewable energy
- CCS

In the analyses CCS will remove 7.5 Mt CO₂ by 2025 and 17 Mt by 2050. It means that by 2050 CCS should be installed on at least 3000 MW electricity generating capacity (utilisation time 6500 hours/year).

Table 5.7. CO₂ removed by CCS in the scenario from Danish Energy Association, 2009.

	2025	2050
From coal	6.0	7
From biomass	1.5	10
Total	7.5	17

5.2.6 International network with connection to Utsira

Various scenarios exist with respect to layouts of the pipeline network for these five countries transporting CO₂ streams to the Utsira formation in the North Sea. In this section we classify them into three types and identify their respective features.

Figure 5.3 shows a schematic representation of two of the four network layouts and variants that were considered in WP 5 of this project (Wu and Ramirez, 2010) together with the organisation of investment and operation of the networks. In the first type of network, Network I. In the layout, each country builds and transports CO₂ streams to Utsira through its own pipeline. In the second type of network, Network II, a trunk pipeline towards Utsira or the country is close to storage site (e.g. Norway), the countries might still transport CO₂ directly to Utsira via their own pipelines. Other countries with less mass flows like Denmark, could collaborate and transport CO₂ streams together through a joint trunk. In Network type III a trunk with large transport capacity is constructed from Utsira to the border of Norwegian exclusive economic zone in the North Sea. A sub pipeline is used to bridge CO₂ flows from Norway to this common trunk. The other four countries connect to the transport trunk through constructing individual sub pipelines inside their respective exclusive economic zones as well.

⁴ <http://kemin.dk/en-US/climateandenergypolicy/EUclimateandenergypolicy/climateandenergypackage/CCS/Sider/Forside.aspx>.

⁵ http://www.ens.dk/en-us/policy/eu/climate_energy_package/ccs/sider/forside.aspx.

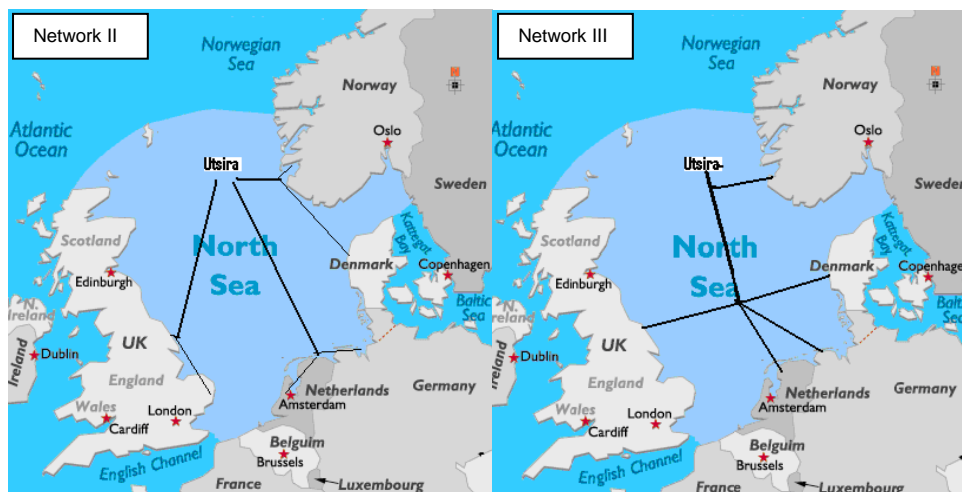


Figure 5.3. Alternative layouts of pipeline network to Utsira

In each of the network layouts there is a connection from Denmark, either from Hanstholm or Esbjerg. In the regional model the Danish hub is called Nybro, which is the location (near Esbjerg) of the gas treatment plant and the landing point for the pipeline from the Danish gas fields in the North Sea. The possibility of a common storage in Denmark, e.g. the large near-shore capacity at Hanstholm in the build-up phase was not considered in WP5.

In Table 5.8 the direct distances from the main power stations to Esbjerg and Hanstholm are shown. From all locations in Jutland (in particular Aarhus, Aalborg, Esbjerg and Skærbækværket) the distance to either Esbjerg or Hanstholm is below 150 km, which does not require a booster station. The distance from the most interesting source location, Copenhagen, is 250-300 km, which will require a booster station.

Table 5.8. Direct distances to Esbjerg and Hanstholm

	Latitude N	Longitude E	Esbjerg	Hanstholm
Esbjerg	55 28	8 27		
Hanstholm	57 06	08 35		
Copenhagen	55 40	12 34	260	292
Århus	56 08	10 11	131	145
Odense	55 24	10 23	122	219
Aalborg	57 02	9 54	196	80
Skærbæk værket	55 31	9 37	74	187
Esbjerg	55 28	8 27	0	182
Kalundborg	55 41	11 06	168	221
Åbenrå	55 03	09 25	77	234
Stignæs værket	55 12	11 15	178	268
Kyndbyværket	55 48	11 52	218	248

5.2.7 Key assumptions for CCS modelling in Denmark

According to the assumptions made for the Pan European model up to 22 Mt CO₂ per year from Denmark can be transported and stored at costs below 5.5 €/t CO₂, of which hard coal fired power plants represent the major and most reliable emission sources.

Conversely, the data from industrial installations seems less reliable, which may be due to insufficient or obsolete information in the database used for the model.

Concerning CO₂ storage, low transport costs can be reached, if onshore aquifer storages are available. This seems to be the case for Denmark. In contrast to Germany, the Netherlands and the UK Only the cheapest option, “Aquifers onshore” will be needed for storage of the quantities that were identified by the analysis.

5.2.8 Heat recovery by large district heating systems

The models contain techno-economic parameters that quantify expectations on gradually increased efficiencies and lower costs during the next 3-4 decades. The most critical parameter is the loss of thermal efficiency during carbon capture. For example, the efficiency of modern coal-fired steam turbines (pulverised coal) will be reduced from 46 % to 36 %. This will improve in the future for both with and without CCS, and for some of the variants of CCS technologies the difference may be reduced. Table 5.9 shows the assumptions chosen for quantitative modelling in the Storage Utsira project

Table 5.9, Efficiencies for new large gas and coal fired power plants and the same technologies with CCS.

		2010	2020	2030	2040
<i>Reference plants</i>	NGCC	58.0	60.0	63.0	64.0
	PC	46.0	50.0	52.0	52.0
	IGCC	46.0	50.0	54.0	56.0
<i>Post combustion, capture rate 85 %</i>	NGCC	49.0	52.0	56.0	58.0
	PC	36.0	42.5	45.0	46.0
<i>Pre combustion, capture rate 85 %</i>	IGCC	38.0	44.0	48.0	50.0
<i>Oxyfuelling plants, capture rate 94 %</i>	NGCC	48.1	50.1	51.6	52.1
	PC	38.0	40.5	43.0	44.0

Although cogeneration technologies for both district heating and industrial processes has been a key issue for The MARKAL and TIMES models, the use of combined heat and power (CHP) has not been systematically studied together with CCS. Obviously some of the energy lost in the carbon capture process could be recovered for heat to supply large-scale district heating systems or industrial processes.

Recent studies by the Dutch partner in the project, Utrecht University has addressed this issue for industrial CHP in different scales, (Kuramochi et al. 2010). The figures for decentralized CHP plants differ substantially from the figures for large scale central generation units (>500 MWe) that are reported in Table 5.9.

For the large scale industrial CHP plants studied in the Netherlands, the energy required for the capture of CO₂ is for a large part used in the form of heat in post-combustion capture systems (mainly for regeneration of solvents). This implies that the total efficiency loss of heat + power is actually higher for CHP plants than for dedicated electricity plants.

Apparently, these results are not valid for Denmark, where large-scale CHP is used exclusively for (mainly large-scale) urban district heating systems. For this type of CHP it has never been studied how much of the lost energy that can be recovered, and the required additional investment in the capture process is unknown, but the additional costs for heat recovery are most likely less than the uncertainty of the investment costs.

Only in few countries the necessary infrastructure is available for a massive use of CCS in combination with CHP. Denmark is the exception, where heat recovery from CCS could have a significant impact within a relatively short time horizon.

5.3 First Danish Reference Case for the Pan-European model

This section presents the first reference case by the Pan-European model that was used for scenarios until 2050, and the following Section 5.4 describes the subsequent development of the Pan European model with results from the RES2020 project.

Forecasts for import prices for crude oil, oil products and natural gas follow the general forecast for all countries. These forecasts were modified and updated during the development of the first version of the Pan-European model, following the latest European forecasts by the GEM-E3 model. Export prices for the same fuels are 1 % lower than import prices. Delivery costs are specific for technologies and fuel types, and should be considered as national specific. Crude oil prices in the scenarios are increasing from 6.51 €-2000 per GJ in 2005 to 7.53 € in 2050, equivalent to 47 and 53 \$-2005 per barrel. These prices are between those used by IEA for ETP 2006 and 2008.

The Danish model was developed as one of 29 harmonised models for European countries. The primary aim at this stage of development is to select assumptions that were able to provide reasonable forecast results, which may be studied in further details in order to evaluate and improve the large number of parameter assumptions. In many cases the best choice of parameter assumptions are values used in other national models, in particular those that were used as basis for development of several national models. For this reason German data were preferred for parameter assumptions for the development of the Danish model.

5.3.1 Electricity

Electricity system issues

No new large fossil fuelled units are assumed before 2010.

The Base Case of the Energy Strategy 2025 assumes that 27 % of the Danish electricity generation in 2025 is covered by wind. This increase is modest compared to the current 20 %. It is also assumed that Denmark will be net exporter of electricity in the whole period. At an annual basis the Danish demand will be covered by wind power and CHP generated electricity. However, import and export will be essential for the operation of the Danish electricity system.

These features can be modelled in TIMES only by setting appropriate constraints and parameters, which need to be developed partly by trial and error. In the first version wind power capacity was exogenous following the assumptions of the Danish Energy Strategy 2025.

Retirement profile

In the first approach (May 2006) all condensing thermal plants (electricity-only technologies) is reduced from 100% in 2000, (2.59 GW) to 75 % in 2005 50% in 2010 25% in 2015 and zero by 2020. These plants are mainly older plants located away from district heating networks.

Retirement of the newer CHP units – both central extraction-condensing units and decentral back-pressure – units follow a similar path, but 5 years later. The total capacity

in 2000 was 6.41. GW. For wind power the capacity in 2000, 2.8 GW, will be retired during a ten-year period from 2010 to 2020.

This retirement profile is consistent with the main assumption in the Danish Energy Strategy to 2025. The current electricity spot price on the Nord Pool electricity exchange is too low to justify investment in new capacity. It is assumed that the spot price will increase gradually until about 2015, as the existing reserve capacity will be phased out. The higher spot price will make investment in new generating capacity attractive.

The retirement profile was not modified in the development process. However, the Energy Strategy and more recent planning efforts in Denmark includes a detailed decommissioning assumption. These assumptions should be implemented into the Danish model at a later stage.

Wind power

According to Eurostat the wind power capacity in 2000 was 2.8 GW. In recent years many older wind turbines have been scrapped and replaced by fewer, larger turbines. In addition several pilot projects for off-shore wind power has been developed. According to Danish Energy Strategy to 2025 off-shore wind farms could be commercially interesting after 2011, depending of the framework conditions. The range of the assumed off-shore development in the period 2011 to 2030 is wide: between 800 MW and 4200 MW new off-shore capacity.

The energy strategy (Base Case) assumes 400 MW offshore wind power until 2010 (from about 2002) and net increase of onshore capacity at 173 MW. By the end of 2000 the total wind power capacity was 2972 MW, of which 210 MW was off shore. By the end of 2005 these figures were 3135 MW and 399 MW, respectively. For the Pan-European model it can be assumed that additional 400 additional offshore capacity will be installed until 2010. This is consistent with the target in the energy planning since the mid-1990s, and tendering for this capacity was agreed by a large majority in Parliament in 2004 (www.windpower.org).

Thus, the minimum installed wind capacity by 2010 is set 3550 MW, of which 800 MW will be off shore. This will be the minimum capacity for the rest of the period until 2050 in the BAU scenario. The maximum capacity is set at 8000 MW, of which 4000 MW will be offshore.

District heating and gas grids

Investment in new district heating and gas grid cannot be optimised without a very detailed representation of the geography in the model. This means that the grid development must be exogenous. Most areas suitable for district heating and gas were developed during the 1980s and 1990s, and further development of district heating may be limited. There is still a potential for adding customers to existing grids, but unit consumption is likely to decrease because of better insulation. New single-family houses may be too energy efficient to justify major investments in water-based heat distribution systems.

5.3.2 Resource and infrastructure constraints

It was assumed that oil and gas resources in the North Sea would be exhausted within the modelling period. The highest production level is about present. A constraint that limits the production to the present level will be the first approach in for the model..

Outside the electricity and district heating sector constraints on the use of some fuels will be necessary, either assuming no investment in some technology processes or no use of some fuel commodities, e.g. coal outside the electricity sector.

5.3.3 Energy demand

The demand forecasts in the NEEDS Pan-European model is based on GEM-E3 forecasts.

These assumptions includes forecasts of demand drivers, assumptions on income elasticities, price forecasts and emission coefficients. The method and assumptions are described by Kanudia and van Regemorter (2007).

5.3.4 Results of the base case of the Pan-European model till 2050

The development of the Pan-European model within the NEEDS project was finished in the Autumn of 2007 and the aggregated results for all countries have been presented at several workshops afterwards.

This means that the Danish model is ‘frozen’. The results and assumptions can be studied in details and compared with other models, but any modification and improvement should be made with reference to the ‘frozen’ model version. The following figures are selected from those that were developed for the presentation of the Pan-European model.

Electricity generation

Figure 5.4 shows the net electricity generation in the base case till 2050. The increase in wind is the result of the planned investment and not of the optimisation. In the shorter term until 2015 the role of coal will be reduced and gas gains a larger share. This is partly a result of decommissioning of older – mainly coal-fired capacity. After 2015, most new investment will be in new coal-fired technology, because the emissions of CO₂ are not constrained in the base case. These results are reflected very directly in Figure 5.5.

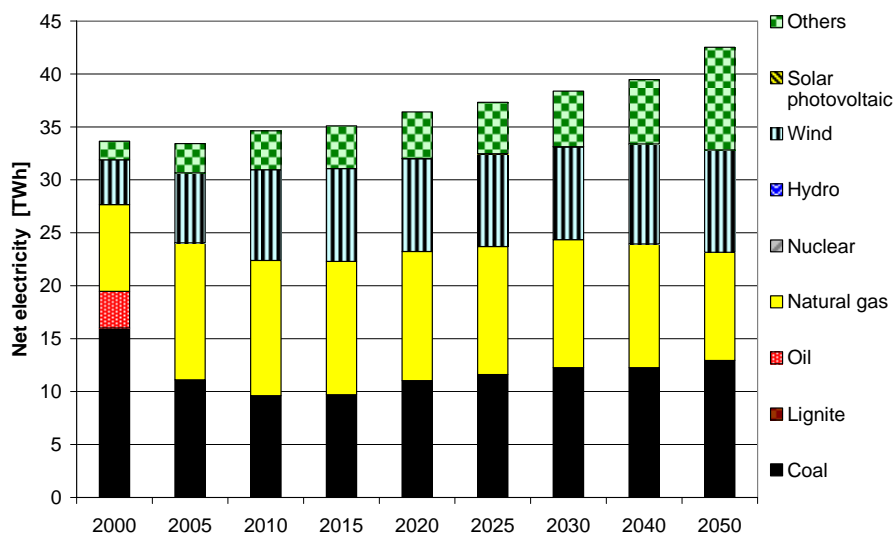


Figure 5.4. Pan-European model October 2007, BAU. Net electricity generation, Denmark.

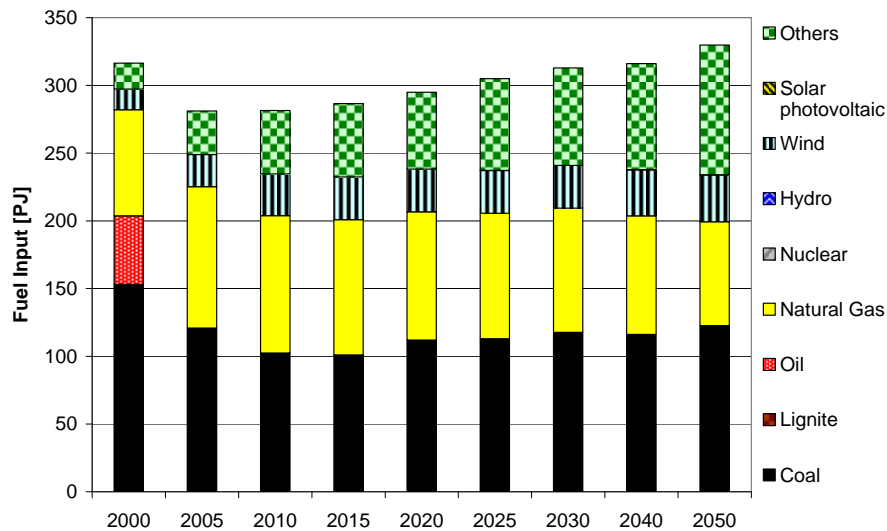


Figure 5.5. Pan-European model October 2007, BAU. Fuel input for electricity generation, Denmark.

The relative small electricity generation by oil disappears in the optimisation from 2005. This indicates that the technical constraints may not be sufficiently detailed. Danish coal-fired plants normally use oil for start up, but not as much as shown for 2000. An appropriate constraint for the share of oil should be calculated and tested for a later version of the model. In Figure 5.6 showing the development in capacities, the oil-fired capacity is phased out. These units are mainly kept as reserves with very few operation hours, and there is no new investment in oil-fired units.

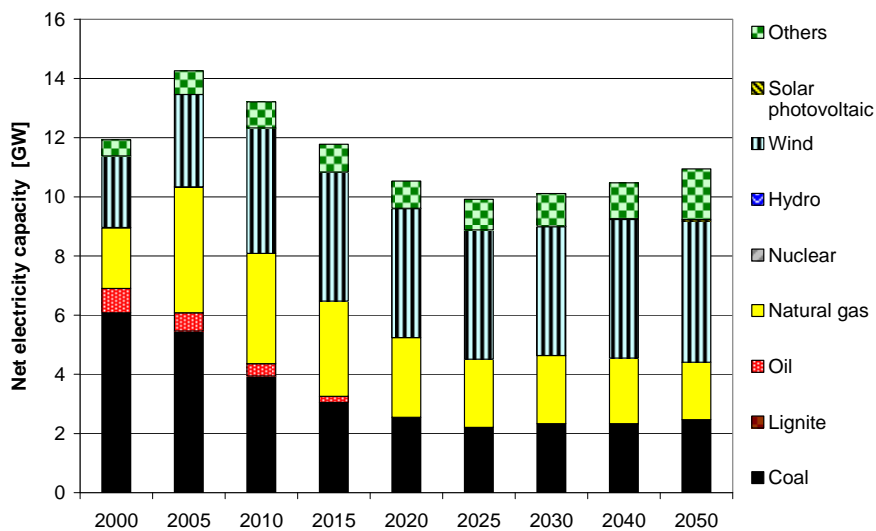


Figure 5.6. Pan-European model October 2007, BAU. Net electricity capacity, Denmark

Final energy demand

The current model specification tends to select coal, biomass and other renewables for the end-use sectors. Some resource-limited fuels, e.g. geothermal, were constrained by their resource availability already in the initial development of the model. In the later development, coal was excluded from the residential, commercial and agricultural sectors, and a lower limit was set for natural gas to avoid an unlikely phasing out of gas,

which would be due mainly to the relative prices currently used in the model as well as more detailed infrastructure constraints.

For transport only constraints used in several national models were used. The current results show that hydrogen, methanol and natural gas is chosen by the model after 2020.

Air Emissions

Figure 5.7 shows the unconstrained development of CO₂ emissions as calculated from the current result of the optimisation.

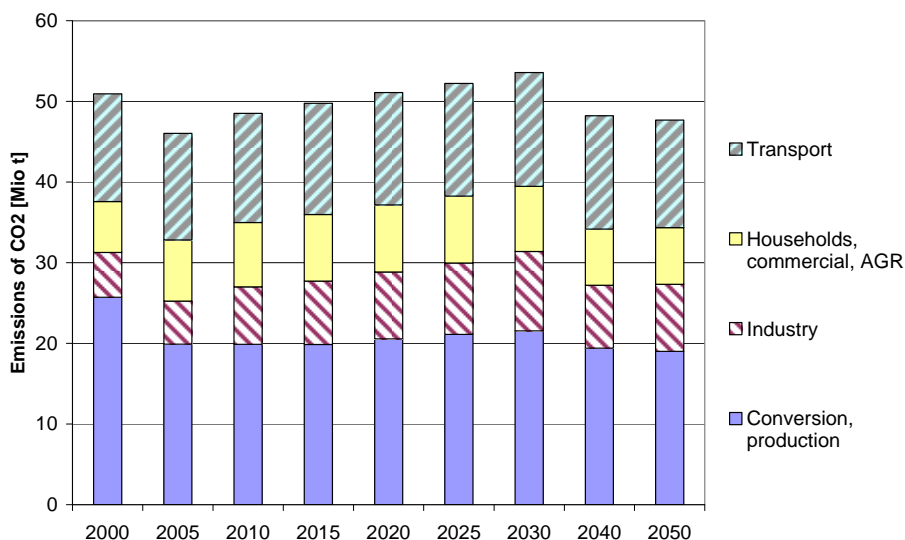


Figure 5.7. Pan-European model October 2007, BAU CO₂ emissions, Denmark

5.3.5 Scenarios of special significance to the national system

For Denmark electricity trade will have particular impact on the electricity system. It means that scenarios focusing on electricity prices and their distribution among time-slices and the treatment of the stochastics of hydro power will be of particular interest. Addressing these issues may depend on an analysis of preliminary results from the Pan-European model.

These scenarios shall be co-ordinated with the neighbouring countries, focusing on hydro power in Norway and Sweden and wind power in Germany – in particular the northern parts of Germany.

5.3.6 Conclusion on the status of NEEDS-TIMES

The results of the NEEDS-TIMES Pan European model is an important common reference for all further developments of the Pan European model made by different teams and financed under different programmes. Using the input documentation features in TIMES as described in Section 4.2.1 it is possible to compare all assumptions for different versions of the Pan European TIMES model or other TIMES models.

5.4 Using the RES2020-TIMES Pan European model as basis for national model studies

This section is developed from a conference paper describing a national application of the Pan-European model (Grohnheit et al. 2010) focusing on the potential for bioenergy in Denmark, originally based on a simplified spreadsheet model (Callesen et al., 2010a,b, Grohnheit, 2008).

5.4.1 The EU RES2020 project

RES2020 (2006-09) aimed at analysing the present situation of the RES implementation, i.e., defining future options for policies and measures, calculating specific targets for the RES contribution that can be achieved by the implementation of these options and finally examining the implications of the achievement of these targets to the European economy.

The NEEDS-TIMES Pan-European model has been enhanced for the renewable technologies that are in the focus of the RES2020 project. These are

- Renewable electricity generation, including wind and distributed electricity generation
- Biomass for electricity and heat

In the original project plan it was assumed that the NEEDS-TIMES model should be run by the model teams with the enhancements country by country. This was changed, so that the Pan-European model, which has been taken over from NEEDS, was run centrally as a multi-regional model. This means that both enhancements and calibration of 2005 data from Eurostat have been made centrally. The final results, corrections and main sensitivity results were distributed May-July 2009, now available online via www.res2020.eu. A huge material covering all sectors of the energy system with consistent results for several policy scenarios and variants is available for further analyses.

5.4.2 Primary and final energy use in Denmark

The four scenarios analysed in Res2020 were (BAU) based on policies without the ingredients of the January 2008 energy and climate package and 3 policy scenarios: (RES) a reference scenario for the 2020 policies, in which the essentials of this package are implemented, (RES-T) where – next to physical trade of (renewable) electricity and bio-fuels – a virtual trade mechanism in RES production rights is in place, and (RES-30%) in which the greenhouse gas emission reduction objective for EU is 30% instead of 20%. These scenarios were calculated for all countries (EU27 plus Norway, Iceland and Switzerland). For some countries further variants were analysed.

For Denmark the share of renewable was 9 % in 2000. This figure will increase to 24 % by 2020 in the BAU scenario, and 27 % in the policy scenarios, with very little variations among these scenarios, mainly due to the planned increase in off-shore wind and biomass in the electricity and heat sector. Also for primary and final energy, the three policy scenarios give very similar results. The most important development of renewables is the further penetration of wind power, which is policy driven. Further, there is a significant increase in bioenergy from 2000 to 2020 in the BAU scenario and some additional increase in the policy scenarios, but little difference among these three scenarios (Figure 5.8). Some small variations among the policy scenarios are found in the central electricity and heat sector for 2020.

For Denmark the RES and RES-T scenarios mean 30 % share of RES in final energy by 2020 and for all sectors, which do not fall under the European Emissions Trading scheme, a CO₂ emissions cap of 21.2 Mtons.

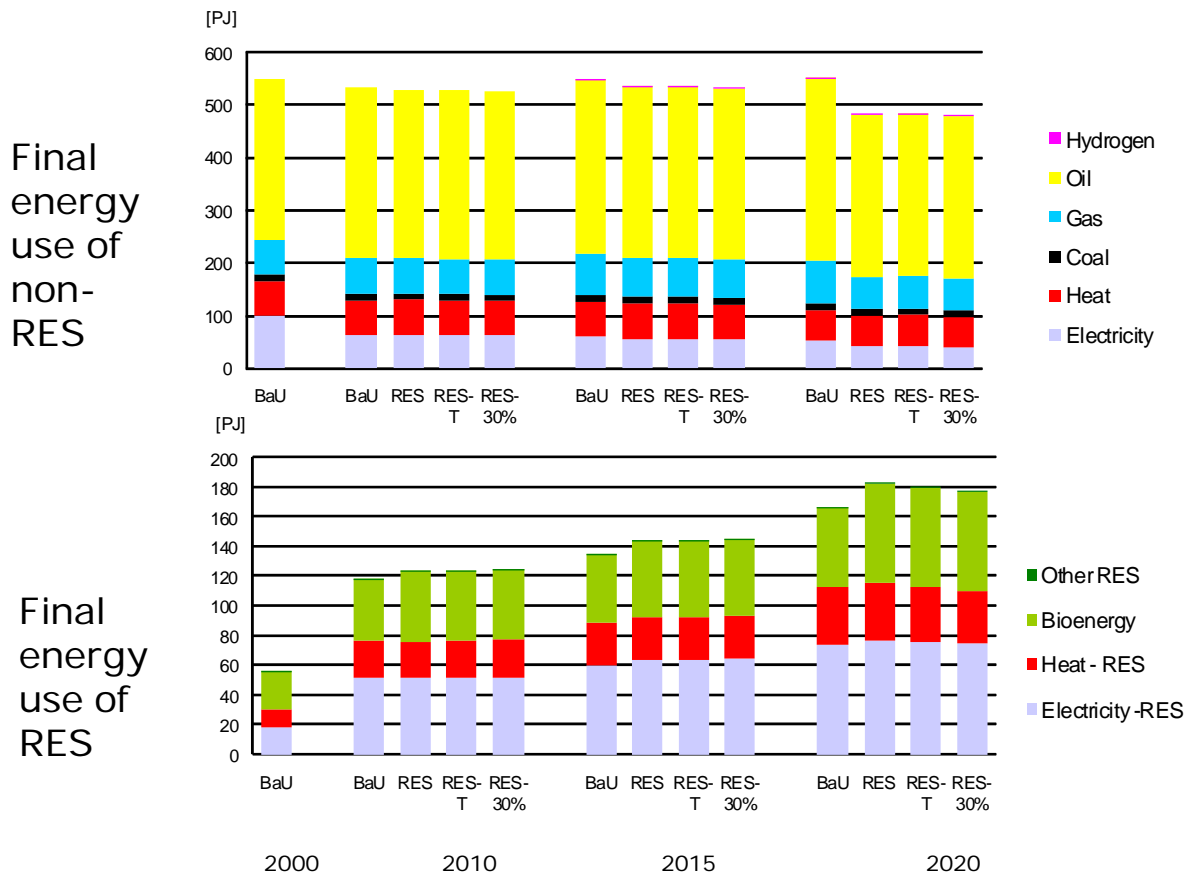


Figure 5.8. RES2020 Results: Final Energy use of renewable and non-renewables

5.4.3 Use of renewable energy sources

Analysed by sector, the use of renewable energy in the scenarios reveal that bioenergy (wood) based central heat & power is the dominant source. Renewables in agriculture are mainly based on agricultural waste, in particular straw and biogas in a small scale. However, the preferred use of agricultural waste is in the district heating sector, mostly for CHP supplying small district heating systems, although straw is also used in large-scale CHP units. The model results for industry are uncertain.

There is little tradition for optimization modelling of large energy consuming industries in Denmark, because there are only few plants, i.e., one cement plant and one steel work which has operated only in short periods during recent years. The central electricity and heat is by far the most important user of renewables.

5.4.4 Electricity and heat

In the 1980s nearly all new capacity was medium-sized extraction-condensing units for large-scale CHP; in the 1990s a significant share was small-scale gas-fired CHP units for decentralised district heating systems. Wind power covers about 20% of the electricity demand in the years 2004-2008 on an annual basis. 2.8 GW installed capacity and 6.6 TWh of wind generation covers approximately 20% of the nation's demand (2005-2008). The Government's new energy strategy supports the expansion of wind energy capacity for on- and offshore. Prospects for micro CHP are limited due to the large role of district heating in heating of single-family houses. Industrial autoproducers have generated about 9 % of the total demand after 2000.

The district heating infrastructure covers all the more densely populated urban areas, including small towns and villages (22% of the heat supply for single family houses and 66% for multi-family houses). Base load heat in nearly all district heating networks is supplied CHP plants, ranging from less than 1 MW gas motors to large-scale power plants. In urban areas with interconnected district heating systems incineration of urban waste for energy have priority over other sources for heat supply. Natural gas covers individual homes in areas less suitable for district heating (18% of the heat supply for single family houses and 9% for multi-family houses in 2005). All densely build up areas are zoned for district heating or natural gas depending on heat densities and access to networks. Electric resistance heating (about 5 % of the heat market) is being phased out in areas zoned for district heating or natural gas. Outside these areas heat pumps or biomass renewables are encouraged. Expanding the district heating systems with flexibility using heat storages will be one of the measures to accommodate much larger amounts of wind power.

5.4.5 Transport fuels

The available biomass resources may be used for either transport or electricity and heat. The infrastructure for the use of biomass for electricity and heat is available, and it is being further developed. The key priority for new transport fuels is electricity for charge of batteries for electric vehicles. This technology will be needed for an efficient further penetration of wind power. Thus, electric cars supplied by wind power are seen as an important means to achieve the target of 10 % renewable in transport. Biofuels for transport is an important Danish research priority.

5.4.6 Trade and import dependency

Currently, the only import of fossil fuels to Denmark is coal for the central electricity and heat sector. The current oil and gas production exceeds the national demand, so the surplus is exported. However, both oil and gas production has peaked about 2005 and is expected to decrease over the next decade.

The trade pattern for electricity is determined by the variations in hydro power in Norway and Sweden and wind energy in Denmark. The remaining fossil electricity-only production has become the ‘swing producer’ on an annual basis, and in recent years this production has become larger than gross export. The current RES2020 Pan European model is not designed to model this trade or the intermittency of wind power.

5.4.7 Impacts of policies on emissions and costs

The model results for 2020 show reductions of CO₂ emissions for both the ETS sectors and the Non-ETS sectors for the policy scenarios compared to the BAU scenario. The reductions in the residential and industry sectors are mainly due to increased use of RES in these sectors, which is the same for all policy scenarios. For the central electricity and heat sector increased use of wind power and biomass as combustible renewable lead to reduction of CO₂. The reduction is largest in the scenario with the most ambitious CO₂ reduction target.

The total investment costs and operational costs of renewable technologies are calculated by the model between 500 M€ and 1000 M € by 2020, or about 0.01 % of GDP with no significant difference among the BAU scenarios.

5.4.8 Conclusions of RES2020 for Denmark

The BAU scenario for Denmark shows a significant increase in renewable energy sources until 2020 as shown in Figure 5.8. This leaves little room for further penetration

of renewables in the policy scenarios, and even less room for optimisation results of different policy scenarios. However, the results, which are now available online, may be explainable within the logic of the optimisation model.

The first set of results from the Pan European model – as a result of the NEEDS project – from the autumn of 2007 was presented primarily as European totals as a long-term reference until 2050 for the selection of new technologies (see Grohnheit, 2008). The next step has been the enhancements of some of the model sectors and the much shorter time horizon until 2020, which gives much less room for large-scale penetration of new technologies. These results are now being improved by further analyses of the assumptions and results in the individual national models. The common structure of models for 30 European countries will allow accumulation of model experience, and thus improve the conclusions that may be drawn from the results – mainly using the national models individually. The current results for biomass trade indicate that the Pan European model may be used to disclose a trade pattern that will benefit from the differences in infrastructure and existing equipment among the European countries.

5.5 Evaluating sustainability of bioenergy production using ecological and economic models

This project initialised spring 2007 will develop and apply quantitative models for evaluating sustainability of energy production from agriculture taking into account biomass production (e.g. growing system), technologies to convert biomass into different types of energy and recycling of residues and products. Sensitivity of model conclusions will be studied by comparing different models and systems as well as by including statistical uncertainties of input data.

The project is part of an interdisciplinary collaboration between 1) a group at the Biosystems Department with a long established expertise on the agro-ecosystem and modelling biological interactions, and a strong network with Danish and international agricultural research, and 2) a group at the Systems Analysis Division with a long established expertise on analysis of energy systems and energy technologies and a strong network with international organizations.

Ingeborg Callesen, who holds a PhD in forest ecology, is working on the project, which includes participation in the modelling activities within the EU RES2020 projects

This section focuses on the selection of data for modelling bioenergy production, while the following Section 5.6 considers the implementation of these data into the Pan European TIMES model. Both sections are based on Callesen et al. 2010a and Grohnheit et al., 2010.

5.5.1 Bioenergy yield from cultivated land in Denmark

To further resolve the sources and potentials of bioenergy supply in Denmark the framework of the TIMES model was used in a much simpler model for a fuel mix of bioenergy and fossil energy with more elaborate data for cultivation of bioenergy and based on an economical optimisation of the choice of crops grown. The biological production potential of cultivated land is a combination of physiographic conditions (soil quality and climate), crop type, seed material, cultivation method, fertilizer and irrigation. Assessment of the potential sustained biomass supply is needed in order to evaluate the potentials of switching from fossil-based carbon to actual biomass sources for energy and goods.

For Denmark, energy policy goals have been set by the Danish Government (Danish Energy Agency, 2009). By 2011, the Danish energy supply from renewable energy sources should be 20%. The utilization of biomass is closely linked with the structure of the Danish bioenergy sector. The combustion of biomass for district heating and combined heat and power (CHP) is well developed as technology and infrastructure. There is no pulp and paper industry in Denmark, and by 2005, a fuel ethanol industry was non-existing.

5.5.2 Biomass in energy models

Estimation of biomass feedstock potentials from energy crops and crop residues in future scenarios may be based on various modelling approaches, taking into account environmental concerns such as loss of biodiversity and water quality in the agricultural landscape (EEA, 2008). Biomass is all kinds of photosynthetic tissue, and for simplicity potential bioenergy crops may be grouped into starch, oil, sugar, grassy and woody biomass products like in two recent projects under Intelligent Energy Europe, REFUEL (Fischer et al. 2010a,b) and RES2020 (2009). REFUEL includes an assessment of biomass potentials for biofuel feedstock production in Europe, which is based on IIASAs agro-ecological zones modeling framework.

Technologies for use of biomass for energy are considered in RES2020. In contrast, the upstream technologies, i.e. cultivation of crops, were not considered in RES2020 TIMES. However, these technologies were in the focus of the work within a project to provide a transparent analysis of bioenergy yields from crops that are suitable for bioenergy in Denmark, which is reported in Callesen et. al., 2010a,b.

An optimisation model in an Excel workbook was used to explore links between energy demand, bioenergy and food&feed supply via the price of fossil oil. This approach serves the purpose of creating overview of primary bioenergi potentials, food&feed production and consequences for land use. Constraints to biomass production are included in modelling of bioenergy potentials e.g. by reservation of crops for food and feed or excluding biomass extraction from protected nature types. The outcome of the model is a crop area distribution of Danish cultivated land and an assessment of the biomass feedstock available for conversion to heat, electric power and transport fuels. The model is purely static with no endogenous investment in conversion technologies.

The energy efficiency of plant based bioenergy depends on land productivity, cultivation, and conversion methods. The question now remains in what quantity and at what cost bioenergy from different crop types can be supplied from cultivated land, and how the fossil oil price interacts with biofuel costs.

5.5.3 Materials and methods

The analysis is based on a static cost minimization model for bioenergy feedstocks grown in Denmark in a single year using currently grown crop classes and yield levels, Table 1. For each feedstock type a crop representative was selected, e.g winter wheat represents all starch crops. The model uses linear programming for providing solutions to an objective function that minimizes the cost of a fuel mix of bioenergy and fossil oil, represented by diesel oil, by changing the crop area distribution. Data on crop yields, input factors and input prices from the year 2005 were used. A key issue in the model, comparing the results using 2005 parameters with alternatives, is the changes in real fossil fuel prices and its influence on other costs of inputs used in the cultivation. Higher future cost price in proportion to the real oil price increase was based on an evaluation of

the direct and indirect energy used in the production of these input factors: seeds 25%, fertilizers 50% (nitrogen and potassium) or 75% (phosphorus), lime 50%, machines 25%, fuels and lubricants 100%, pesticides 25% .

Constraints on crop area use were delineated based on land data, limitations due to crop rotation requirements, protection of forest area (600 kha evenly distributed on average and low productive soil), permanent grassland (175 kha) and other constraints set by biological requirements of the crops.

Table 5.10. Feedstock types, crop representatives, conversion methods and efficiencies used in the model.

Feedstock type	Crop representative	Conversion method and efficiency
Woody lignocellulosic	Norway spruce, yield level PK8 and PK12 in 60 yr rotation Willow in short rotation forest (22 yr) on sandy and loamy soils.	Heat and combined heat and power (69-81%)
Grassy lignocellulosic	Grass-clover ley with 30-50% clover	Biogas (54%)
Oil crops	Oil seed rape on sandy (JB1-3) and loamy soils (JB5-6)	RME, Rape Methyl Ester (70%)
Starch crops	Winter wheat on sandy (JB1-3) and loamy soils (JB5-6)	1 st generation bioethanol (57%), straw used in combustion (90%)
Sugar crops	Sugar beet on loamy soils	1 st and 2 nd g. bioethanol (54%), tops used for biogas (54%)

Key scenario parameters: Food and feed requirement and fossil fuel prices.

In this application of the model we analyzed two sets of scenarios each with fossil oil prices ranging from index 25 to index 200 in intervals of 25 (<oil index 100) or 10 (>oil index 100), and cost levels were as experienced in the year 2005. The food, feed and timber demand was set to 167 PJ starch crop yields, 6 PJ oil crop yields, 11 PJ sugar crop yields, 38 PJ grass for feed based on 2005 crop yields. The reservation of timber for wood products was 5 PJ corresponding to about 25% of wood fellings. The main difference between the two sets of scenarios is the reservation for food and feed and some corresponding constraints on the area for short rotation forest (willow for energy use) and permanent grass.

- (a) A set of scenarios based on the food&feed production in 2005 (=100%). The area with willow was 0.2% of the available land area.
- (b) A set of scenarios with only 50% food and feed reservation as a variant of the scenario (a). Constraints on area use were due to prioritization of bioenergy and the environment. The short rotation willow was restricted to a maximum of 25% of the land area.

The feedstock cost reflected the combination of yield level (soil quality) and crop type and the cultivation intensity applied.

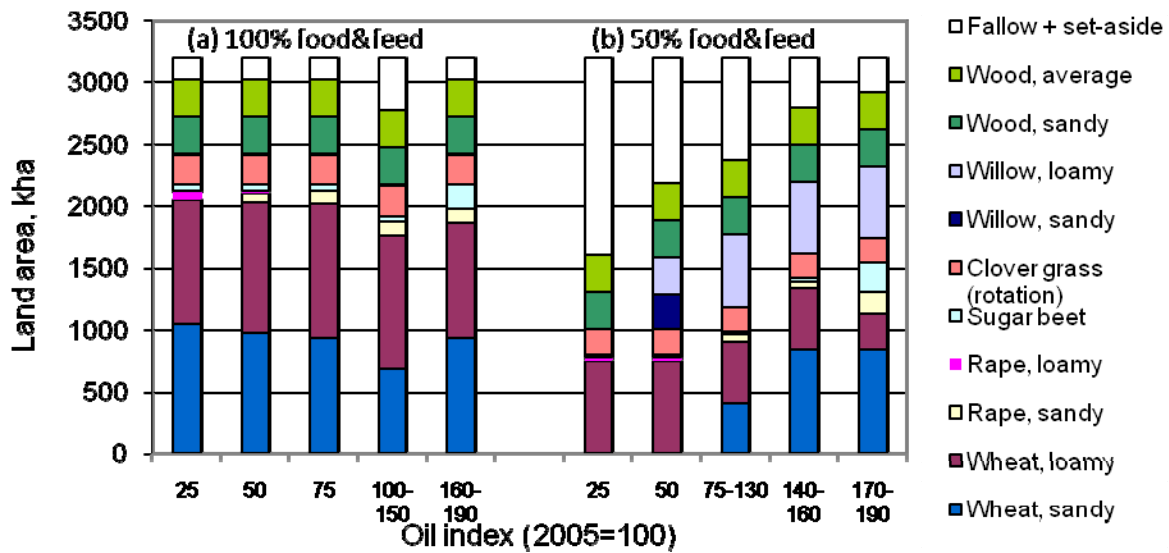


Figure 5.9. Area distribution of the (a) scenarios with 100% food&feed and the (b) scenarios with 50% food&feed for oil index 25 to oil index 190. Willow is allowed to occupy 25% of the crop area in the (b) scenarios.

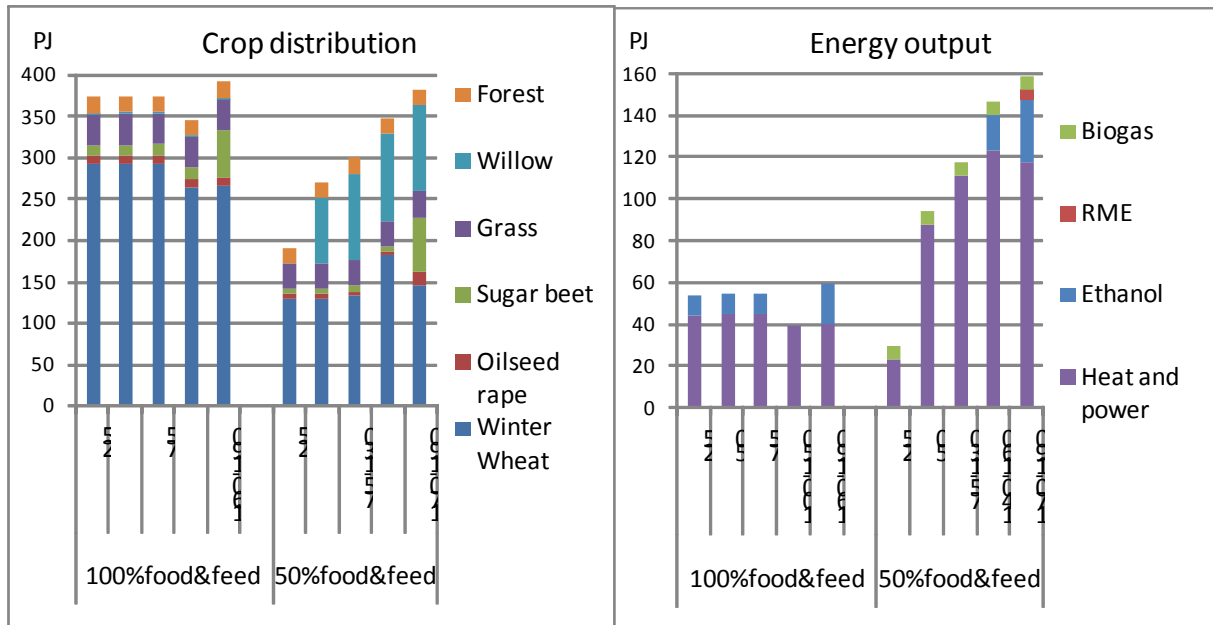


Figure 5.10. Scenario results for Cropdistribution in PJ and biomass energy output. Oil index range from 25 to 190 (2005=100).

In the (a) scenarios the cost minimized crop area distribution reflected the food constraints laid down in the model and the very limited constraints on willow plantations. Oilseed rape was grown on a very limited area, and sugar beet was only relevant for bioenergy beyond oil index 160 (Figure 5.9). In the oil index range from 75 to 150, the biofuel costs for wheat per GJ final energy were quite close to the fossil oil index. Different crop area distributions as solutions to the cost minimization may therefore result in quite similar values of objective function. The suggested optimized wheat area is a range, since fallow land, wheat and fossil oil compete in this price range.

In the (b) scenarios with much less crops reserved for food and feed, no or very limited crop area was allocated to energy crops at oil index 25. With increasing fossil oil index

the effect of the low yield level was evident since willow on sandy soil was only present at oil index 50. In the remaining price range the maximum willow area was grown on the high yielding loamy soils. Oilseed rape on sandy soil and sugar beet exceeding the mandatory area reserved for food did occur, but only at a relatively high oil price beyond oil index 160 with a concurrent reduction in wheat on loamy soils. The areas shown in Figure 5.9 are converted into energy units in Figure 5.10 (left), while Figure 5.10 (right) shows the energy output after conversion of the biomass available. The lower reservation for food and feed means that more biomass will be available for energy use. The total bioenergy supply across fossil oil prices in the (a) scenarios in Figure 5.9 ranged between 40 PJ and 60 PJ per year, and the (b) scenarios between 30 PJ and 160 PJ per year.

5.5.4 Short rotation forest

If the reservation of land for food supply is decreased, much more land would be set-aside or planted with forest in short or long rotation. The environmental benefits for the environment by reducing nitrogen loads (Erisman et al., 2008) through cultivation of perennial woody crops or setting land aside are obvious. Guesses of the potential available area for willow are 100 kha – far lower than the 581 kha that occur in the model result, Figure 5.9. There is no knowledge base for large-scale willow cultivation in Denmark indicating if the actual yields and costs can be sustained over time, and if it is accepted by the public. Willow plantations may be a way of increasing the forest area in the long term. The energy sector and the agricultural sectors are regulated, taxed and subsidized in numerous ways. The analysis indicates that volatile oil prices are contributing to the uncertainty of price developments for both food&feed and bioenergy markets. The market for solid biofuels, such as wood chips and energy grain, is well established and flexible. Switching between different biofuels and co-firing with fossil fuel in both small and large heat and heat and power plants is possible. In comparison with an annual total primary energy use of 800-850 PJ the bioenergy supply would range from 4% to 19%.

Domestic bioenergy feedstock production is very limited in comparison with the energy consumption. The possibilities of a substantial increase e.g. by cultivation of willow, even up to 25% of the available crop area, will not increase the bioenergy supply substantially, but the landscape would change dramatically. Biomass imports are needed if the contribution of bioenergy to the total energy production is to increase above current levels.

Apparently, willow in short rotation is a cost effective solid biofuel alternative to annual crops, but issues like actual future yields, landscape planning perspectives, environmental performance, and landuse flexibility need further consideration.

5.6 Implementation into the RES2020 TIMES model

The assumptions made for the static optimisation model described above will be implemented into the national model, which is included in the RES2020 Pan European model. In contrast to the simple model, the latter is a dynamic model covering the period 2005-2020 with model calculations until 2025. The results will be tested against the simple model and the final results from the RES2020 project.

5.6.1 Exploring the online results

Comparing Figure 5.10 (right) with Figure 5.11, which is extracted from the online results of the RES2020 TIMES model shows that the results of the static model with

50% food&feed restrictions for high prices on fossil fuels are very similar to the results from RES2020 for Denmark.

The price index for diesel oil in the RES2020 scenarios with 2005=100 is 147 in 2010, 155 in 2015, 168 in 2020 and 177 in 2025.

The similar results from the two different model approaches mean that both models are suitable for further analyses and comparisons.

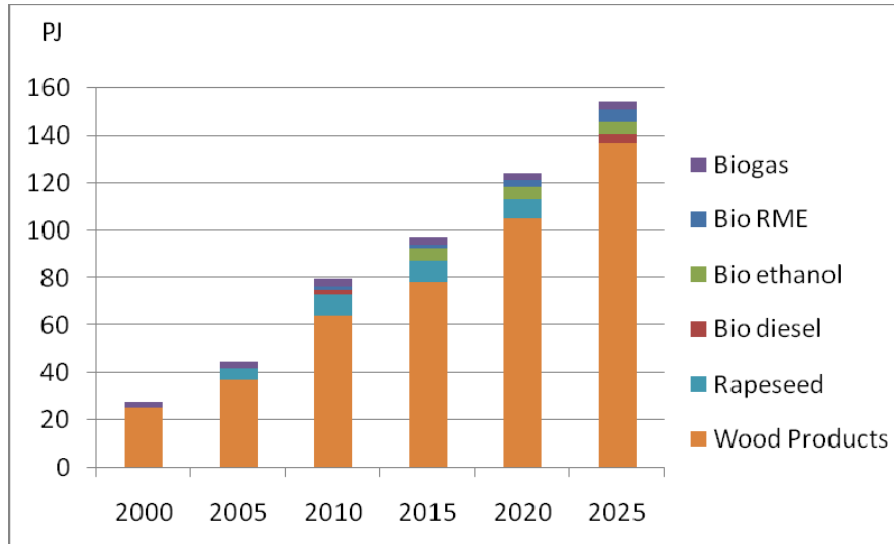


Figure 5.11. RES2020 Scenario 2020 for Denmark. Biofuels except municipal waste.

5.6.2 Exogenous variables

In RES2020 TIMES the commodity set “ALLBIO” includes waste incineration for energy, which is not shown in Figure 5.11, because the results would be misleading.

Investment in incineration of urban waste is driven by the need for environmentally optimal treatment of urban waste rather than the demand for energy. Thus, it does not make sense to consider all these technologies in the same optimisation. In the current RES2020 results waste for energy is phased out for nearly all countries. This result is most visible for Denmark, where waste incineration is used for treatment of nearly all urban waste that is not recycled. (Grohnheit et al. 2008).

For the same reason the food and feed requirement is exogenous in the static bioenergy model and not included in the optimisation.

5.6.3 Conclusion and perspectives

The static bioenergy model contains the structure of processes for an upstream module for RES2020 and the data that is needed for a national application for Denmark. A similar module for other countries will require a similar study of national agricultural and forestry statistics. However, similar to the original development of the Pan European model, a common base-year template may be developed – starting from international statistics on cultivated areas and crops – to develop a harmonised set of processes and parameters.

The most important methodological conclusion of this study for the further development of the RES2020 TIMES model is that requirements on food and feed from agriculture and non-energy material from forestry must be exogenous to an optimisation model driven by the demand for energy services.

6 Results of vthe ETSAP global models

This chapter summarises Danish contributions to international studies using the TIAM and EFDA EFDA-TIMES models.

6.1 Climate change policies and sustainable development in China and India – project

DKC is currently involved in a modelling project together with the Energy Research Institute (ERI) in China, the Indian Institute of Management in Ahmedabad (IIMA), and the Basque Centre for Climate Change (BC3) in Spain. The project aims for an improved representation of the Chinese and Indian energy systems in global models, including TIAM, and seeks to analyse interlinkages between sustainable development strategies and climate change mitigation policies in the two countries. Specifically, the project will analyse the consequences of alternative economic growth paths, as well as alternative developments in the agricultural and biomass sectors.

In relation to ETSAP work, it is worth emphasising that the project seeks to improve and update the representation of China and India in the TIAM model.

6.2 A global renewable energy system: A modelling exercise in ETSAP/TIAM

The purpose of the first runs made by DTU Climate Centre at Risø National Laboratory for Sustainable Energy in TIAM was to test the ETSAP-TIAM global energy system model for how far the it could go towards a global 100% renewable energy system with the existing model database. As a part of this, this paper investigated where limits in global resources and data available in the model are met.

Before this paper was made, no 100% renewable global energy scenarios had been modelled with TIAM, but many analyses had focused on keeping the increase in global mean temperature below 2°C. As a part of the solution to reduce GHG emissions all these scenarios include non-renewable energy such as nuclear power and fossil fuelled power plants with carbon capture and storage (CCS).

In the scenarios examined a 100% renewable energy system was not achieved in the scenarios examined, yet the system came close to several of the renewable resource limits. It is therefore important to refine the data on renewable resource potentials if a global 100% renewable energy system is sought. The high economic growth scenario used in the current TIAM 15 region version from 2008 makes it hard to reach a 100% renewable system, even though the high energy prices reduce commodity demand due to the price elasticities of demand and increase investments in more efficient technologies. Therefore, the conclusion from these initial analyses was that it is still important to further improve data on existing and likely future efficiency potentials in TIAM. See Føyn et al. 2010.

6.3 GHG mitigation targets and potentials in large emerging economies

The following is an extended abstract of a paper presented at the IEW 2010 and the Danish Environmental Economic Council's Annual Conference 2010.

The outcome of the UN climate change negotiations at the COP15 in December 2009 was the non-binding Copenhagen Accord stating that the countries signing the agreement will commit themselves to limiting global temperature increase to 2 degrees. Countries have then had the possibility to submit their intended mitigation actions, simply referred to as “pledges”. If the accord is not to become empty politics, the total emission reductions resulting from these pledges should amount the required reductions necessary to limit the temperature increase to 2 degrees; taking into account that there may be different long-term emission paths compatible with the target. However, the pledges do not necessarily amount to what is needed, and this is the background for this analysis.

There have been several studies analysing the pledges of the Copenhagen Accord. The studies vary in their estimated levels of emissions in 2020; in their calculated “business as usual” (BAU) scenarios, their calculated emissions under the low and high levels of pledges, and also in their claims on what emission levels are compatible with the 2 degree target.

This paper will focus on the countries in the so-called BASIC group – Brazil, South Africa, India, and China. The participation and commitment of these countries, as well as other emerging economies, are crucially important for any climate mitigation work. Firstly, these countries account for substantial shares of the world’s population, GDP, and GHG emissions, and the shares are expected to increase in the coming years. Secondly, the rapid emission growth in these countries, especially in China, will make mitigation efforts Annex-I (industrialised) countries futile on their own. This was illustrated by the EMF 22 International Scenarios, where none of the 10 participating models could solve for a strict 2 degree – or 450 ppm – scenario if mitigation action in non-Annex I countries are delayed. Finally, global mitigation costs increase significantly when action is delayed in non-Annex I countries. The effort made by the BASIC countries to combat climate change will therefore be of high importance, as the ambitious goal of staying below 2 degrees is impossible without severe reductions also by these countries.

In contrast to Annex-I countries’ pledges, the BASIC countries’ pledges are not formulated as reductions from a specified reference year, and they do not give very firm sizes of emissions in 2020. For instance, Brazil and South Africa pledge reductions compared to BAU emissions. Thus, calculated emissions, as well as the evaluation of the real effort in 2020, depend completely on calculated BAU emissions. India and China, on the other hand, pledge reductions in emission intensities compared to 2005, and thus calculated emissions in 2020 depend exclusively on assumed GDP-growth.

The pledges of the BASIC countries are summarised in Table 6.1. The third column summarises the resulting emissions in 2020, as calculated by various other studies, and the fourth column summarises the resulting emissions in 2020 from calculations in ETSAP-TIAM. The numbers in parenthesis represent the percentage deviation from the BAU or reference emissions. As with the global emissions, the calculated BASIC emissions vary greatly between studies. It is difficult to make a complete comparison between studies because they often do not report all core assumptions, such as GDP growth and BAU emissions. In ETSAP-TIAM, Brazil and South Africa are not represented as separate regions, but are aggregated together with other countries into larger entities, and thus in the following, focus will be on China and India.

Looking at India, our calculations of pledged absolute emissions are within the range of the other studies, but relative to the reference scenario they differ. Indian reference

emissions in TIAM are relatively low, and thus pledges result in higher emissions. For China on the other hand, the calculations of pledged emissions relative to BAU emissions based on TIAM runs are more on level with other studies, but absolute emissions are lower than any of the other.

Table 6.1 BASIC countries' pledges.

Copenhagen Accord pledge		Emissions in 2020, Gt (% deviation from BAU/Ref)	
		Other studies	Own calculation, based on ETSAP-TIAM
Brazil	Reductions of 974-1051 Mt CO ₂ e in 2020, or 36.1-38.9% below BAU. Several specified NAMAs, incl. reduced deforestation.	1.5-2.2	N/A
South Africa	Reductions of 34% below BAU in 2020 and 42% in 2025, depending on provision of financial resources, technology transfers and capacity development support	0.4-0.5	N/A
India	Emission intensity reduction of 20-25% by 2020 compared to 2005. Emissions from agriculture not included in assessment of the intensity.	2.7-3.8 (-19 to 0%)	2.8-3 (+8 to +15%)
China	Emission intensity reduction of 40-45% by 2020 compared to 2005. Share of non-fossil fuels in primary energy consumption to be increased to around 15%, increase in forest coverage by 40 mill. hectares and forest stock volume by 1.3 bill. m ³ compared to 2005.	11.4-13 (-13 to -2%)	9.5-10.3 (-4 to +5%)

Data sources: Lowe et al. 2010, Stern and Taylor (2010), Houser (2010), Climate Works Foundation and European Climate Foundation (2010; Project Catalyst), Elzen et al. 2010, ETSAP-TIAM.

In order to put the pledges made by China and India into perspective, the resulting emissions in 2020 are compared with their emissions under an optimised climate policy, under a radiative forcing target of 3.5 W/m², in order to investigate China and India's role in an optimised global energy system with a climate constraint. Note that TIAM optimises the energy system so that the marginal emission reduction costs are equalised across regions, i.e. assuming full trading of emission allowances, and no assumptions are made regarding who will actually pay for the reductions.

Table 6.2 summarises the Indian and Chinese GHG emissions in 2020 relative to reference case, under their pledges and in the climate constrained scenario respectively. The conclusion from this work is that China's high pledges seem to be close to the optimal for the 3.5 constraint, but as we know, this is too high for the 2 degree target. India's emissions under pledges are way above what they ought to, and emissions in the reference case are closer to the target.

Table 6.2. Indian and Chinese GHG emissions in 2020 relative to reference case. Calculations in ETSAP-TIAM.

	Pledged emissions	Emissions in climate scenario (3.5 W/m ²)
India	8-15% above reference case in 2020	6% below reference case in 2020
China	4% below to 5% above reference case in 2020	5% below reference case in 2020

Figure 6.1 depicts the additional total discounted system costs of the climate constrained scenario compared to the reference scenario, on the time horizon until 2100. In India and China the discounted system costs increase by 8 and 10 % respectively, while they increase by only 3 % in the RoW. Optimisation in a climate scenario in TIAM takes the approach that marginal abatement costs are equalised across regions. When costs increase relatively more in China and India than in the RoW, it is an indication of the fact that there are large amounts of reductions available in these countries, at a relatively low price. Here it is important to notice that the costs are allocated to the regions based on where the reductions take place, and this does not say anything about who should or will pay – and though this is an important and interesting topic in itself, this is not a topic for this paper.

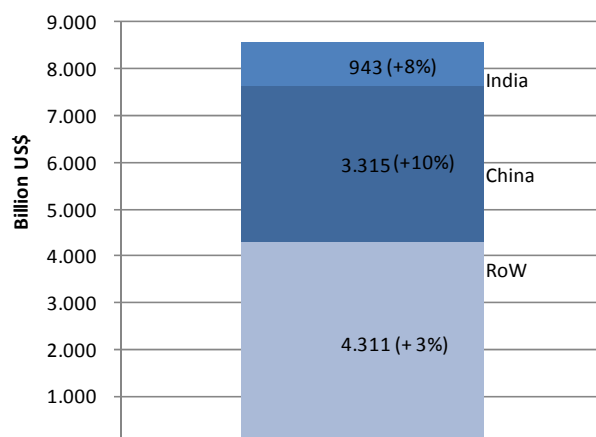


Figure 6.1. Additional system costs of 3.5 W/m² compared to reference (total discounted system costs 2005-2100). ETSAP-TIAM.

Figure 6.2 shows the primary energy consumption by fuel in China and India, and how it changes over the coming century; from the figure one can see how the countries' energy systems change in the climate constrained scenario compared to the reference. Firstly, the overall trends in the fuel composition of primary energy seem to be more or less the same in China and India. Until 2020 the changes between the reference and the climate scenario are not large, but in the long run the changes are radical, and gas and renewables come to play huge roles.

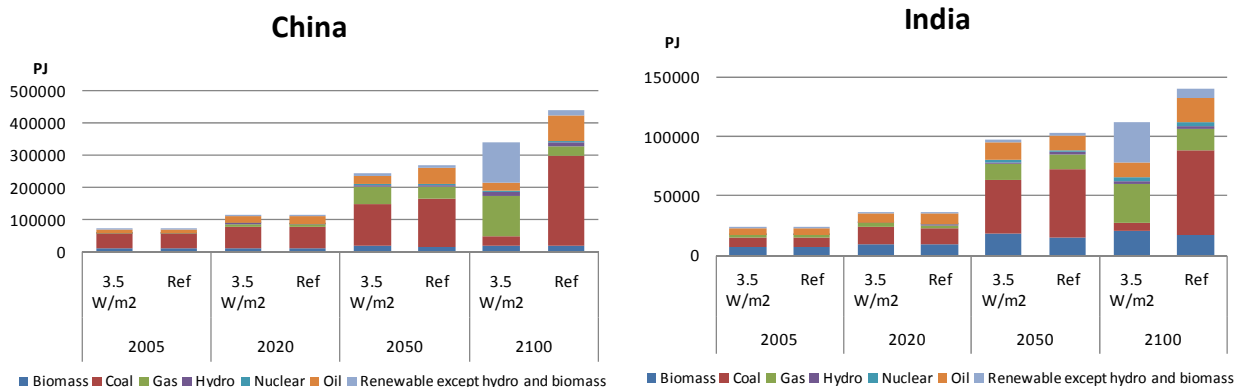


Figure 6.2. Primary energy consumption by fuel in China and India. ETSAP-TIAM.

Figure 6.3 shows the composition of the electricity production in China and India over the coming century, and again the trends are similar in China and India. Until 2020 the changes between the reference and the climate scenario are not large, but again, in the long run, they are absolutely radical, and CCS and solar play huge roles.

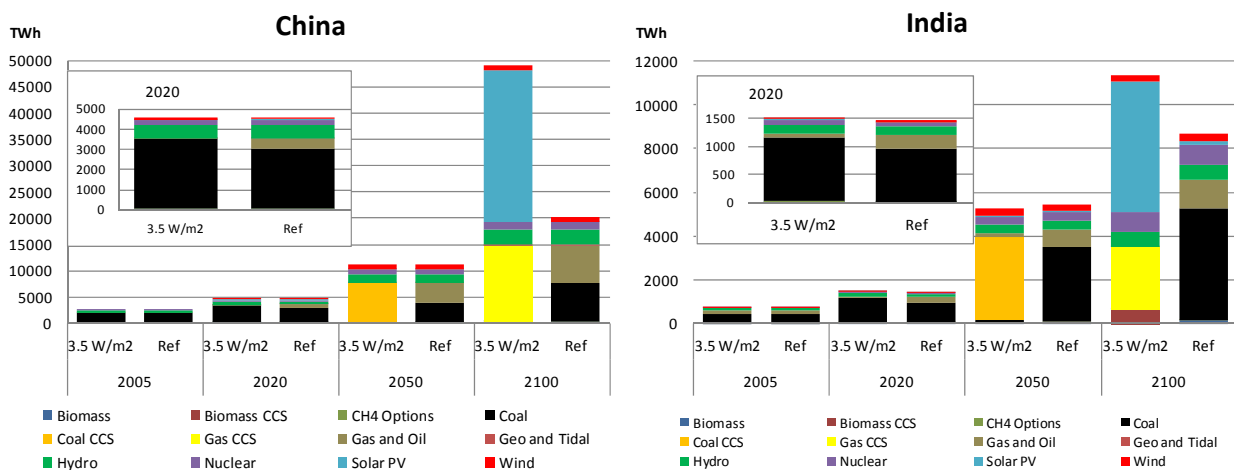


Figure 6.3. Electricity production by fuel in China and India. ETSAP-TIAM.

For all of the BASIC countries, both national and international studies have looked at their national mitigation potentials.

Comparing these studies and the calculated potentials with the countries' pledges, it seems that Brazil has pledged quite large relative reductions compared to the potentials reported here; however, this is likely to mainly be the consequence of the fact that mitigation options in LULUCF are not included in these studies. When it comes to South Africa it seems that the country's pledges are close to the potentials found by both the national LTMS and EcoFys studies. In contrast, both India and China's potentials seem much larger than the pledged reductions calculated based on TIAM data, corresponding to the results from the climate constrained scenario.

This paper has shown that the 2°C target agreed upon in the Copenhagen Accord will be very difficult to reach, as well as to model, and that it will be more or less impossible without early participation of large emerging economies. The future mitigation efforts of the BASIC countries are thus of great importance and interest, and this paper has looked

closer at their pledged efforts and compared them with estimated emission reduction potentials for the same countries.

The 2020 pledges by China and India are close to their BAU/reference emissions, and appear to be small compared to estimated potentials. Contrastingly, Brazil and South Africa have pledged large reductions from BAU, and their pledges appear close to estimated potentials.

According to the current assumptions and data in TIAM, even in a non-constrained world it would actually be optimal that China by 2020 develops an energy system with lower emissions than its low pledges amount to, and the same is true for India's both low and high pledges. The potentials for large, relatively cheap reductions in China and India are also reflected in the total discounted system costs in the climate scenario, where large shares of the additional costs take place in China and India. The conclusion is thus that, for the world as a whole, it is optimal to do large reductions in these countries. However, this is not to say that China and India should necessarily pay for all these reductions by themselves; the reduction may require large amounts of financial transfers and an international agreement on who should pay, as well as on technology transfer, but this topic is outside the scope of this paper.

To summarise, it is clear that the BASIC countries play a large and increasing role in regard to energy consumption and GHG emissions, and it is hugely important that they are involved in any future mitigation efforts. However, it is important for these countries that mitigation efforts do not conflict with their development objectives, and if they do, this will most certainly limit their interest in participating in the efforts. One of the main concerns for developing countries in general, when it comes to emission reduction targets, seems to be that they may have to lower their ambitions for economic development. However, research shows that policies and strategies taking into account both sustainable development priorities and GHG emission targets may achieve climate targets effectively, and that such integrated policies may be cheaper and more sustainable than traditional climate focused policies alone (see e.g. Shukla et al., 2009). Furthermore, some studies even show that with this approach, policies to reduce GHG emissions may actually improve sustainable development in other areas, through changes in energy efficiencies, resource use, urban and land use planning, transportation systems and behaviour etc. Thus, an integrated approach to climate change and development is necessary.

6.3.1 Biomass and CCS

Reducing the risk of dangerous climate change will require ambitious efforts to stabilise atmospheric greenhouse gas (GHG) concentrations. Within the next 20-40 years, carbon intensive economies will have to dramatically shift to more renewable energy sources and to capturing and storing carbon emitted from facilities that consume fossil fuel.

For high ambitions on global climate mitigation to be achieved, the participation and commitment of China is crucially important. First, China accounts for a substantial share of the world's population, economy, and GHG emissions: China has the world's largest population and the second largest economy, and has recently become the world leader in GHG emissions. Second, China's GDP, energy consumption and GHG emissions are expected to increase rapidly in the coming years, and this rapid growth in emissions could offset mitigation efforts in other parts of the world, e.g. Annex I (industrialised) countries. Third, because of the speed with which China's energy demand is growing, the country is facing a large challenge in expanding supply rapidly enough. Domestic

coal is currently the most used and most readily available energy supply source, but it is also the most carbon intensive of all fossil fuels. Therefore, aligning the security of supply requirements with environmental and climate change objectives is a great challenge for China. Finally, global mitigation costs increase significantly when action is delayed in non-Annex I countries, including China. The effort made by China to combat climate change will therefore be of high importance, as the ambitious goal of staying below a mean global temperature increase of 2°C is impossible without substantial greenhouse gas emissions reductions from China.

A forthcoming paper by DKC looks into the role of China in global mitigation efforts, and in particular it goes into details about China's potential for the use of carbon capture and storage (CCS) technologies, both in relation to coal and gas and in relation to biomass. CCS combined with biomass has the potential to "produce" net negative emissions. The paper goes into future energy demands in China, the country's coal and biomass resources, and its potential for the use of CCS, including storage potential. For the purpose of analysing China's role in global mitigation efforts, the paper employs TIAM, with information about biomass potential and carbon dioxide (CO₂) storage facilities in China. The model is used to simulate the socio-economic effects of meeting atmospheric GHG concentration targets. Using these stabilisation constraints, the model will optimise the most economic utilisation of biomass with CCS for China. Different scenarios are investigated, including different growth rates and the scale of possible implementation of both CCS and biomass.

China's role and possibility for utilising CCS and biomass as mitigation options is investigated in a world with ambitious climate goals. It is assumed that the world society has agreed on keeping increase in global mean temperature below 2° C. This is reflected in the integrated assessment model by following the GHG emission trajectory from IPCC RCP3-PD emission scenario (RCPs are Representative Concentration Pathway, pre-scenarios to develop new scenarios for IPCC AR5), Van Vuuren et al (2007). The RCP3-PD peaks in atmospheric CO₂ concentration in 2040 and decline thereafter ending around 490 ppm CO₂eq in 2100.

China's role in the world achieving atmospheric stabilisation of GHGs is highly dependent on the economic development in China, their biomass resources, market entry for CCS technologies and when China starts reducing GHG emissions. Therefore, a selection of scenarios is created representing different combinations of these important assumptions.

The paper will provide insight and potentials for biomass and CCS for China and how the growing energy demand for China can be fulfilled while restricting GHG emissions. Preliminary results show that it can be difficult to reach a strict target given high economic growth. The analysis also shows that CCS can play a substantial role in reducing emissions, while the available domestic biomass for energy is a limiting factor.

6.3.2 A global or a partial climate agreement – what difference does it make?

Together with VTT in Belgium and IFE in Norway, DKC is currently working on a paper with the above title, aiming for presentation at the IEW 2011. The following is a long abstract of the paper.

The current status of the United Nations (UN) negotiations on climate change is that there is a global agreement to limit global temperature increase to 2° C, i.e. a top-down goal. This is stated in the non-binding Copenhagen Accord, which was the outcome of

the UN climate change negotiations at the COP15 in December 2009, and which was adopted by the UN member countries in at COP16 in 2010. Countries have had the possibility to unilaterally submit their intended mitigation actions, simply referred to as “pledges”, and the negotiations thus follow a bottom-up approach. If the accord is not to become empty politics, the total emission reductions resulting from these pledges should amount the required reductions necessary to limit the temperature increase to 2°C; taking into account that there may be different long-term emission paths compatible with the target. According to the Intergovernmental Panel on Climate Change (IPCC), in order to limit global temperature increase to 2°C it is required to limit global emissions in 2050 to 20-50% of 1990 levels.

This paper will investigate how different hypothetical international agreements on climate change mitigation will affect the global outcome in terms of climate change and costs, and how different regions of the world will contribute to the reduction of greenhouse gas (GHG) emissions. Different constellations can be imagined for future agreements regarding climate mitigation. The agreements can have different reduction goals for developed and for developing countries and it is also possible that some countries will not join a common global agreement. The work of the EMF22 demonstrated the consequences for the world’s climate and for the energy system costs of having certain regions of the world entering the mitigation efforts at a late stage (e.g. Clarke et al. 2009, Loulou et al. 2009, and Russ and van Ierland 2009).

This paper explores different scenarios concerning future climate agreements to better understand the climatic and economic effects of different types of climate agreements. This analysis will shed light on the following questions: Is it possible to achieve atmospheric stabilisation of greenhouse gases such that the global mean temperature increase does not exceed 2°C if the USA, China, and the Middle East do not participate in a global policy? What are the economic outcomes for regions participating in such a partial climate agreement? Will a partial agreement lead to higher system costs for the participating countries and lower system costs for non-participating countries? Would a separate carbon market for developed and developing countries (versus a single common market) be as effective at meeting the climate stabilisation targets?

This paper will analyse several scenarios for international climate change mitigation cooperation. It will investigate the consequences of various designs of an international agreement, through the use of the TIAM model.

First, a reference scenario is created in TIAM, representing a world with no climate policies. Second, the paper will investigate various climate policy scenarios (alternative scenarios). In TIAM, all end-use sectors have a demand price elasticity reflecting macro-economic impacts of future prices and thereby changes in demand. In alternative scenarios prices will change and the loss in welfare can be measured against the reference scenario.

The different alternative climate scenarios are constructed to reflect the discussion about investigating different types of climate agreements. Four scenarios have been constructed, representing the different types of agreements. They are built up by varying two factors – whether an agreement is global (i.e. all countries participate) or partial (certain countries stand outside the agreement), and whether there is one single carbon market or two separate carbon markets. In all scenarios it is assumed that the industrialised countries reduce their GHG emissions by 80% in 2050 compared to 2005 levels, and the developing countries reduce emissions by 50%. When the agreement is

assumed to be partial, this means that the USA, China, and the Middle East stand outside of an agreement, and are free to emit greenhouse gases. When two separate carbon markets are assumed, this means that the industrialised countries and the developing countries trade within each their group (corresponding to the 80% and 50% groups). The scenarios are:

Global agreement

The whole world participates in a global agreement, but with different goals for industrialised and developing countries. GHG emissions from industrialised countries are limited to 20% of their 2005 levels and GHG emissions from developing countries are limited to 50% of their 2005 levels from 2050 and onward. Carbon trade takes place in the two separate groups.

Global agreement - cost optimal

This scenario is the same as the Global agreement scenario, but with one common global market for trade with GHG-permits, opening up for a cost optimal global solution.

Partial agreement

This represents a scenario where a global deal could not be reached, but a subset of countries decides to enter a carbon market without the stalling countries, still with different goals for industrialised and developing countries. Carbon trade takes place in the two separate groups. GHG emissions from industrialised countries (except for the US) are limited to 20% of their 2005 levels, and GHG emissions from developing countries (except for China and the Middle East countries) are limited to 50% of their 2005 levels.

Partial agreement - cost optimal

This scenario is the same as the Partial agreement scenario, but with one common global market for trade with GHG-permits, opening up for a cost optimal global solution.

Global and regional GHG emissions will be compared between the scenarios as well as total global and regional costs will be treated in this section.

Preliminary results show that a global agreement that includes all countries results in the most reductions of the scenarios analysed here, going from 74 Gt in the reference to 15 Gt (80% reduction compared to reference). A partial agreement will also result in reduced global GHG emissions, but only by 30% compared to the reference. Emissions from the countries not included in the climate agreements are actually higher in the partial climate agreement scenarios than they are in the reference where there was no restriction on GHG at all. The mechanism behind this is the global markets for fossil fuels (oil, coal and gas). When some countries agree to reduce GHG emissions, they switch away from fossil fuels, reducing the pressure on these markets and thereby reducing the prices. The countries outside a climate agreement can therefore buy cheaper oil, coal and gas and as a result they increase their consumption of these fuels.

The emission pathways in the different scenarios are translated to CO₂ concentration in the atmosphere in TIAM's climate module. As can be seen from Figure 6.4 the global agreement causes an atmospheric stabilisation around 420 ppm CO₂, while the partial agreement reaches 600 ppm in 2100 and the reference reaches 680 ppm, but the latter two continue to grow and do not achieve a stabilisation within this century.

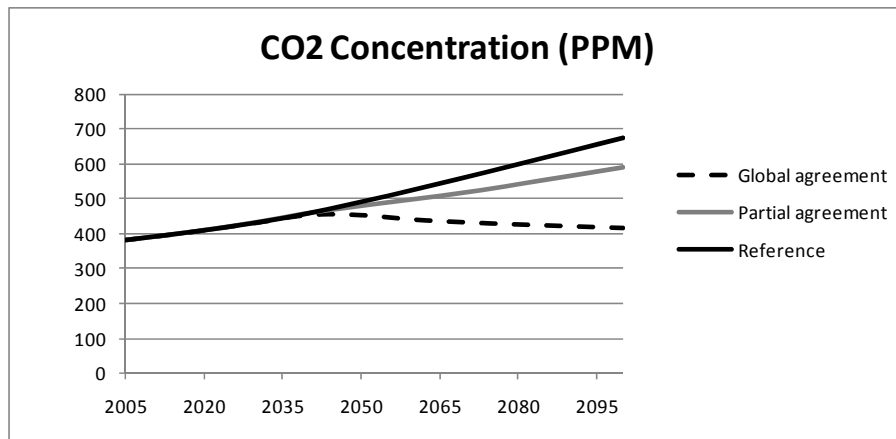


Figure 6.4. CO₂-concentration in the atmosphere in three different scenarios.

The electricity sector is highly influenced by climate agreements and therefore the electricity generation in the investigated scenarios will appear to be different both globally and regionally. In the countries joining a global agreement, the preliminary results show an accelerated increase in electricity production around 2040 compared to the reference scenario. This is mainly due to a shift towards electricity in the industrial sectors, but also in the transport sector for electric vehicles and production of biofuels and synthetic fuels.

Figure 6.5 and Figure 6.6 illustrate electricity production in 2050 in the reference, Global agreement and Partial agreement scenarios respectively. The type of an agreement has an influence on the electricity production technologies for both participating and non-participating countries. As a result of the GHG reduction commitments, the share of electricity production from fossil fuels is considerably reduced and the share of CCS (carbon capture and storage from coal, natural gas and biomass) and renewable electricity increases in the Global agreement scenario. GHG reductions are met by a larger share of renewable power, especially in the United States, the Middle East and in China. Wind is the largest renewable energy source in the United States and the Middle East while solar photovoltaic dominates in China.

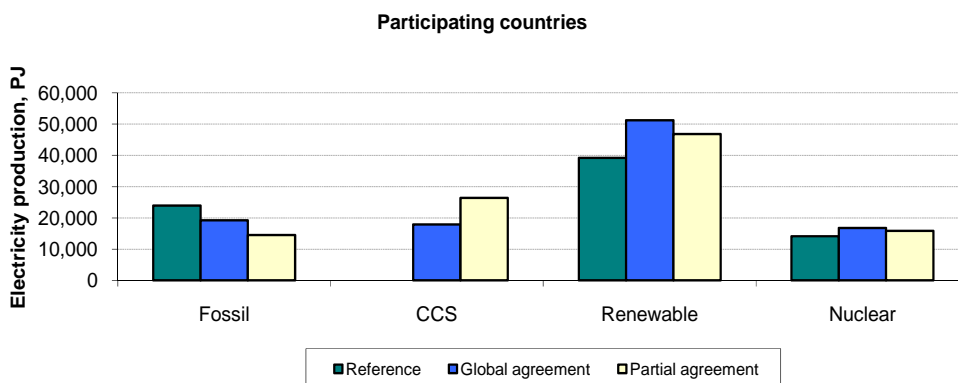


Figure 6.5: Electricity production in 2050 in the participating countries in the reference, Global agreement and Partial agreement scenario

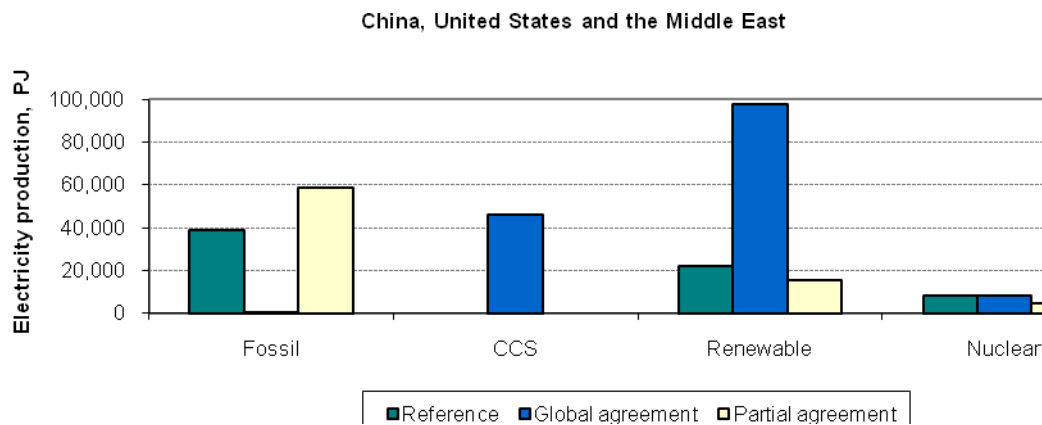


Figure 6.6: Electricity production in 2050 in China, USA, and the Middle East countries in the reference, Global agreement and Partial agreement scenario

For the non-participating countries in the partial agreement, the majority of the electricity production is based on fossil fuels. It is 50 % higher than in the reference case. In the Partial agreement scenario, a larger share of fossil technologies is cost optimal in light of cheaper fossil resources. For example in the Middle East, 75 % of the electricity production is by coal power in 2050 in a partial agreement. There is no coal production in this region by 2050, and all the coal used is imported from Africa. The African GHG commitments make possible a larger export of coal to the non participating regions and in this case reducing the marginal costs of coal power in the Middle East.

The failure to include USA, China, and the Middle East in an international climate agreement has serious implications for the global climate. The Chinese economy is growing fast, and China is becoming an increasingly important player in the global economy, world politics, and in the competition for energy and resources. USA, as the richest country in the world, is a large consumer of goods and energy. Oil production in USA has peaked, and the country is heavily dependent on import of fossil fuels. The Middle East has the largest reserves of oil and gas in the world and therefore has little incentive to reduce consumption or support a global climate agreement.

Looking at preliminary results for the partial agreement case, it is clear that a lower demand for fossil fuels from countries within an agreement will reduce the cost for fossil fuels for the countries outside the agreement. This leads to a higher consumption of fossil fuels in these countries than in the scenario with no climate policy at all.

A possible solution to avoid the increased use of fossil fuels in the non-participating countries could be an embargo, or high export taxes, on fossil fuel trade with the non-participating countries. However, as the Middle East has the largest estimated oil resources in the world, a trade embargo would mainly have an effect on the coal market. Furthermore, the political feasibility of such a solution must be considered low, even though a so-called border adjustment tax has already been discussed in the EU.

Further subjects to be discussed are global and regional costs of the different scenarios, resource use and technological development.

6.4 Further development of EFDA-TIMES

The development and use of the EFDA-TIMES model as an important part of the programme Socio-Economic Research for Fusion (SERF) continued under the EU 7th

Framework Programme (EFDA 2008). The EFDA work programmes from 2008 to 2010 considered validation and benchmarking for EFDA-TIMES.

6.4.1 Biomass and CCS in EFDA-TIMES

EFDA-TIMES (December 2009 version) contains a full dataset for biomass and CCS, which is identical or consistent with previous versions of EFDA-TIMES, but these technologies hardly appear in the results of the reference scenario or the scenario variants that were reported so far (Grohnheit, 2010b).

These technologies are highly controversial, and key parameters such as potentials and costs are very uncertain. However, various studies on national and global level until 2050 have shown that both biomass and CCS have large potentials for economic efficient CO₂ mitigation. The task for EFDA-TIMES in WP 2009 has been to identify the combination of assumptions that will allow biomass and CCS to play a significant role by 2050 and after. By the end of the model period fusion may replace fossil fuel with CCS, which still emit some CO₂, or energy crops, which may compete with food production.

An Excel workbook has been developed for the management of a large number of cases for sensitivity analysis, which is used for various versions of TIMES.

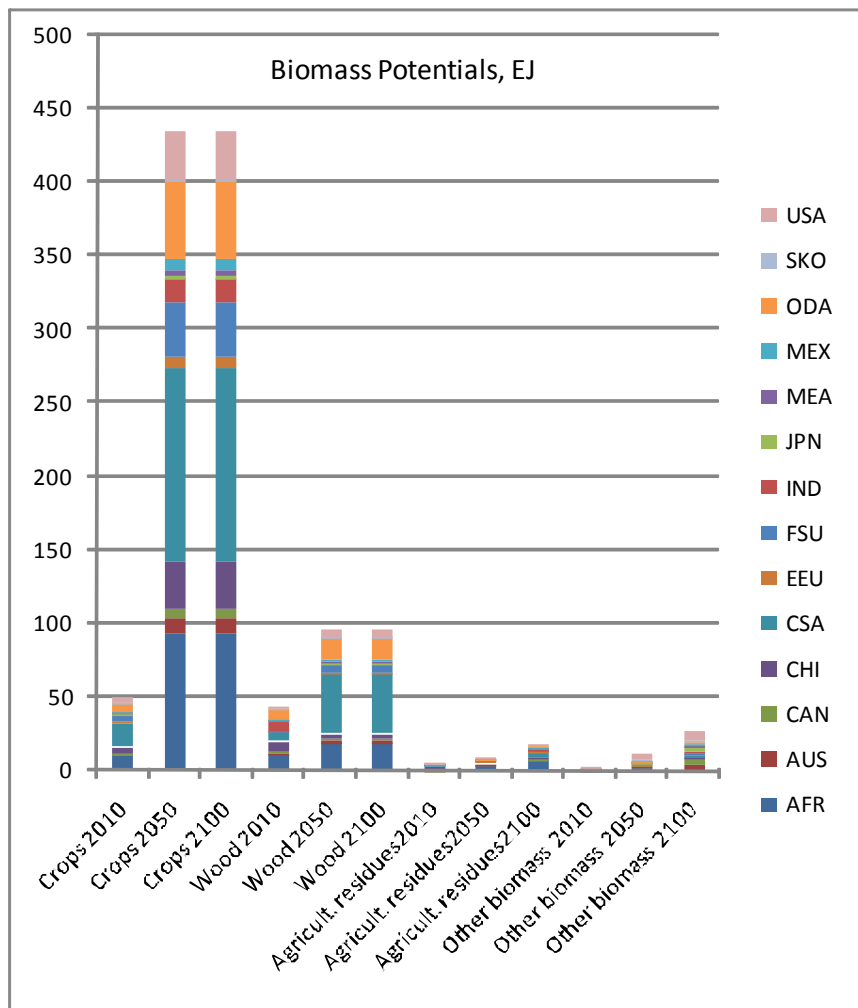


Figure 6.7. Biomass potentials

Biomass potentials

In the report on resource potentials update (Labriet et. al, 2007) the general recommendation was to clean and simplify all what concerns biomass resources and use. Thus, it was been decided to keep the following categories:

- Energy crop
- Agriculture residues
- Wood fuels (including traditional wood energy, as well as wastes from wood processing industries)
- Other (municipal wastes, other industrial wastes, gas from landfill)

A higher level of details does not appear useful given the facts that energy crops dominate the future biomass potential (see Figure 6.7)

As regards municipal wastes, their energy role remains debatable: on one hand, high costs are associated with sorting them, and recycling and packaging policies make very uncertain the future quantity of municipal wastes; on the other hand, waste-to-energy policies are also promoted in several countries, for example in Europe. Given these uncertainties, municipal wastes and landfill gas have been kept in the “other” category.

Figure 6.7 shows the global potential – divided into regions – in the Base Scenario. The variant “Biomass high” the energy potentials are 50 % higher for crops and wood, several times higher for “energy from agriculture residues”, and unchanged for “Energy from other”. However, the impact of this variant on the energy mix is very limited.

CCS Storage Capacity

Figure 6.8 shows the cumulative capacity of CO₂ storages in world regions. These capacities are highly uncertain.

In particular for Europe, there are various estimates for the carbon storage capacity. Very comprehensive analyses of the European storage potential, focussing on saline aquifers and hydrocarbon fields’ have been done within European research projects. According to the most recent study, GeoCapacity the theoretical storage potential in Europe amounts to about 400 Gt CO₂. Assuming that not the total storage volume can be used effectively, GeoCapacity states a conservative estimate of about 120 Gt for Europe (here the EU-27 plus Norway, Switzerland and Iceland).

In Figure 6.8 the capacity in WEU for the dominant resource, deep saline aquifers, is 375 Gt., which is similar to the theoretical potential in GeoCapacity, but several times the conservative estimate.

6.4.2 EFDA-TIMES Sensitivity analyses

In contrast to fusion, CCS is a technology with a more temporary role, which may be needed to bridge the gap between the current energy system dominated by fossil fuels and a future system based on renewables and nuclear fusion. By the end of the century fusion power may replace fossil fuel with CCS, which still emit some CO₂, or energy crops, which may compete with food production.

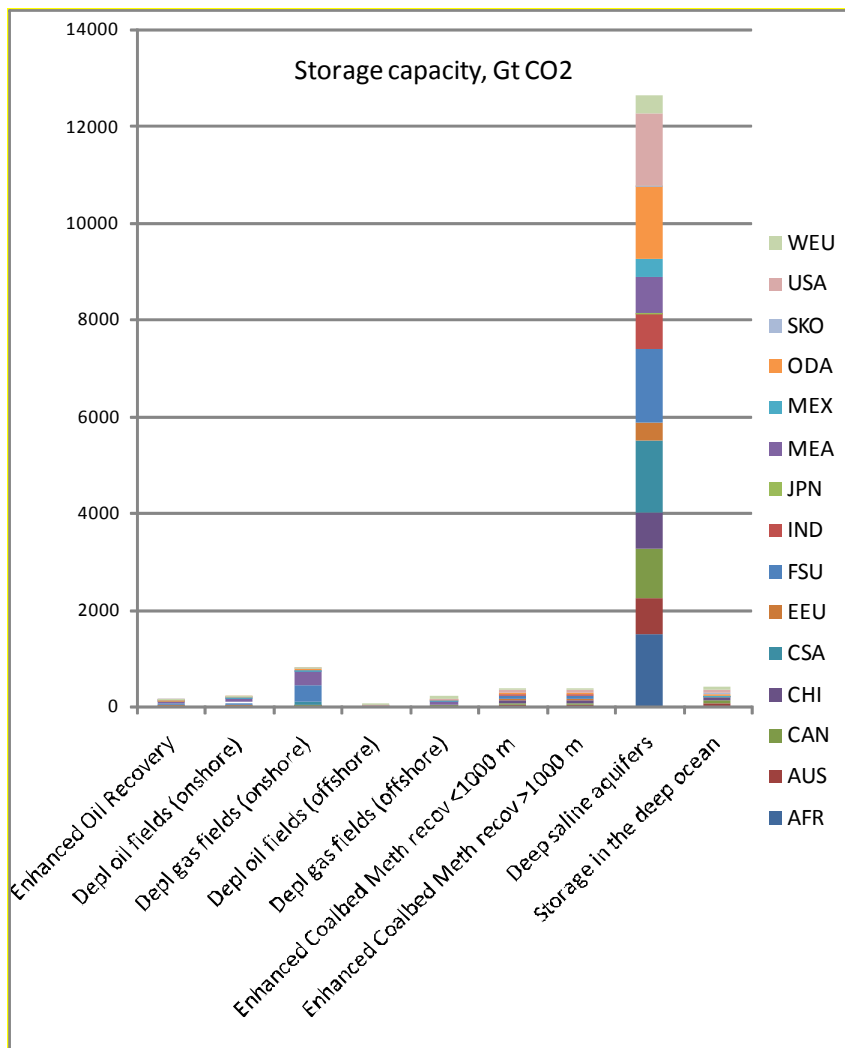


Figure 6.8. Cumulative CO₂ storage capacity,

The Reference (BASE) Scenario

In the Base Scenario a carbon price, representative of a moderate concern about climate change, has been included; the scenario contains no incentives for CO₂ reduction at 2010 and a carbon price differentiated between OECD and non OECD regions for the following periods. The carbon price gradually increases from 10 \$/tCO₂ in 2020 to 25 \$/tCO₂ in 2100 in non OECD regions and from 20 \$/tCO₂ to 50 in 2100 in OECD regions.

The electricity generation in the Base Scenario shows an annual growth rate of nearly 2.6% in 2000-2050 period and of 1.5% in 2050-2100. The growth of energy production in EFDA Base Scenario (31,400 TWh in 2030) is very close to the Reference Case of IEA's World Energy Outlook 2008 (33,265 TWh in 2030). In the EFDA scenario electricity production grows up to 67,300 TWh in 2050, and 105,200 TWh in 2100.

Electricity demand

Economic development is expected to increase all over in the world, although the rate of increase is very different in different world regions. Socio-economic development is captured in the model by a set of underlying drivers: population, number of households, GDP and GDP per person. Demands are a mixture of final energy demands, energy services and materials. The global demand for primary energy in the model increases from 383 EJ in 2000 to 844 EJ in 2050 and 1,528 EJ in 2100. This demand increase in

the model is high, but it is in line with other models (e.g. TIAM), and the per capita increase in primary energy is not implausibly high.

6.4.3 Scenarios to illustrate biomass and CCS

Constraints on CO₂ emissions will have the greatest impact on the fuel mix during the whole 21st Century. In contrast to all other technologies, which are competing mainly on the basis of their costs, fossil fuels with CCS will penetrate only when the emission constraint is effective.

All renewables – including biomass – are subject to resource constraints, which are effective in all regions and all periods, while the uranium resource constraint for nuclear fission may not be effective until late in the century. This may lead to results with nuclear fission dominance far beyond public acceptance or the capacity for treatment of the accumulated volumes of spent fuel. A side effect of this dominance is that there is no room for fossil fuels with CCS. Thus, some kind of limit for nuclear fission will be necessary to reach results with a balanced mix of technologies for electricity generation.

A conservative assumption will be that nuclear fission should not increase above 25 % of electricity generation each region during the rest of the century. In few regions (JPN, SKO and WEU) the share of fission was higher than 25 % in 2000 and maximum values are set in for 2010 in the Base Scenario, which is higher than generation in 2000. However, with increased demand for electricity, nuclear fission may increase in all regions after 2050, in absolute terms from 8.8 EJ (2,435 TWh) in 2000 to 45.5 EJ (12,645 TWh) in 2100.

The scenarios selected to illustrate the role of biomass and CCS are summarised in Table 6.3, which also shows the variation of the objective value. The combination of the NucReg25 scenario and emission constraints leading to CO₂ concentration in the atmosphere at 550 ppm (Emi550) was chosen as the starting point for further sensitivity analyses.

Table 6.3. Scenarios selected for analysis of CCS.

Selected Scenarios	Objective value			Core scenario=100		
	Base	Emi550	Emi450	Base	Emi550	Emi450
Base	186895			99.1		
NucReg25	187031	188627	193604	99.2	100.0	102.6
Biomass_High, CCSminus		188540			100.0	
Eplus		209085			110.8	
Demand20		174053			92.3	

The difference in objective value between the Core Scenario at 550 ppm and the nuclear fission constraint is less than 1 %.

The variants higher biomass potentials, and “CCSminus”, assuming that investment costs for CCS technologies are 20% lower than in the base case, will reduce the objective value by less than 0.1 %.

In contrast, the more severe constraint on CO₂ emissions leading to CO₂ concentration in the atmosphere at 450 ppm (Emi450) gives the objective value that is 2.6 % higher than the Core Scenario.

Figure 6.9 shows the global emission profile for the two scenarios Emi550 and Emi450.

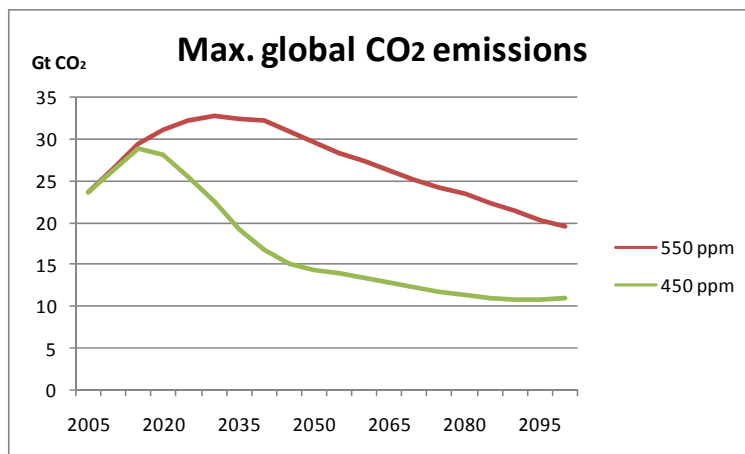


Figure 6.9. Global CO₂ emission profiles for the 450 and 550 ppm .

Two additional scenarios were also reported:

- Eplus scenario – (representative of a growing concern about climate change): No incentives at 2010 in all region but WEU⁶ (10\$/tCO₂) and a undifferentiated carbon price increasing from 50\$/t CO₂ in 2020 to 200\$/tCO₂ in 2100.
- Demand20 scenario in which the demand forecasts in the Base Scenario are reduced by 1 % every five years from 2000 to 2100. Thus, the demand forecasts are reduced by 10 % for 2050 and 20 % for 2100.

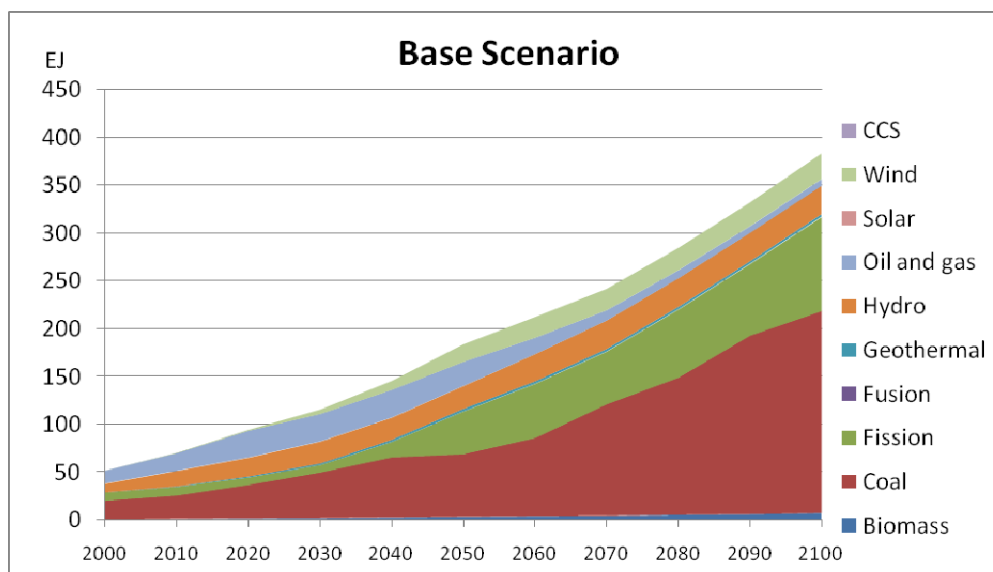


Figure 6.10. Power generation, Base Scenario.

Global results for electricity generation

Consistent with many energy scenario models, a strong increase in electricity and primary energy demand but with no limits on CO₂ emissions is expected to rely on coal to supply a large fraction of the primary energy in 2100. Nuclear fission is also expected to play an important role in the electricity sector see Figure 6.10.

⁶ In order to insert a proxy for the European Union Emission Trading System (EU ETS).

Total power generation will increase from 52 EJ (14,000 TWh) in 2000 to 184 EJ (53,000 TWh) in 2050 and 383 EJ (106,000 TWh) in 2100. As expected the increase in power generation by a factor of more than 6 is larger than the increase in primary energy by factor 4.

The constraint on nuclear fission is constrained to maximum 25 % in each region will reduce the global amount of nuclear fission to 18 % or less, which is about the nuclear share of power generation in 2000. The reduction in nuclear fission will be replaced mainly by coal, but the overall picture is not very different from Figure 6.10. Even without any constraint on CO₂ emissions, fusion enters into the solution by a small, but increasing amount the end of the century, up to 5 % of total power generation in 2100.

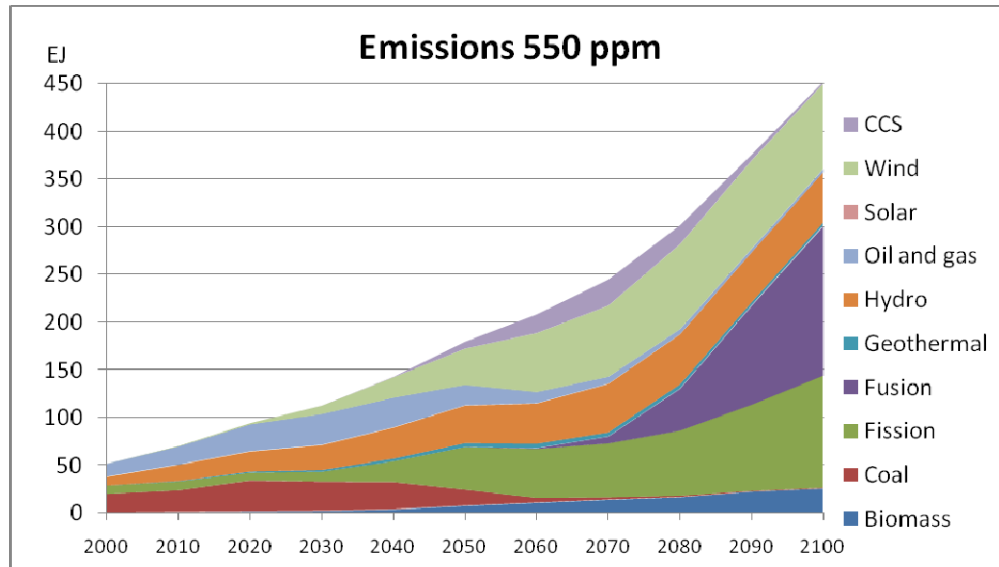


Figure 6.11. Power generation, Core Scenario: Emission reduction 550 ppm.

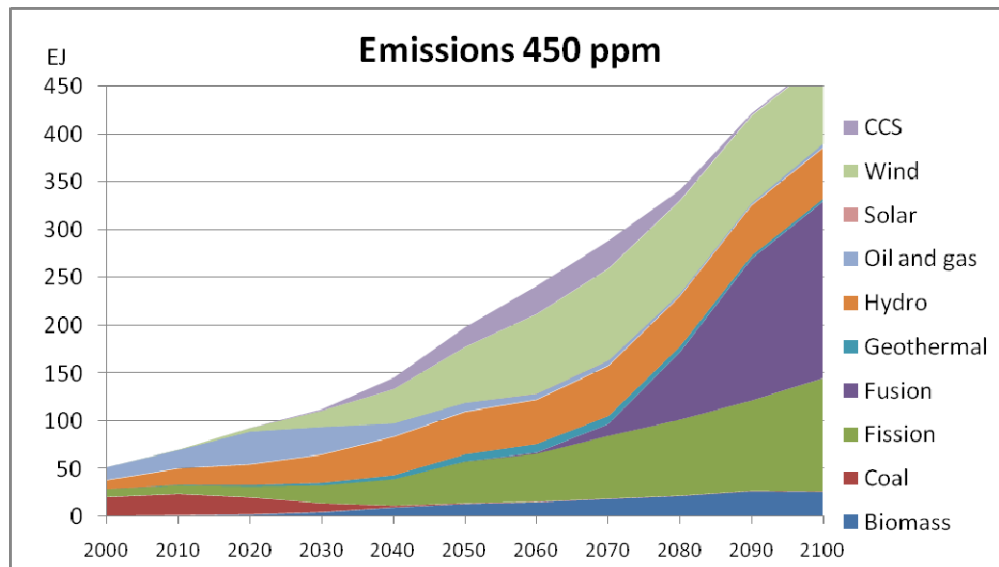


Figure 6.12. Power generation, Core Scenario variant: Emission reduction 450 ppm.

Figure 6.11 shows the global electricity production in a carbon constrained scenario equivalent to restricting the atmospheric CO₂ concentration to 550 ppm (equivalent), which is chosen as the Core Scenario for further sensitivity analysis. In the period before

fusion is able for take-off, CCS can play a significant role – up to 11 % of the global power generation in 2060-2070 – as a contribution to bridge the gap between a fossil dominated energy system and a large contribution from fusion.

The first variant to the Core Scenario is the stricter constraint on emissions equivalent to restricting the atmospheric CO₂ concentration to 450 ppm. The most significant change compared to the 550 ppm scenario is that electricity generation increases from 451 EJ in the Core Scenario to 479 EJ. This is explained by a substitution from direct use of fossil fuels to electricity, which is more suitable for emission reduction. The most significant change in the technology mix is before 2050 – with much less fossil fuels and more biomass, geothermal and CCS. In both scenarios wind power and nuclear fission become very important in the second half of the century, but starts earlier in the 450 ppm scenario. Also fusion will have a larger share in the 450 ppm scenario, Figure 6.12.

Higher biomass resources and lower CCS investment cost will lead to a slightly higher share of biomass by the end of the century and a higher – but still modest – share of CCS in the mid-century. In the "Eplus" scenario with carbon price 200 \$/t CO₂ in 2100 the overall picture is nearly the same.

Results for selected regions

The development of the two fast-growing regions, China and India, is very similar to the global development. Nuclear fission is steadily growing, but constrained by the 25 % share, which becomes effective by 2050. Hydro, wind and biomass are constrained by resource limitations. Fossil fuels without CCS are phased out during the first part of the century, but gradually replaced by CCS, until fusion takes off from about 2070.

In Europe the combination of high population density and long coastlines with shallow water means that the potential of wind power is very high. Together with the modest increase in electricity demand the share of wind power becomes very high in the second half of the century. However, the current model is not designed to respond to a large amount of intermittent power. The figures show the sum of the regions EEU and WEU, which covers EU27 and more countries, but not the three Baltic countries.

In the 550 ppm scenario, Figure 6.13, CCS will cover only a few per cent of the power generation by the end of the century.

In the 450 ppm scenario (Figure 6.14) CCS will play some role in the middle of the century – up to 9 % in 2060 – but a small amount of fusion will take over by the end of the century. Biomass will increase to about 10 % by the end of the century.

The massive penetration of wind power in the emission constrained scenarios for Europe must be balanced by flexible thermal production, in particular gas or biomass, preferably with CHP. The current version of the EFDA-TIMES model has not been calibrated to meet these requirements.

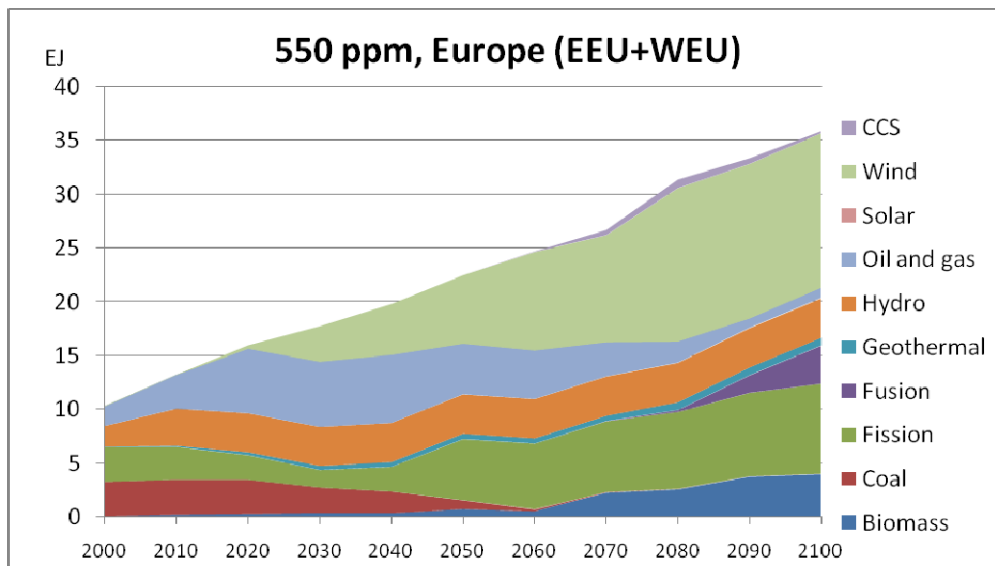


Figure 6.13. Power generation, 550 ppm (core) scenario for Europe.

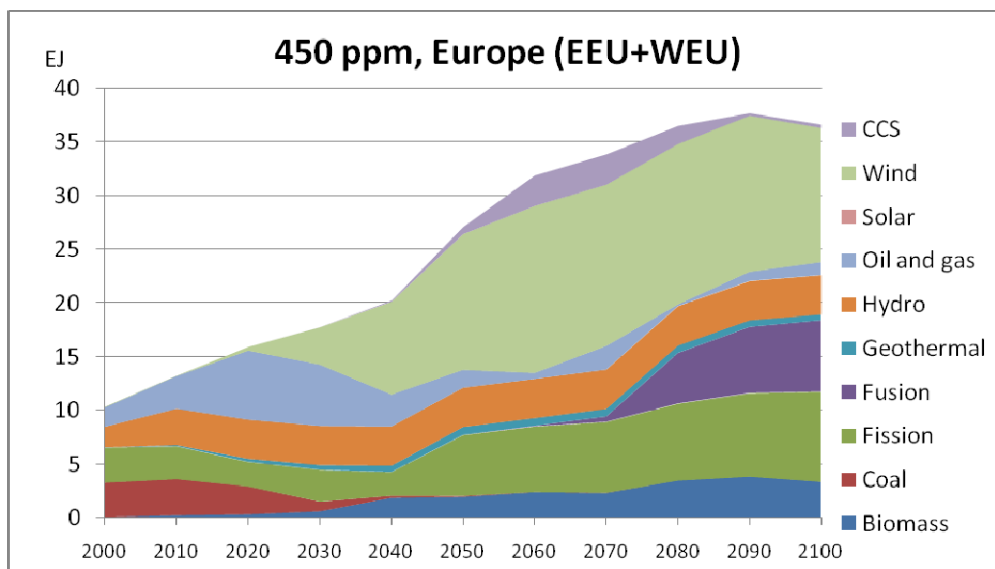


Figure 6.14. Power generation, Core Scenario variant for Europe: Emission reduction 450 ppm.

6.4.4 Fusion to replace CCS with heat recovery for heating and cooling

The key parameter for the extraction of heat from extraction-condensing power stations is the power loss ratio, i.e. the loss of electricity load per unit of heat extracted. If the heat loss ratio is higher for a nuclear station than from available coal or gas fired stations, it is cheaper to extract heat from these stations. The power-loss-ratio from fossil fuel fired stations has been very constant during the last decades, about 0.15 (Grohnheit, 1993).

The access for CHP from future fusion power to large-scale urban district heating grids, which could be developed during the next half-century, would improve the relative position of fusion power compared to the competing technologies, but it would not drastically change the conclusions of the study.

An early study (Hazelrigg and Coleman, 1983) titled “A Preliminary Examination of the Economics of Cogeneration with Fusion Plants” – with time horizon 2030, assuming that

fusion reactors would be available from 2010 – concludes that fusion can “provide increased economic incentive to the implementation of cogeneration systems. Conversely, cogeneration improves the economics of fusion”. This article appears to use the prospect of future fusion power as a driver for the development of CHP for district heating in the Mineapolis/St.Paul metropolitan region in the US.

Today, CCS may be used as a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Northern and Eastern Europe, Korea and China, and with large additional potentials in North America. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used, which will support the penetration of both technologies.

In addition, district heating systems with CHP and heat storages offer some of the flexibility in electricity generation that is required for wind power and other intermittent electricity generation.

The steam parameters for fusion power – with temperatures in the range 600-800°C – are similar to advanced coal or combined cycle gas turbines. Fusion units will operate as very large base-load units, and the unit size will be 1.5 GW, similar to recent nuclear fission units with light water reactors units or 2-3 large coal units. This is suitable for large-scale combined heat and power (CHP) for urban district heating systems. These systems require several decades for development, mainly by interconnection of existing smaller systems. In addition, fusion reactors will be suitable for other types of cogeneration, e.g. catalytic hydrogen generation.

This issue – including the introduction of a very aggregate technology to represent large-scale district heating infrastructure – was discussed in the ETSAP workshop at Cork, Ireland, November 2010, Grohnheit (2010c). Further analysis is proposed for the next EFDA-TIMES workprogramme to assess appropriate parameter values and a more disaggregated representation of the infrastructure.

7 Future work

The development of a Danish model using the ETSAP tools is still ongoing. The further development of the model benefits from the wide range of international and national activities both within the framework of ETSAP and outside, in particular Danish, Nordic and European research.

The national and regional models that are developed using the ETSAP tools normally cover the whole energy system, which is a collection of several sectors with numerous parameters and assumptions. To maintain and improve the quality of these assumptions it is important to isolate parts of the system to study the impact of the choice of specific parameter values.

7.1 Wind power

Wind power is the topic of numerous models, often in great details concerning time resolution, geography and stochastics. However, little will be gained to develop models using the TIMES model generator in details necessary to address such issues. A different path will be to use aggregated parameters based on model studies using a model approach designed for wind. This is necessary for a model that shall be able to consider investment in wind power in competition with thermal generation. This issue has been addressed within the framework of ETSAP Annex X, but no satisfactory solution has yet been found. The issue will become even more important in the future, because wind power will become a very significant technology for electricity generation with significant implications for system operation and security.

7.2 Large energy consuming industries

Large energy consuming industries are not important in Denmark, but they have traditionally been the topic for many optimisation models, including NEEDS-TIMES. Some activities will be useful for completion of the Danish NEEDS-TIMES model, in particular for comparison with other national models.

7.3 Agriculture, forestry and biomass

Agriculture and forestry is the basis for biomass energy. This has been the topic for several modelling studies, which are also being implemented into the ETSAP tools, e.g. within the RES2020 project. However, the topic need to be studied both in further details and with the objective of creating aggregate parameters that is consistent with other sectors and, thus, more useful in models that are covering all energy sectors.

7.4 Modelling infrastructure

Modelling the infrastructure in the form of electricity, gas and district heating grids is a weak element in technology-rich optimisation models. Trade between regions is modelled by transport costs and capacity limits of pipelines or interconnectors, but trade within regions can be made only for grids that are aggregated into a single point, to which costs and capacity limits are assigned. This is treated differently in the various TIMES models. In EFDA-TIMES and TIAM intra-regional electricity and gas grids have been neglected so far, while the Pan European TIMES model includes the electricity grid in three levels with parameters for efficiencies, capacity limits and expansion costs. The same method is used for natural gas and district heating at a single level.

To model district heating supply from large power stations suitable for CCS or future nuclear fusion plants, it is necessary to introduce heat transmission as a technology for endogenous investment assuming a flow efficiency and cost (investment and annual operation) per unit of annual flow. Preliminary model runs show that investment cost in the range 25-50 \$ or € per GJ annual flow will lead to results that may be used to illustrate the competition among heat supply options.

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