Methods and Models

used in the project **Pathways to Sustainable European Energy Systems**

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THE AGS
The Alliance for Global Sustainability

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Pathways to Sustainable European Energy Systems

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Foreword

This book reports on the methods and models that were applied in the project "Pathways to Sustainable European Energy Systems", which is a 5-year project (2006-2010) aimed at evaluating pathways to a sustainable European energy system, with a focus on the stationary energy system and the time period up to the year 2050. The results obtained during the project are reported in the book "European Energy Pathways - Pathways to Sustainable European Energy Systems" and in various scientific papers.

The present energy system has been included in the analysis, as this will have a significant influence on possibilities to transform the energy system over the coming decades. Therefore, a cornerstone of the project has been the establishment of extensive databases related to the European energy infrastructure, and including the global fossil fuel infrastructure. The pathway analysis has applied a variety of energy-related methods and models that originate from different scientific disciplines and traditions. Some of the applied analytical tools are well-known, well-documented, and widely used in academic research, while others have been developed (or refined) during the Pathways project and are therefore unique. To a certain extent, the Pathways project has also served as a "testing ground" for exploring the possibilities and challenges of co-ordinated multi-model analyses of complex problems. The aim of this book is to give a more in-depth presentation of the project from a methodological viewpoint than that provided in the Results book. In all, some 40 researchers have been involved in the work.

The project is the result of several initiatives at Chalmers University of Technology, and has benefitted greatly from discussions with persons who have shown an interest in how we in Sweden and Europe can transform our energy system so as to take the lead in promoting a more sustainable global society. The Chalmers Environmental Initiative has facilitated the genesis of the project presented in this book, and the Alliance for Global Sustainability (AGS) created a perfect framework for initiating the project.

I would like to thank all the researchers who have participated in the writing of this book. Special thanks to Dr Ulrika Claeson Colpier (Chalmers University of Technology) and Dr Erik Axelsson (Profu), who took upon themselves the heavy responsibility of coordinating and compiling this book.

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Filip Johnsson
Project leader

Göteborg, December, 2010

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I. Introduction

I

The aim of this Methods and Models book of the Pathways project, is to give a more in-depth presentation of the project from a methodological viewpoint. This applies to the Pathways project as a whole and to specific parts of the project. The book is organised into two main parts (Chapters I-III and Chapters 1-29, respectively). The introductory part deals with the Pathways project in its totality, providing an overall portrait of the work and presenting the background to the project, the research questions, the major objectives, and the scope of the project. Also included are descriptions of the work structure and the executive processes of the project, as well as the framework, which constitutes the basis for co-ordinating and integrating the different parts of the project. Some examples of this co-ordination are provided. The second part of the book comprises more-detailed descriptions of the specific methods and models that have been developed and applied within the different parts of the project.

Background

Over the last century, the demand for commercial energy services, such as electricity, heat, and transport, has increased dramatically in Europe and in the rest of the world. Currently, about 85% of all commercial energy consumed originates from fossil sources. Owing to a heavy reliance on fossil fuels, and the associated release of CO_2, the world now faces huge environmental and technological challenges.

To reduce the increasingly serious threat of climate change, the world must urgently address the challenge of substantially reducing emissions of CO_2. Therefore, policy-makers must develop near-term strategies to set both the European and global economies on the course towards energy sustainability. Technologies already exist or will soon be available, which if implemented on a sufficient scale would begin to reduce CO_2 emissions very soon. Moreover, reduction of CO_2 emissions (as well as emissions of other greenhouse gas emissions) must be carried out in a way that maintains the security of supply as well as social and economic sustainability.

To support policy-makers, research is needed to identify technological options that are robust and to investigate how these options can be effectively implemented. To be effective, this research must be interdisciplinary (benefitting from the latest developments in, e.g. technology, policy, and economics), multi-regional (taking into account the economic and social differences around the world), and relevant to the needs of end users, which implies strong participation by stakeholders. This project has been developed to meet these needs on a European basis.

Aims and research questions

Scientific objective

The overall aims of the Pathways project are to study how pathways to a sustainable energy system can be characterised and visualised and to evaluate the consequences of these pathways with respect to the characteristics of the energy system *per se* (types of technologies, technical and economic barriers) and for society in general (security of supply, competitiveness, and required policies).

These objectives are addressed on three levels: (i) an energy systems analysis (technology assessment and technical-economic analysis); (ii) a multi-disciplinary analysis; and (iii) an extended multi-disciplinary policy analysis.

The overall focus of the project has been divided into the following key questions and topics:

1. Criteria and indicators for the pathways

- What are the criteria for defining "pathways to sustainable energy systems"?
- How will the choice of criteria influence the design of the pathways towards a sustainable energy system?
- What pathways do not lead to a sustainable energy system?

2. The current "pathway" (business-as-usual development)

- Will the current "pathway" lead to a sustainable energy system?

3. Two pathways to a sustainable European energy system

- How can pathways to a sustainable energy system be characterised and visualised?
- What are the consequences of these pathways?

4. Key technologies and measures (including bridging technologies)

- What are key technologies and measures for the identified "pathways"?
- Where are the greatest uncertainties regarding technology choices?
- What is the critical timing for decisions to ensure that a pathway to a sustainable energy system can be followed?

- What role will the stationary systems, e.g., the power system, district heating system, and demand side, play in the different pathways?
- Where are the critical regions located with respect to aspects such as CO_2 emissions and required investments?
- What are the roles of different options and measures, such as renewables, nuclear power, and energy efficiency?
- Where and when can risks for technology lock-in effects emerge?

5. Will a deregulated market in Europe pave the way for sustainability?
- Are deregulated energy markets suitable for facilitating development towards a sustainable energy system?

6. Political actions and decisions
- What type of political action is necessary?
- What issues have to be addressed at the international level?

7. Acceptance by society and the roles of different actors in the transformation of the energy system
- What possibilities and obstacles can be foreseen?
- What choices that lead to sustainability are consumers likely to accept? How will these choices affect political decisions, and vice versa?
- Are the present market actors prepared for the changes entailed by a pathway towards a sustainable energy system?

Methodological objective

The research within the project also has a methodological focus, i.e., to develop new methods and models and to adapt already existing tools, so as to resolve the research problems. The aim of this book is to illustrate the developments achieved within the Pathways project, both on a comprehensive, inter-disciplinary level, as well as on a more detailed intra-disciplinary level.

The work of the Pathways project is built upon a specific project framework (Chapter II). This framework is largely based on experiences gained in previous research projects. One aim of the project is to test the validity of this framework and to provide inputs for the development and refinement of the framework.

Educational objective

Apart from addressing the different research questions and developing methodologies to do so, the work within the Pathways project has an educational purpose. Students at the doctoral or masters level have participated in the project. So far, the work in the Pathways project has resulted in seven doctoral and licentiate theses and several Master theses. Thus, a secondary objective of the project has been to provide Swedish and European industry and academia with highly educated people in the energy field.

Scope

The main focus of the Pathways project is to analyse possible transformations of the stationary energy system in Europe up until 2050. The transportation sector, which is an important part of the European energy system, is considered in the development of the stationary sector. However, the development of the transport sector in its entirety has not been scrutinised in a comprehensive and detailed manner.

An important condition when transforming the energy system is that there is already a system in place – the present energy infrastructure. The energy infrastructure consists of components that typically have long life-times (i.e., the turnover time for capital stock is long), which means that once investments have been made in a power plant, transmission network or a natural gas pipeline it will be costly to shorten the expected life-time. Typically, such systems have a technical life-time of at least 25 years, although it can be up to 40 years. Therefore, when transforming the energy system it is important to discover new technologies and measures and to identify technologies that fit into the existing energy system. In an analysis of the technical energy system, one should also consider the consequences of and the impacts on developments in inter-related systems, such as energy resource systems and institutional and legal systems.

Up to the year 2050, the successful application of what in this project are referred to as "bridging technologies and measures" will be of great importance for transforming the system. Bridging technologies are dependent upon the existing energy system. This is of course nothing new, as this is more or less true for all technologies and measures that can be employed at scale over the coming decades. The term is here used merely to stress that all the technologies and measures that we currently have and can expect to apply over the next decades must fit into the existing energy system or rely heavily on the present system for good performance. This is obvious for co-firing biomass in existing power plants, first-generation biofuels, retrofitting of the existing building stock, and carbon capture and storage (CCS) but it also holds true for the technologies and measures that are needed to facilitate the integration of emerging sustainable technologies into the existing energy system.

Although there will be strong development of entirely new and more "sustainable" technologies (e.g., hydrogen-based technologies, solar cell technologies, and nuclear fusion), these are likely to play less-important roles in the generation and use of energy up to the year 2050, which is the time frame of this project. When handled in an appropriate way, bridging technologies can facilitate a cost-effective transformation of the energy system without lock-in effects.

With respect to the stationary energy system, one could argue that leading up to the year 2050 almost all technologies and measures that we have currently to hand will have to be adapted to the existing system.

An important starting point for the Pathways project is that the goal of a "Sustainable Society" in itself is impossible to define and does not represent a static final state. Instead, the focus has been on identifying steps or pathways that are positive and non-regrettable. Yet another important aspect of the focus of the project is to decide whether the solutions lead to a diversity of subsequent steps or towards more specific solutions that may constrain development (here, it should be noted that it is not necessary to prove that a lock-in situation represents an unsustainable state, rather the point is that uncertainty regarding future priorities and crossroads in society demands flexibility and variety when it comes to possible options for continued development).

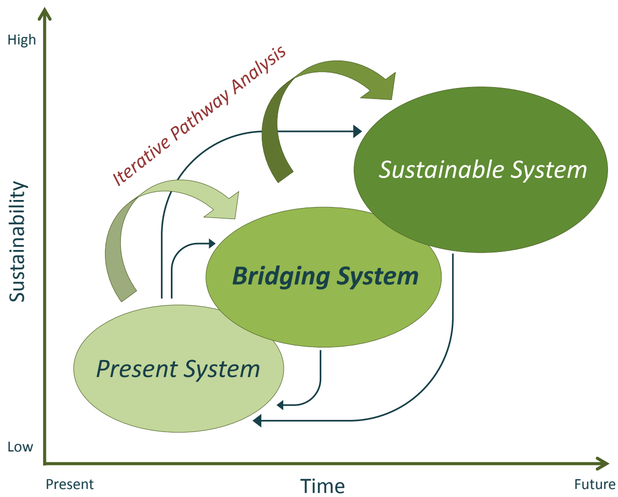


Figure I.1. The Pathways project's approach to analysing transformation of the present energy system to a more sustainable energy system.

Figure I.1 summarises the development from the existing system to a more sustainable system across a bridging system that includes sustainable and bridging technologies. The figure also emphasises that any analysis to investigate possible pathways to a more sustainable system must be carried out in an iterative fashion, both within the time-frame of this project and in future projects. The scheme should be seen as dynamic, in that new possibilities and barriers will evolve over time.

Work structure

Answering the overall research question necessitates an inter-disciplinary approach. However, a detailed intra-disciplinary research approach is also required to assess in depth the transformation of the energy system and to identify barriers and opportunities for key technologies and measures.

The work conducted within the Pathways project is organised into five main research areas, corresponding to the different sectors in the energy system. These research areas are:

- The power supply system and the use of fossil fuels (including CCS)
- Industrial energy systems
- The use of biomass and the biomass supply system
- The district heating system
- Energy use in the residential and service sectors
- Waste management

Even though there is an emphasis on the technical aspects of the transformation of the energy system in the project, the analyses not only consider technology-oriented issues, but regard the transformation in the larger context of economical, societal, and institutional factors. The Pathways project consists therefore of researchers from different disciplines.

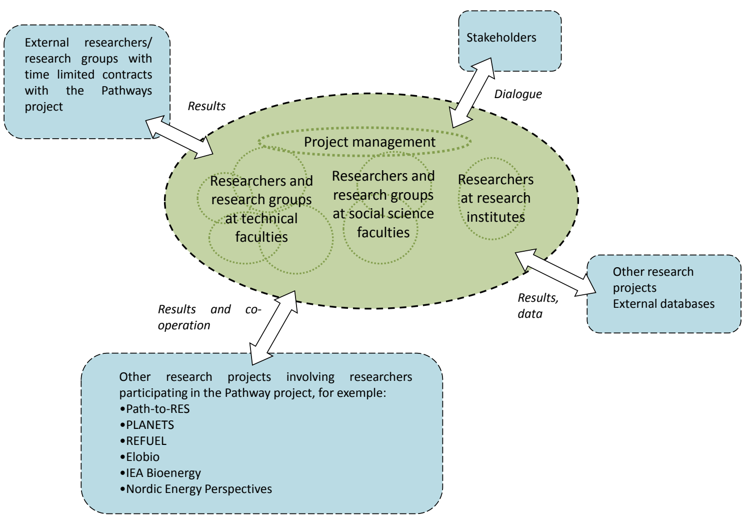


Figure I.2. The work structure in the Pathways project.

The core of the Pathways project consisted of researchers at the university (in the faculties of technology and social sciences) and at research institutes (Figure I.2). The research projects involved doctoral students as well as senior researchers. Over 40 researchers participated in the project (although not always for the entire 5-year project period, 2006-2010). The project management has played an active role, both by participating in the research work, but also by transferring knowledge and facilitating the dialogue between different research groups to find common grounds for additional co-operation.

Each research group (representing the above mentioned research areas) investigated a research question and sub-research question within its discipline and area of focus. However, strong inter-relations were promoted between the different energy sectors, as a development in one area might impact development in the other sectors. Therefore, aggregated research groups were formed, as illustrated in Figure I.3, so as to address the multi-disciplinary and inter-sectorial aspects, whereby common research questions were analysed and common boundaries, the effects of specific results and possible synergies/opportunities or pitfalls could be discussed.

Within the Pathways project, collaborations and interactions between involved researchers and research groups have been fostered. These interactions have involved joint research projects and seminars and workshops for the presentation of research results. Through these activities, important concepts have been reflected upon and comprehensive issues have been discussed. An example of a concept that has been discussed is the concept of "path dependency" in different areas of research, as discussed in Chapter 4.

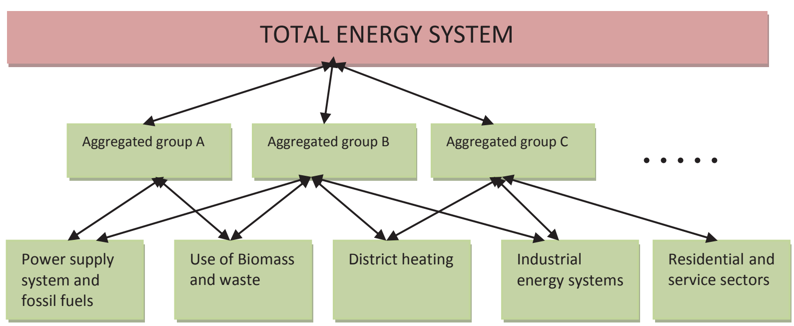


Figure I.3. Work organisation and research groups within the Pathways project.

The work of the Pathways project has also involved contributions from several actors outside the constituent research team (Figure I.2). To elucidate specific research topics, external research groups or researchers with valuable knowledge of the topic have performed short-term projects and studies. Many of the

Pathways researchers have also participated in other research projects, e.g., in the EU-funded projects PATH-TO-RES, PLANETS, and REFUEL, as well as in international projects (e.g., Nordic Energy Perspectives and IEA Bioenergy) and national co-operative ventures. This has provided opportunities to elaborate the research topics in a different context and for mutual knowledge transfer between projects and collaborators. To ensure the relevancy of the research questions addressed, there has been a dialogue with different stakeholders in the project, such as the European utility industry, European and national policy-makers, and other energy-related industrial partners. Data and results have also been obtained from other research projects, databases, and international and national energy analyses. In turn, the results from the Pathways project have been shared with the wider scientific community and other stakeholders through participation at conferences, seminars, and workshops, publications in scientific journals, and by involvement in international work groups.

The work process

A common basis for research in the Pathways project was to use a bottom-up approach, meaning that the analysis started from a detailed description of the existing energy system, and from this description different pathways, including the identification and assessment of bridging technologies and measures, were discussed. The work process was therefore similar for all the research groups, even if the specific models and methods applied in the research differed between the groups and specific projects (the different models and methods are described in greater detail in the latter part of this book). The work process can be divided into four main steps that included the participation of all research groups:

A. Descriptions and analyses of the present system and current trends

B. Assessments of bridging technologies and measures

C. Analyses of sector-specific scenarios and their contributions to sustainability

D. The creation on a cross-sector level of two pathways towards a sustainable European energy system

For steps A–C, each of the research groups contributed with results. Even if every researcher did not supply results for all three steps, there was a collective responsibility in that the group as a whole contributed with results for each research area. The ultimate goal of steps A-C was to show the total effects of all the important bridging technologies and their contributions to sustainability on the EU level for a number of EU sector-specific scenarios. However, calculations of contributions were also made for: (i) the national and regional levels; (ii) case studies; and (iii) technology assessments (single key technologies). Even if the analyses on each level were made by the research groups, they were not necessarily performed for every key technology and measure, but an adequate level was chosen for each task.

The work for steps A to C was performed on several levels, initially at the sector level, i.e., corresponding to each of the research areas, and subsequently at more aggregated levels comprising two or several sectors, as illustrated in Figure I.3. The cross-sector analyses ensured that issues such as limited resource potential and benefits from economies of scale were considered in the assessments of key and bridging technologies applicable to several sectors of the energy system.

The use of scenarios was an essential approach in the Pathways project. The aim of the scenarios was not to forecast what will happen in the future, but to explore the question "What if this or that happened?" and thereby arrive at important insights and conclusions. The researchers and research groups were not limited by specfic criteria e.g. regarding choice of bridging technologies or specific sustainability targets when constructing their inital scenarios in step C, but such criteria were developed based on the perspectives of the different groups and sectors.

Finally, in step D, the results from steps A to C were combined and processed to create two different pathways to a sustainable European energy system. This creation of pathways was an iterative process in which the results and scenarios for a total energy system level were passed back to the research groups, to allow for processing of the new results to a higher level of complexity and comprehension.

In the following sections, the contents of the steps A to D are described in greater detail. Within the Pathways project, efforts were made to develop and combine methods and models so that both intra-sectorial and inter-sectorial analyses could be used in the work process. Examples of these interactions are presented in Chapter III as well as in various chapters in the latter part of this book.

A. Describing the present situation

This first step in the work process was intended not only to respond to the research question of describing the current pathway, but also to provide a detailed description of the existing energy system used as the basis for subsequent analyses and to establish relevant baselines. Thus, this step included the creation of different databases available to the project, reviews of current national and EU policies and targets, analyses of current trends, and the establishment of common boundary conditions to be used by the different research groups.

Creation of databases

In the Pathways project, the analysis of future developments in the European energy systems started with a detailed description of the existing energy system. Each research group was responsible for creating databases that contained data regarding the present situation (which could also include historical developments and near-term plans). The databases were built on data obtained from different sources, including in-depth interviews, data and literature surveys, available statistics, and direct contacts with, for example, energy utility companies, energy plant owners, and international and national energy agencies. In addition, data from external databases derived from official national and European statistics, EU-funded projects, research institutes, and private companies were used.

Five of the databases are gathered as sub-databases in the Chalmers Energy Infrastructure database (CEI db). The CEI db describes different parts and areas of the European energy system, both on the demand side and the supply side (Figure I.4). Currently, the main sub-databases are: the Chalmers power plant database; the Chalmers fuel database; the Chalmers industry database; the Chalmers CO_2 storage database; and the Chalmers Member States database. The key features of these different databases are summarised in the page 11. The CEI db is continuously being updated and the scope is gradually being extended. More extensive descriptions of some of the sub-databases and their applications in the Pathways project are given in Chapters 1-3.

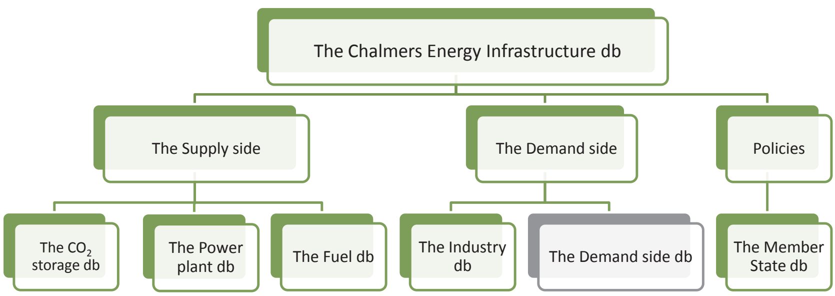


Figure I.4. Structure of the Chalmers Energy Infrastructure database. The databases marked in green are ready to use, while the one shown in grey is under construction.

Common boundary conditions and political targets

Scenario analysis is an important tool in the Pathways project for assessing the potential of specific technologies and for analysing possible developments of specific energy sectors or the total energy system. Comparisons of the results and impacts of different technology options or measures, for example, mitigation costs, are facilitated if common boundary conditions are applied to the different analyses.

Therefore, researchers have jointly established datasets that can be applied to, for example, fuel costs, based on project-related results and projections from the EU and IEA. An example of this is the applied energy market parameters presented in Chapter 20.

Key characteristics of the databases presently included in the Chalmers Energy Infrastructure database

Chalmers power plant database

- Covers the EU27, Iceland, Norway, and Switzerland
- Contains all power plants and wind farms≥10 MW; smaller plants (and on-shore wind power plants) are aggregated
- The following items are registered for each plant: location, age, fuel capacity (thermal and power), technology, present status, scrubbers, and re-powering
- Annual levels of electricity generation and CO_2 emissions are provided for most of the plants
- Separates autoproducers from the electricity supply industry and combined heat and power from conventional power production.

Chalmers CO_2 storage database

- Covers the EU27 and Norway
- Contains all European gas and oil fields with storage potential of at least 1 $MtCO_2$, as well as 370 aquifers
- Contains site-specific storage parameters, such as water depth, depth to top reservoir, initial pressure and temperature, formation volume factor, degree of API, reservoir density, R/P ratio, and CO_2 storage potential
- Identifies key reservoir properties, such as permeability, lithology, water content, age of inner structure, as well as sensitivity to over-pressurised Jurassic and Triassic zones in the North Sea
- Contains annual and cumulative production levels, as well as data on economical and geological reserves (oil and gas fields)
- Exact location listed by geographical co-ordinates, as well as by name on the local, regional, and global levels

Chalmers fuel database

- Global coverage
- Contains data on coal mines and on coal, gas, and oil fields
- Includes production history, estimates of remaining and ultimately recoverable reserves in oil and gas fields
- Contains fuel distribution infrastructure for Europe
- Exact location listed by geographical co-ordinates, as well as by name on the local, regional, and global levels

Chalmers industry database

- Covers the EU27, Norway, and Lichtenstein
- Covers eight industrial sectors
- Exact geographic locations listed for industrial plants with annual CO_2 emissions exceeding 0.5 $MtCO_2$
- Contains verified CO_2 emissions and allocated emission allowances
- Includes plant-level characteristics, such as type of production process, fuel mix, and age

Chalmers Members State database

- Comprises the EU27 countries
- Identifies key energy-related policy decisions and statements
- Identifies key energy-related targets both at the national and EU levels
- Identifies key energy-related documents, e.g., the National Climate Strategy and National Energy Strategy
- Identifies key indicators for security of supply, fuel infrastructure, and CO_2 emissions
- Identifies key infrastructural constraints
- Compiles energy-related statistics, as well as GHG emission statistics

Several political targets influence the development of the European energy system. The political goals can be formulated at different levels, e.g., the global, EU, and national levels. Energy policies are typically targeted to three different areas: (i) climate and the environment; (ii) security of supply; and (iii) competitiveness.

The EU "20-20-20" targets have served as important guidelines for the establishment of targets in the analyses conducted by all the research groups. These targets include:

- Reduction of EU greenhouse gas emissions by at least 20% by 2020, as compared to the corresponding levels in 1990
- An increase to a 20% share of the EU total energy consumption for renewable energy resources, to be achieved by 2020
- A 20% reduction in primary energy use relative to the projected levels, to be achieved through energy efficiency improvements by 2020

In the longer-term perspective, there is also an ambition to limit the global temperature increase to 2°C, which is often translated into greenhouse gas emission reductions of 60-80% in the developed countries and 50% on the global level. In the other two policy areas, the targets are less clearly defined, although there are proposals to maintain or improve the security of supply within the EU and to ensure the economic competitiveness of the region.

When the concept of "sustainability" is used within the Pathways project it means that the targets in all three energy policy areas can be met, i.e., that climate change can be successfully combated while preserving the security of supply and competitiveness for the region. In addition, there has been a deeper discussion within the project on the meaning of sustainable development, and it has been assumed that no negative environmental side-effects can be associated with the reaching of climate change targets.

The current pathway (business-as-usual development)

One of the research tasks is to describe the present pathway of the European energy system and to investigate whether this will lead to a sustainable system. The current pathway constitutes business-as-usual development, to which other pathways are compared, and this is used as a reference when the contributions to sustainability for different technologies/measures are calculated.

The current pathways were developed based on official baseline or reference scenarios from e.g., the IEA's "World Energy Outlook" and the European Commission's "European Energy and Transport Trends to 2030", as well as on results from the research and analyses in the Pathways project. It has been important to consider the impact of the existing energy system, as described in the databases. Current pathways are constructed for several levels of the energy system, on a sector level as well as on a total energy system level. The approach of developing current pathways has also been applied in a social science research context, for example, studies of the legal framework or discussions of path dependency.

B. Key technologies and measures, including bridging technologies

Several key and bridging technologies or measures have been identified and assessed in the project. A bridging technology or measure can be a short-term or medium-term option, for example, to reduce CO_2 emissions and/or increase the security of supply, while also facilitating the transformation towards a more sustainable energy system. It can be a technology that can be integrated into the existing energy infrastructure (e.g., co-combustion of biomass) or used as a "stepping stone" technology to establish new infrastructures that will be needed in the future (e.g., a large-scale biomass supply system).

Each research group has analysed several technologies and measures to determine their relevancy and contributions to reaching long-term targets. However, as mentioned above, a technology may be applicable to several sectors of the energy system, implying a risk of competition for limited resources or use of infrastructure, as well as the existence of other barriers in related systems, even though there may also exist opportunities for synergy effects and/or large-scale advantages. Therefore, an assessment has also been performed on a more aggregated research area level (Figure I.3). In step B, the analysis is primarily focused on each technology and measure separately, while in step C, the key and bridging technologies and measures are analysed together, and in relation to other technologies and measures. Examples of some of the options and measures identified and assessed in the Pathways project are: the co-combustion of biomass in fossil fuel plants, the integration of wind power into existing power generating systems, the implementation of energy efficiency measures in supply and demand sectors, and the introduction and use of CCS technologies.

C. Sector-specific scenarios and contributions to sustainability

This step was performed on a sector level and no specific criteria regarding choice of bridging technologies or specific sustainability targets were assigned, instead the choice of adequate technologies and ambition were initially determined by each research group. The purpose was to gain insights into possible pathways and the potential of each sector to contribute to sustainability and to identify key technologies and measures. It also included an investigation of the combined effect of several bridging technologies and measures from a system perspective. Although the final aim was to provide scenarios on the EU level, the analysis was initially performed with a more limited geographical scope, e.g., as case studies or developments on a regional or national level.

Several examples of sector-specific scenarios can be found in the results chapters in the *European Energy Pathways* book.

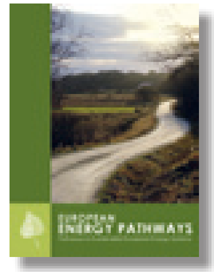
D. Developing pathways

One of the most important tasks for the project was to describe two pathways towards a sustainable European energy system (see page 5 in the *European Energy Pathways* book for a description of these pathways). These pathways are the result of an interdisciplinary synthesis of the results from all the research groups.

In a first step of the synthesis, the framework for the sector-specific scenarios in step C were narrowed and specified to distinguish a Policy and a Market case. This part was carried out in an iterative way using the EMER model, as explained in Chapter 22. The synthesis work has also been a learning process, during which the different disciplines and research areas have met to contribute different methods and model configurations and coverage. Comparing the results from the different groups increased the understanding of the crucial drivers for developments. Any differences in outputs gave an added value to the synthesis, since they pinpointed uncertainties in the system in focus and required the researchers to identify and characterise these uncertainties. In contrast, when the outputs were relatively similar for all the results, this was considered a strong indication that such specific results were robust.

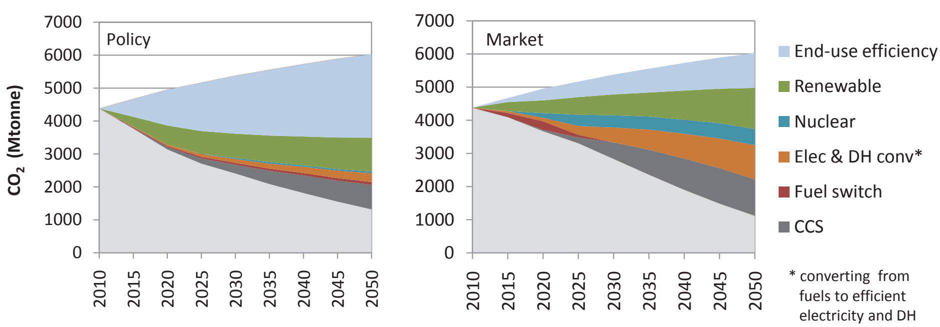
An important part of the construction of the pathways was to match the technical potentials with the barriers and potentials reported by the social scientists included in the Pathways project. For instance, the expansion of wind power can be limited by a juridical framework, especially in certain countries of the EU. An example of possibilities is that the company strategies that are currently outlined in many cases opens for a sustainable development. Besides the development of the Policy and Market Pathways, a Baseline scenario was developed, to which the pathways could be compared.

Two pathways have been developed



Two pathways to sustainable European energy systems – the "Policy Pathway" and the "Market Pathway" - have been developed in the Pathways project. The Policy Pathway takes its departure from the EU Energy and Climate Package and has a strong focus on targeted policies that promote energy efficiency and energy from renewable sources (RES). In the Market Pathway, the responsibility of choosing mitigation measures for transforming the energy system is left to the market. In this pathway, assigning a cost to emit CO_2 (and other GHGs) is the dominating policy measure. The two pathways are presented in the *European Energy Pathways* book and are based on the results from the sector-specific scenarios and analyses described in Chapters 1-46 of the *European Energy Pathways* book. The methods and models used to develop the sector specific scenarios as well as the pathways are presented in this book.

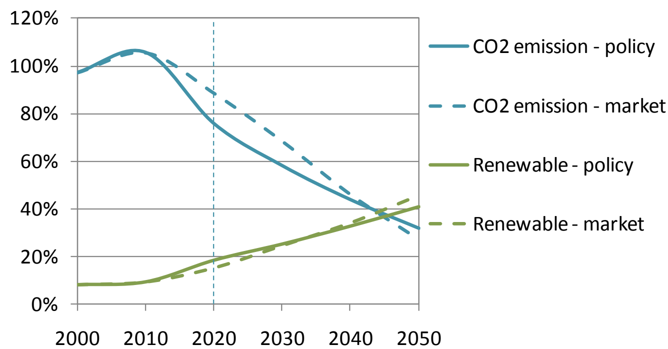
Both pathways require significant changes in the infrastructure of the energy system and related power plants, transmission networks, fuel infrastructures, buildings, and transportation systems. Obviously, there is no simple "silver bullet" solution and transforming the energy system will take time. Since only four decades remain until the system needs to be virtually CO_2-emission free, and considering the slow turnover in capital stock of the energy infrastructure, it is important to start with a good description of the existing energy system (c.f. the Chalmers Energy Infrastructure database) and thereafter, evaluate how technologies and measures can be implemented in a step-wise manner over the next decades.



CO_2-emission mitigation measures, as "wedges", for the Policy Pathway (left) and Market Pathway (right). The targets for reductions in CO_2 emissions are the same in both pathways, i.e., 70% reduction by 2050.

Energy and emission trends in the two pathways

The targets for reductions in CO_2 emissions are the same in both pathways, i.e., about 70% reduction by 2050. However, the mitigation measures needed to achieve this target vary between the two pathways. In the Policy Pathway, a rapid and powerful emission reduction occurs already by year 2020, due to the promotion of end-use efficiency measures and renewable energy sources. The EU goal of a 20% reduction in GHG emissions will thus be surpassed, since the emission levels of other GHGs, mainly methane and nitrous oxide, are also expected to decrease. However, in the Market Pathway, the progress of emission reduction will be slower during the first decade. To achieve the 20% reduction target by 2020, the EU may therefore have to be a net buyer of emission allowances on a global carbon market. The share of renewable energy increases in both pathways, reaching a share of 40% of the final energy use in 2050. In the Policy Pathway, the EU goal of a 20% share in 2020 is within reach. In 2050, the renewable primary energy use will surpass 5,000 TWh in both pathways, which represents a four-fold increase compared to the situation in year 2000.



CO_2 emissions and the share of renewable energy in final energy demand in the EU27, for the Policy and Market Pathways.

II. A framework for setting up and co-ordinating the methodologies used in the Pathways project

The Pathways project provides an excellent opportunity to apply, in a co-ordinated manner, a large variety of energy-related methods and models, which have their origins in different scientific disciplines and traditions. To a certain extent, the Pathways project represents a "testing ground" for exploring the possibilities and challenges associated with co-ordinating multi-model analyses of a complex problem. The sharing of experiences and perspectives has further contributed to the project being expanded into new areas.

The framework that is presented below summarises the approach used for co-ordinating different methods and models during the course of the Pathways project. The project is, as described in Chapter I, a comprehensive multidisciplinary research project that involves complex research questions and that both uses, and co-ordinates a wide variety of methods and models from different scientific disciplines and traditions.

1. Structure the research questions and let them govern the research activities...

In the Pathways project, the research and analysis processes were determined by the task of tackling the comprehensive research questions. This has been a common task and a collective responsibility for all the researchers participating in the project, even though not all the researchers have contributed to the response to each specific research issue.

Based on experiences gained from other large research projects, having common research questions provide an appropriate and efficient focus for multi-disciplinary research projects that involve many researchers. All the researchers, in accordance with their own research discipline, methods, and tradition, deliver insights into the questions addressed. This analytical approach of combining and synthesising results based on different methods and models has, in the Pathways project, been considered a more appropriate, effective, and transparent approach than the development and application of a super-model or common "multi-disciplinary methods" with full coverage of the energy system and inter-related systems. The organisation of the research and the work structure (e.g., workshops, seminars, and common research sub-projects) successfully facilitated the exploitation of the diversity of the research group by creating an arena for common learning and for accumulating new perspectives on the research issues addressed.

...although research questions may be re-defined as a consequence of newly gained insights

However, the extent of the project – in terms of research scope, researchers involved, and time-frame (5 years) – has meant that the research questions have been subjected to refinement and reformulation as a consequence of new insights gained in the project. Therefore, even though the research questions have governed the research and the work process, these should not be considered as being set in stone; certain degrees of flexibility and re-interpretation must be allowed.

2. Involve stakeholders at an early stage and throughout the project

The project has striven to involve various stakeholders in the research work and has promoted the participation in project-related activities of parties outside the consortium (individual researchers and institutions). Thus, inputs and results have been validated and verified by other project participants and external experts throughout the project. This has ensured a higher degree of credibility for the research work and represents a strong outreach for the project.

3. Introduce inter-disciplinarity at all levels, and...

Many of the issues related to energy and sustainability policy analysis have an inter-disciplinary character. Therefore, these issues can be regarded as being more than technical, corporate, or legal issues to be resolved, in that they concern a collective view obtained from different perspectives, which may provide a solution that can be implemented or indicate new opportunities and bottlenecks to be overcome. Therefore, it is desirable to have more than one scientific discipline or method represented in the research, and it is crucial that the results and insights are interpreted in and supported by an inter-disciplinary framework.

...include researchers with complementary methods and model approaches

The Pathways project has used an approach that has proven both efficient and successful. This approach involves several methods and model approaches that have been developed independently of each other. Using several methods and models means that the issues in focus may be tackled from different angles, different scientific approaches and disciplines can be used simultaneously, and the risk of bias due to a "common background" is reduced. Furthermore, researchers can consider their established methods and underlying theory in a new light, leading to further development that might not have occurred as an outcome of "in-house" work within their own research group.

…and use each method and model in the situation for which it is best suited

In the Pathways project, the research questions have determined the choice of method and model to be applied, rather than allowing the scope and features of the method or model to dictate the research focus. The different methods or models can be used to address the same (or similar) issues. Thereby, results that are robust (many results are very similar) may be separated from results that are significantly more uncertain (results vary largely among the analyses). Such comparisons are also very efficient for increasing understanding and for validating the methods and models. However, one must also recognise that certain methods and models are not appropriately designed for analysing all the issues under investigation.

4. Gather together researchers with high-level knowledge of different scientific fields

Re-direction of the development of the energy system towards sustainability is a complex process that not only affects the energy system, but also inter-related systems, as it requires extensive structural changes throughout society. The Pathways project has faced the challenges of analysing and illustrating how such structural changes can be introduced and implemented. This necessitates a broad competence base and involves researchers with good knowledge and long experience of fields other than energy, e.g., industry, transport, agriculture, forestry, and waste management. In addition to the more techno-oriented aspects, the project deals with assessments of changes to our institutional structures, the legal framework and corporate business models, and how sustainability may become a part of corporate strategy, which meant that researchers within these fields were involved.

Finally, the Pathways project has been linked to (and co-operated with) other projects, including EU-funded projects (PATH-TO-RES, Refuel, PLANETS etc.) and other international research projects (e.g., the Nordic Energy Perspectives project) (see Chapter I). Thus, results and experiences have been shared in a way that has benefited all the parties. Furthermore, this has opened the way for synergies and opportunities for the diffusion of information.

5. Establish a forum for dialogue and co-ordination, and drive the process in a highly structured way

In an inter-disciplinary project that involves many researchers with different types of expertise, it is important to establish a forum in which the participants can discuss and scrutinise the results from a mutual and agreed viewpoint regarding the research questions. This may also facilitate additional collaborations between the researchers.

The steering document of the Pathways project defined at an early stage the guidelines for structuring and accomplishing the research and analytical processes (as described in Chapter I). None of the researchers has worked alone. All the researchers have co-operated in research groups with a defined focus. On a regular basis, the researchers and research groups have shared their results and findings in workshops and seminars. Each research group has been represented in the (overarching) groups, which have been responsible for the co-ordination of modelling activities and syntheses of the project. These groups have also reported back to all the involved researchers, partly through the representatives of the different research groups, and partly through the common seminars and workshops.

6. Syntheses forming parts to an entirety

The Pathways project is not a traditional energy systems analysis project with a single overarching energy systems model (and/or a single overarching macro-economic model), which carries out the collective analysis of the development of the entire European energy system. Instead, the approach of the project favour to the use of such multi-sectorial models together with detailed and sector-specific models. Thereby, a well-founded and highly detailed basis for analysis within each sub-sector or area is guaranteed. On that basis, we also include the comprehensive databases of the existing energy infrastructures, which have been generated during the project or are at the project's disposal.

However, the research questions make demands on the collected results and the answers formulated from comprehensive assessments. Thus, the results obtained from different researchers must be co-ordinated and evaluated. Indeed, one of the main challenges in the work process has been the co-ordination and synthesis of results and conclusions. In the Pathways project, the answers to the research questions have been developed through an extensive synthesis and quality audit process, for which the synthesis group has been responsible. This process has been iterative, regarding both the group and the researchers, and it has been successful. The tools and the processes that have been used are described in another part of this book. Thanks to the synthesis work, every research result of the Pathways project has been assessed, partly vis-à-vis the entirety of the project and partly vis-à-vis other relevant results. Through this process, the quality and robustness of the results and conclusions of the project have been enhanced.

Differences in method and model configurations and coverage in the performed analyses yield different results, but also increase the understanding of the crucial drivers for development. It is the differences in output that actually gives an added value to the synthesis, since these differences reflect the uncertainties in the system in focus and require the researchers to identify and characterise these uncertainties. If the outputs are relatively similar across all the results, this is a strong indication that such specific results are robust.

7. Work both bottom-up and top-down…

A distinguishing feature of the Pathways project is the many sector- and discipline-specific methods and models that have been used in the analyses. As part of the synthesis process, these methods and models have subsequently been unified. Therefore, one can characterise this approach as "bottom-up". The strength of this bottom-up approach is that it provides a firmly established and detailed analysis and result-oriented database within each subsector.

However, as part of the synthesis work, we have exploited analyses that were made from the top-down perspective, for example, regarding assessments and quality audits. This applies to analyses made within the project and closely related projects (such as the model analyses for the EU energy system using Markal/Times, as well as the global econometric analyses), and also to the external analyses (such as the Primes analyses for the European Commission and Eurelectric).

The integration of a bottom-up approach and a top-down approach has proven to be successful within the Pathways project, and has been of great use in the synthesis process.

...but do not forget to share a common view of future development

Even though individual researchers (or research groups) sometimes adopt rather different approaches or deal with significantly different aspects of the research issues, it is important to share a common view of the overarching questions and developments of the energy system. In the Pathways project, this has been achieved though the definition of two main pathways, the Policy and Market Pathways, which have as acted as guiding principles for each researcher. The pathways have been defined collectively. Since the pathways have been formulated in a relatively broad manner, it has been the task of each researcher to define and adapt further the pathways to that researcher's specific research question(s) and discipline.

8. Synchronise important input data and other assumptions, within reasonable limits…

Many assumptions have to be made before the analyses are carried out. Even though the input assumptions have been harmonised extensively in all the Pathways analyses, it has not been possible to achieve full harmonisation.

One reason for this is that the methods and models are designed differently; some of these differences make it impractical to harmonise fully the inputs and assumptions without compromising the functionalities of the methods and models, and some of these differences turn out to have significant impacts on important outcomes.

...and use the output from one analysis as the input to another analysis

As mentioned above, it was not the intention of the Pathways project to develop or use a “super-model” that would consider the full spectrum of issues and components of sustainability. Instead, the Pathways project has used several distinct methods and models. However, these have to be co-ordinated in terms of inputs and in terms of benefits derived from each other, i.e., linking inputs and outputs between them, as discussed further in Chapter III. While creating the linkages - through a soft-linking-process - it is important to retain a “human touch” in the analysis! The output of one analysis may have to be manually adapted to the requirements of the analysis in which the output is used as an input. This adjustment may simply be due to different system boundaries, although it can also be due to a requirement for context-specific interpretation of model outputs to make them suitable for subsequent analyses. In particular, when researchers from different disciplines co-operate, there may be a need for a “translation process” before the output obtained within one discipline can become the input for another discipline.

9. Recognise the “cultural” differences of the methods,models and modellers

The researchers make their own considerations, deliberations and judgements. Therefore, each analysis is in a sense coloured by the researchers’ experiences and their traditions of thought associated with their respective disciplines. There exist “cultural” differences regarding how best to set up analyses, use models, apply different methods, and interpret results. These cultural differences, which stem from the researchers’ different educational backgrounds and previous research experiences, should be recognised and articulated, so as to ensure that the diversity contributes positively rather than creating dissent and “locked discussions”. During the Pathways project, “cultural” differences with respect to, e.g., the principles and practices of energy markets and policy measures were identified. Another difference between the various scientific disciplines is that they have various approaches to being normative in their analyses. Usually, the analyses conducted within the social sciences are more descriptive in nature.

10. Work on the global, EU, regional, national, local, and case levels

The main tasks of the Pathways project are to describe possible pathways to sustainable European energy systems and to identify the key measures and bridging technologies that will be needed in the transition phase of development of the new energy system. Moreover, the research should highlight important challenges and opportunities for the different actors within the energy systems, including politicians, companies, households, and individuals. All these tasks relate to the analyses and results on different levels, i.e., globally and locally. For example, the EU cannot pursue climate policies unilaterally. For climate change mitigation to be successful, all countries must strive to achieve the same goal. Another example of how actions on different levels are essential is how further expansion of Europe's electricity grid requires both regional co-operation and regional analyses. In practice, the transition must be pursued and implemented locally.

Within the Pathways project, the researchers and research groups have been encouraged to conduct analyses at several geographical levels in parallel. At the same time, it has been an explicit intention that one of these chosen levels should be the European level, since this level is the main focus of the Pathways project. In those cases in which the European level has been lacking, the researcher/research groups have instead been urged to at least discuss their results from a European perspective. In most cases, this has been possible.

III. Synergies achieved through linking methods and models

During the Pathways project, a large variety of different methods and models has been used. Most of these are described in this book. Some of the analytical tools used in the project are well known, well-documented, and widely used in academic research, while others have been developed (or refined) during the Pathways project and are therefore unique. Furthermore, some of these methods and models have been linked together in a pioneering way. Thus, methodological synergies have been created, taking the results to a higher level. This chapter discusses three such examples: (i) the linking of different electricity supply models to reflect generation and transmission of electricity in Europe; (ii) a methodological development for estimating the aggregate potential of European industry based on detailed process simulations and infrastructural conditions; and (iii) the integration of sector-specific results (e.g., concerning buildings, electricity, and industry) to assess developments of the district heating sector in Europe.

(i) Modelling the European electricity system – the electricity-supply model package

The purpose of the European electricity modelling activities in the Pathways project is to evaluate selected strategies and options within the European electricity generation system as an essential part of the overall transformation towards a sustainable European energy system. This involves the identification of key technologies, assessment of costs, estimation of the need for new investments, and consideration of the different challenges that are associated with, in some cases, a dramatic shift in means of production.

The electricity supply model package

The starting point for the electricity supply model toolbox is the Chalmers Power Plant database (see Chapter 2), with its detailed description of existing power plants (on a plant-by-plant basis). The database also includes decided and planned investments. Thus, the development of the *ELOD* model (during the initial phase of the Pathways project, this model was referred to as the ELIN model, and while ELOD and ELIN are virtually the same models, ELOD is a more refined version) was adapted to the features of the database. In brief, ELOD calculates, based on assumptions as to the remaining life-times of the existing capacity and future electricity demand, a cost-efficient mix for new investments in a selected number of EU Member States (ranging from single countries to the entire region). Typical results from ELOD include electricity production and capacity (existing and new investments), by fuel and technology, marginal costs for electricity and CO_2 reduction, and cross-border electricity trade. The time-frame is 2005-2050. Details of the ELOD (and ELIN) model may be found in Chapter 11 and in Odenberger (2009).

Since the seasonal time resolution within a particular year is limited, ELOD model runs may be supplemented by analyses carried out using the *EPOD* model. EPOD is a strictly dispatch-oriented model for any given year and has relatively high time resolution (within the year). The model is an optimisation model (for one year at a time) and uses installed capacity (existing and new capacity) as the input, which is taken directly from the ELOD output. The EPOD model is described more thoroughly in Chapter 12. The development of the European electricity supply estimated by the ELOD and EPOD models may also be complemented from an electricity transmission point of view. This is done by linking the outputs from ELOD and EPOD to the transmission grid model *DC Power Flow* (see more on DC Power Flow in Chapter 13). For this to occur, the hourly production output from EPOD of a selected load segment is fed into DC Power Flow, which enables the highlighting of certain aspects, e.g., bottlenecks in the transmission grid. Thus, the performance of the future electricity generation system, as depicted by ELOD and EPOD, is qualified against the transmission system included in DC Power Flow.

Finally, a more detailed analysis of wind power may be undertaken in the *BALWIND* and *WALL* (Wind power ALLocation) models, which partly use the outputs from ELOD and EPOD. The use of such wind-specific modelling also benefits the use of ELOD and EPOD, meaning that the somewhat simplified description of wind power in these two models can be scrutinised from a more well-founded perspective. The use of the wind power models is not further discussed in this chapter. For additional reading, we recommend Chapter 15 (the BALWIND model) in this book, and in the *European Energy Pathways* book, Chapters 6 and 8 .

A schematic of the electricity-supply model toolbox of the Pathways project is given in Figure III.1.

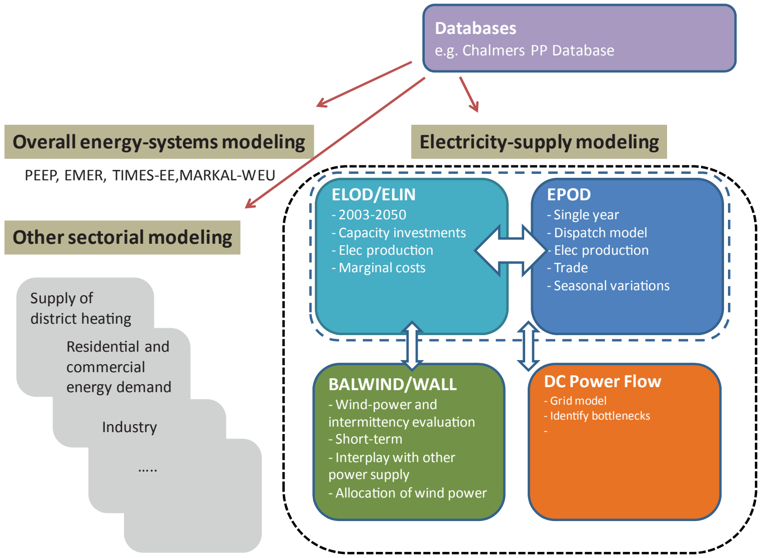


Figure III.1. Scheme for the different model tools used in the Pathways project, with emphasis put on the electricity-supply model package.

Geographical flexibility

The electricity-supply model package may be applied to a single Member State, to a group of Member States or to all the Member States of the EU. Thus, the model results may be presented on a European level, a regional level or on a country-by-country level. This geographical breakdown is shown in Figure III.2 for a typical output from the ELOD model.

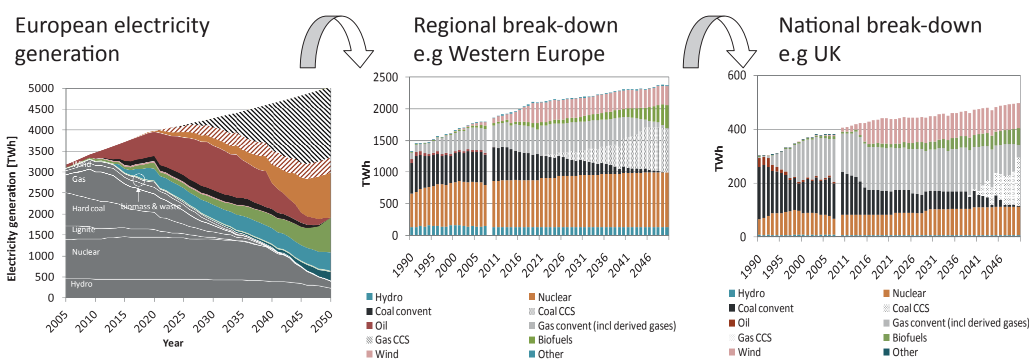
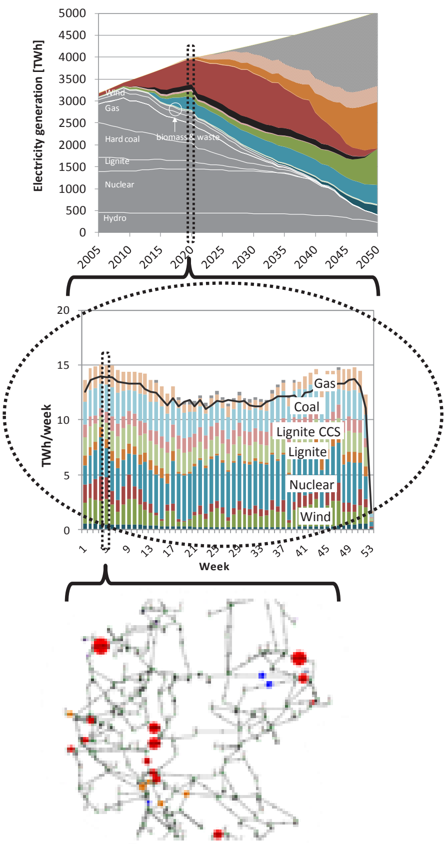


Figure III.2. Example of the geographical breakdown of ELOD model results for electricity generation by fuel and technology for the EU27 countries and Norway (left), Western Europe (middle), and the UK (right), for the Market scenario. Source electricity generation for years 1990-2007: Eurostat (2010).

Linkages between ELOD, EPOD, and DC Power Flow

The ELOD and EPOD models are tightly linked. Electricity generation capacity, marginal costs for CO_2 reduction, and biomass fuel prices are the outputs from ELOD that are used as inputs in EPOD (see Figure III.3). The fossil fuel prices are taken from EC (2008) and used as inputs in both ELOD and EPOD (Figure III.4). The higher seasonal and daily time resolution in EPOD may reveal information on dispatch (generation), CO_2 emissions, cross-border trade, and marginal costs for electricity, in addition to what is obtained from an ELOD model run. Finally, the hourly dispatch data (for a selected time period within a year) from EPOD are used as an input to DC Power Flow, allowing analyses of electricity grid issues, e.g., highlighting transmission bottlenecks (internationally and domestically) and pointing out the need for grid investments for a future electricity generation system. In general, top-load hours are in focus in such analyses.



Principal view of the linkages between the "capacity investment" model ELOD (top), the "annual dispatch" model EPOD (middle), and the "electricity transmission" model DC Power Flow (bottom).

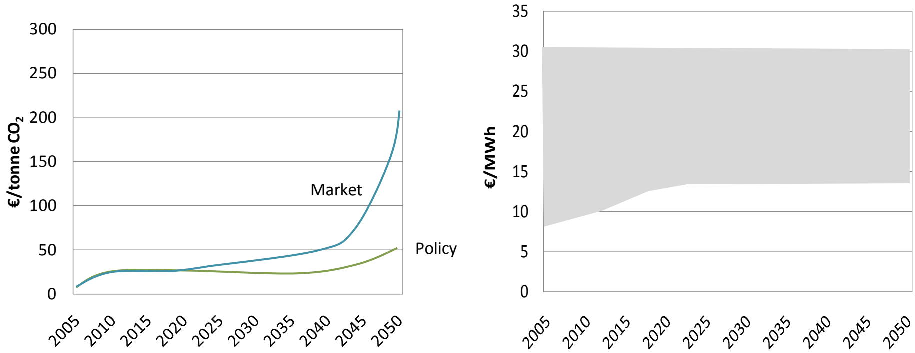


Figure III.3. ELOD model calculations of the marginal costs of CO_2 reduction (left panel) and biomass prices, shown as an interval covering all Member States (calculated by ELOD based on a cost-supply curve estimated by de Wit and Faij, 2010). These prices are used as an input to EPOD.

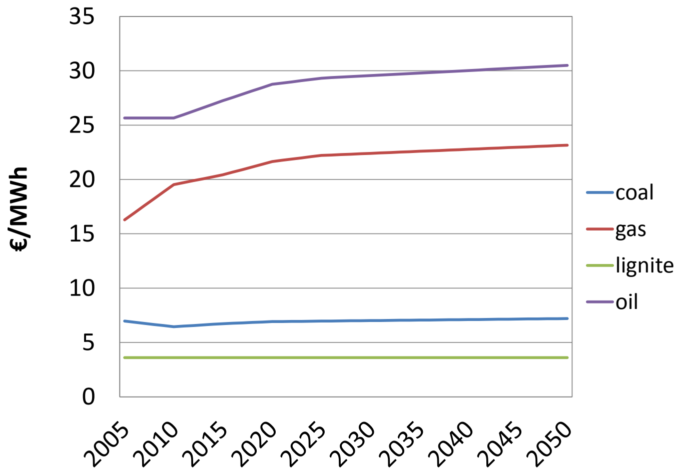


Figure III.4. Fuel price assumptions for fossil fuels at gate (based on EC, 2008). These prices are used as inputs for both ELOD and EPOD.

A typical EPOD output is presented in Figure III.5. The left panel shows the weekly electricity production for the four Nordic countries of Sweden, Norway, Finland, and Denmark for the year 2025 (Market Scenario). The right-hand panel shows the hourly production for the 48 hours surrounding the system top-load hour (an hourly EPOD model run is presently done only for a *selected* 48-hour block based on a preceding weekly model run). The system in this case includes countries other than the four Nordic countries, which means that the system top-load hour does not necessarily coincide with the top-load hour in the Nordic countries. Analysing electricity production during top-load hours may reveal interesting information about the supply system that might have been overlooked in the ELOD model. Thus, these hourly analyses give both valuable information about the future electricity supply system in itself and important feed-back to the ELOD modelling for model improvement. Other hourly blocks of interest may include hours with especially high (or low) wind-power output, possibly in combination with high (or low) load.

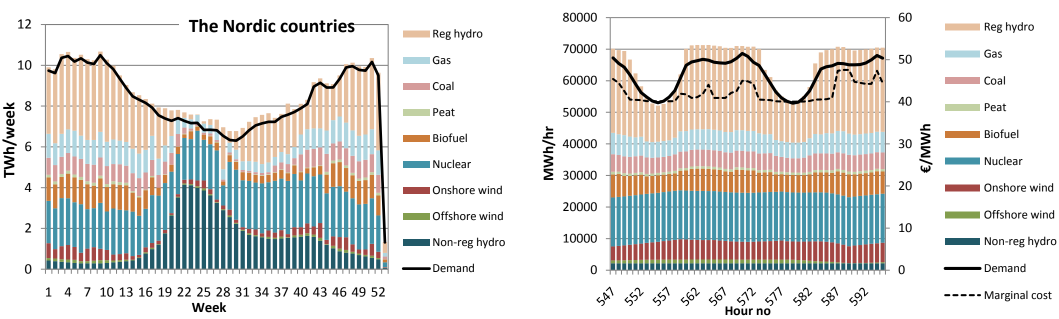


Figure III.5. EPOD model output weekly (left panel) and hourly during a 48-hour peak-load block (right panel) for the electricity generation system in Sweden, Norway, Finland, and Denmark.

This book describes the methods and models used to achieve the results presented in the **European Energy Pathways** book.

Linking supply and transmission – incorporating DC Power Flow into the model package

The purpose of the ELOD/EPOD and DC Power Flow linking is, as mentioned above, to include also the power transmission network in the modelling of electricity generation. A hard-linking approach (i.e., integrating the different models into a single model) would make the computational effort cumbersome. Therefore, a soft-linking approach, i.e. a manual and well-structured exchange of inputs and outputs, was chosen. During the Pathways project the final linkage between EPOD (and ELOD) and DC Power Flow was made primarily to prove the feasibility of such an inter-model linkage rather than for producing actual results. Nevertheless, some of the model analyses based on DC Power Flow relied partly on input from ELOD (see more in Chapter 3 in the *European Energy Pathways* book and Papaemmanouil et al., 2010).

Inputs supplied to the DC Power Flow model include the investment plan for new generation capacities of different types of generation technologies from the ELOD model, and the generation dispatch schedules of the peak-load hours, i.e., a snapshot for different years, from the EPOD model (Figure III.6). Peak-load hours are generally identified for a relatively large system (e.g., Western Europe) by EPOD, while the data transfer between EPOD and DC Power Flow, hitherto, has involved only the German electricity system.

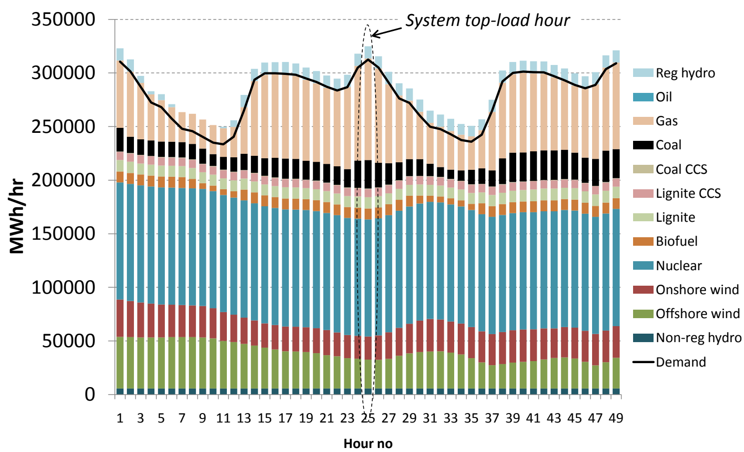


Figure III.6. Hourly electricity production during the 48-hour period surrounding the annual top-load hour (shown for Western Europe), as calculated by EPOD. The dispatch of the system top-load hour (indicated by a broken line in the figure) is used as an input for DC Power Flow.

In the DC Power Flow model, the power network is represented in detail in terms of generators, loads, and transmission lines. The model deals however only with active power and ignores transmission losses. The reactive power is also neglected due to the unavailability of data on reactive power generation and reactive power demand, as well as on the reactive power consumption devices in the system.

For the power flow calculations, the exact locations of power plants or ”generation centres” have to be known. This is also true for the ”load centres”. To perform the power flow calculations, assumptions as to the locations of generators and loads have to be made, since the new generation capacity and the generation dispatch schedule are the aggregated values according to the types of generation technologies (e.g., gas power, biomass power etc.). The new generation capacities, with the exception of wind power, are assumed to be located in the same locations as the existing ones of the same types. The generation centres are identified in the model using the actual network maps from ENTSO-E and the Chalmers Power Plant database. For future load data, it is assumed that the loads will increase equally in different regions. The forecasted load used by ELOD is then used to calculate the load-scaling factors from the existing loads. The loads during the peak hours for different years are used in the calculation, since high load conditions most likely lead to high loads in the transmission systems. This can of course vary with different distributions of power generation and loads.

The DC Power Flow model, which represents the network model of the integrated European power system, can be used to study the whole network or a part of the network, i.e., a region or a country. For the latter, the part of the network has to be isolated from the rest of the network. The rest of the network has to be made equivalent using some extra nodes in the system. To accomplish this, the steady-state power system equivalence technique is used. Figure III.7 shows the results of the DC Power Flow model for the “Business-as-usual” (“BaU”) scenario in 2015 in Germany. In this case, Germany has been isolated from the rest of the network, to allow analyses of the effects of generation on the transmission networks in Germany. The red circles in the figure indicate the lines that are overloaded during the peak hours. Note that not all of the overloaded lines are shown.

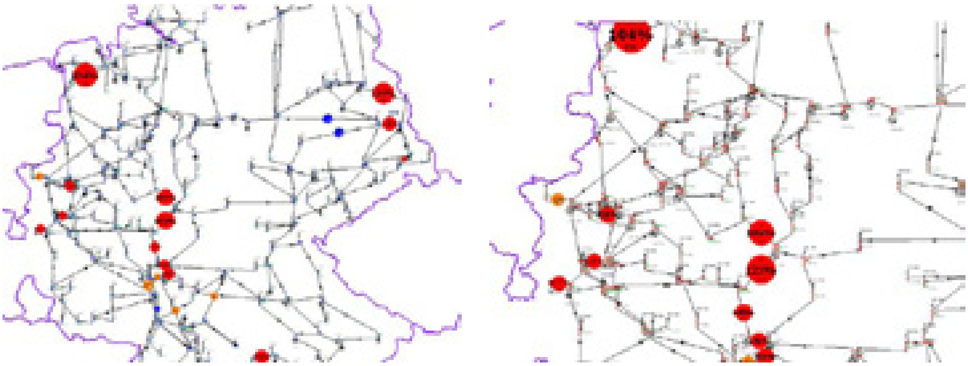


Figure III.7. DC Power Flow output for the whole of Germany (left) and for South-West Germany (right), in the "BaU" scenario (2015).

Table III.1 shows a summary of the transmission lines that are overloaded due to new investments in generation in the two different scenarios, "BaU" and "Efficiency", considered here for Germany. It is evident from the table that the "Efficiency" scenario would lead to fewer problems with network congestion, as compared to the "Baseline" case in 2015. The lower electricity demand due to end-use efficiency measures in the "Efficiency" scenario partly explains this phenomenon. A large share of the overload problem is attributable to new investments in renewable electricity generation.

Table III.1. Summary of network overloading levels for two scenarios ("Baseline" with increasing electricity demand, and "Efficiency" with stagnating or declining demand) in 2005 and 2015.

	BaU 2005	BaU 2015	BaU 2025	Efficiency 2015
Number of violated lines	0	65	67	30
Total number of lines	352	352	352	352
Percentage overload	0	18.5	19.0	8.5

Having identified the network congestion problems, the next step is to identify the measures to deal with these congestions. The measures involve either investments in new transmission lines in the long term for permanent congestions or power flow controllers in the short term for non-permanent congested lines. The results can also be reflected in the ELOD and EPOD models, to examine whether the investment plan for electricity generation can be adjusted. Consequently, the costs of the adjustments need to be compared with the alternative solutions for transmission network reinforcement. Finally, demand-side measures allow circumvention of future transmission-congestion problems. This was mentioned above, in that the “Efficiency” scenario entailed fewer congestion-related problems.

As mentioned earlier, the linking of the ELOD/EPOD and DC Power Flow models was primarily a feasibility study. Although it proved to be successful, it also pointed to the complexity and difficulty of the analysis, particularly with respect to the geographical distribution of future generation. Depending on such geographical distribution the impacts on transmission may be very different. Such issues need to be elucidated in future research. Since this was a feasibility study, the example shown above (for Germany) has not been verified against other activities in the project. The scenarios used in this example have only been used here as a test and are not examined elsewhere in the project. Therefore, the results discussed above are intended primarily to illustrate the concept behind the linking of the different electricity supply models available to the project.

(ii) Methodological development in industrial energy systems analysis

A number of research activities directed towards the industrial sector have been included in the Pathways project. These research activities include studies of the development of specific industrial sub-sectors and/or types of measures for reducing emissions and a top-down analysis of the European industrial sector as a whole. Thus, the methodological approaches used in these research activities vary significantly.

The Pathways industry group

The researchers involved in the industry-oriented research activities have formed a common analysis group for industry, which provides an additional level of scientific quality control, further development of the analytical approaches used, and methodological insights to all the researchers involved.

In the industry group, researchers from three different academic research groups have been included. All three groups are involved in systems analysis of the technical energy system, although with somewhat different methodological backgrounds and different perspectives on industrial energy systems and on systems analysis. Thus, research with a scientific basis in detailed process simulations and process integration studies of energy-intensive process industries, technical energy systems modelling of energy supply systems, and global energy systems and resource analyses with strong linkages to environmental and economic modelling is represented.

Direct co-operation in the same activity framework and with common scientific questions has proven to be extremely valuable in developing methodologies and has led to both collaborative projects and co-authored scientific articles. This has definitely added more scientific value than if the same studies had been carried out separately. Examples of this added value include:

- Increasing the methodological understanding and perspective, which is especially important for widening the perspectives of doctoral students involved in the research activities
- Adding technological depth to systems-oriented studies and strengthening the systems perspective in more technologically oriented analyses, thereby identifying cross-sectional methodological problems and solutions
- Increasing the usefulness and value of common databases and gathering data that is valuable for all the sub-projects or activities

Example of methodological development

Within the industry group, the interaction between separate studies of the potential for CCS in industry and of different types of improvement potentials in the pulp and paper industry have gradually developed the methodology used. The different studies included have been increasingly linked together, which has resulted in mutual benefits for all the parties involved. At the centre of the methodological development are the Chalmers Power Plant database and the other Chalmers Energy Infrastructure databases (see Chapter I) and an extended data collection for industry.

This particular example (Figure III.8), concerns one research activity that focuses on the potential for CO_2 reduction (in a broad sense) through changes in the pulp and paper industry. The research activity has its methodological basis in industrial systems analyses, in which process- and plant-specific case studies provide information on the potentials for efficiency improvements and process development, taking process- and site-specific constraints into account. In the activity, these results from previous studies have been evaluated in an energy market context using the energy systems modelling tool reMIND (see Chapter 39 in the *European Energy Pathways* book), which is an optimising model based on mixed integer linear programming. The evaluation has shown that many technologies and system solutions can reduce the process steam demand, provide a steam/heat surplus, and thus enable the production of additional value products, such as materials, chemicals, transport fuels, electricity and/or district heating. Another alternative is to use the surplus for integrating CCS with the mill (more on this is also found in Chapter 19 in the *European Energy Pathways* book).

To be able to generalise and estimate the potentials for the different technology pathways on a European level, the results from these detailed studies need to be connected to the actual European pulp and paper industry stock (Chapter 10). Therefore, data for individual mills in Europe have been collected. These data include information on the technical age of the mill and specific mill equipment, production, fuel usage, process steam demand, and CO_2 emissions, as well as estimates of the available amounts of excess heat.

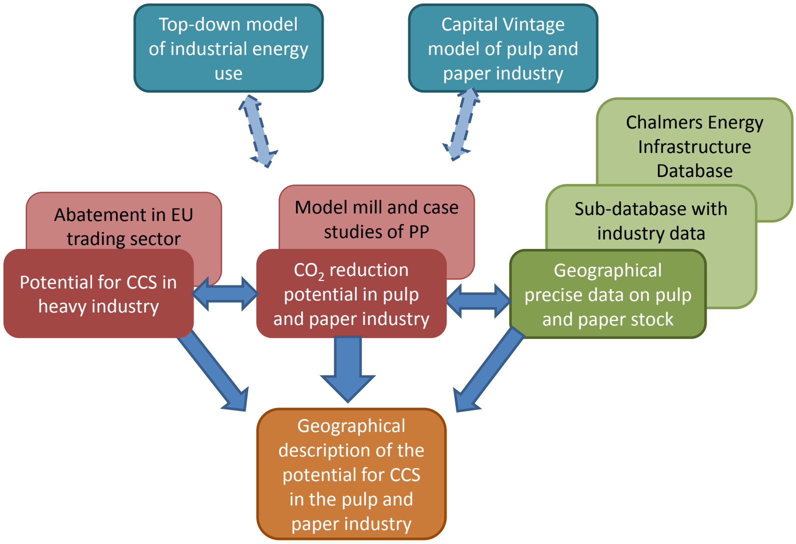


Figure III.8. Illustration of the inter-linkages between studies in the development of the methodology used for estimating the potential for CCS in the pulp and paper industry. Similar inter-linkages have been identified for other industrial sub-sectors (e.g., refineries) and for other issues (e.g., the role of the district heating infrastructure).

In parallel to this work, research was carried out on the potential of CCS in heavy industry, based on similar studies for CCS in power production. One specific methodological feature of these research activities is the inclusion of geographical information, facilities and constraints, and the geographical visualisation of results. The studies are thus to a large extent based on the extensive developed within the Pathways project databases, including for instance, all existing power plants in Europe on a plant-by-plant basis. The study of CCS in industry focuses on the potential in iron and steel production, the cement industry, and mineral oil refineries (see Chapter 18 in the *European Energy Pathways* book). The basis for this analysis is the development of a sub-database that includes facility-level data related to energy use and CO_2 emissions for European industry. This sub-database is an add-on to the Chalmers Energy Infrastructure database and includes the exact locations of plants, emission and emission allowance data, and the plant characteristics for eight branches, including the pulp and paper industry, in the EU27 countries, Norway, and Liechtenstein (see Chapter 3).

In combining extensive knowledge of the sub-sector, detailed data, and methodological approaches, the geographical aspect was added to the methodology based on process- and plant-specific analyses. As a result, geographically precise information on the energy and CCS infrastructures generate new insights into the potential role of industry in development towards sustainability (Figure III.9). For example, adding the geographical aspect gives further insights into the need for co-ordinated planning of the large-scale infrastructure that is needed to realise CCS. To limit the costs for transport and storage, the planning should take the existence of emission clusters into account, in regions with several emission sources that are located close to each other. This can be considered to be an entirely new way of exploring the development of industry, in that it makes it possible to link detailed process-specific system studies to the aggregate level for a country or region. Furthermore, the interconnections and dependencies on energy infrastructure are investigated and visualised.

Through the interactions between these research activities, synergies have been reached in terms of access to and the use of data and methodological development. Furthermore, the development of the methodology has benefitted from parallel modelling studies of the pulp and paper industry, based on other methodologies (as indicated in Figure III.8). These include both top-down modelling of industrial development and capital-vintage modelling of the sector, taking capital stock and capital replacement rates into account.

Capture clusters if both fossil and biomass emissions are included

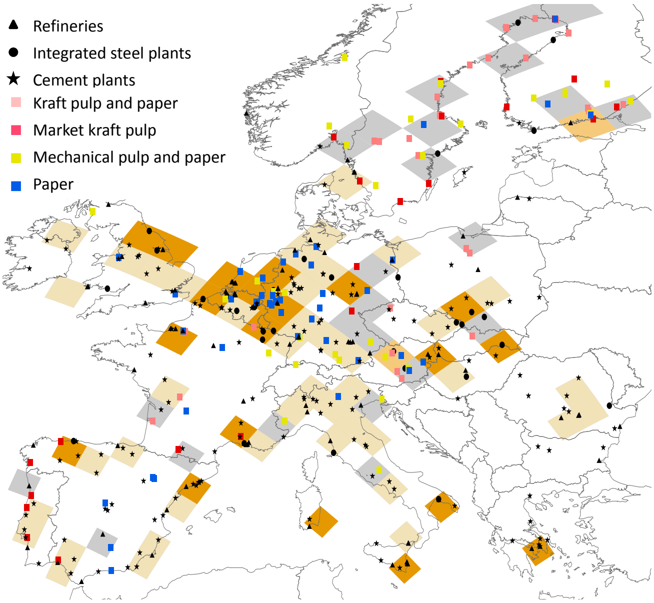


Figure III.9. Geographical visualisation of the potential for CCS in the European pulp and paper industry, and its linkages to the energy and CCS infrastructures.

Wider applications and further work

The same principal methodology is applicable to other industry sectors and other inter-linkages. Examples that are already being explored include the potential for CCS in the mineral oil refinery sector and investigations of the linkages between industry and district heating systems.

By combining the accumulating data on infrastructure and plants with industrial systems analyses (including process-specific knowledge) and energy systems-oriented analyses (providing the context of the surrounding energy system), the potentials and limitations of industrial development can be better understood. To date, extensive efforts have been made to gather data, develop the methodology, and expand the network of researchers. These efforts have led to the first batch of interesting results. From this base, future research has the potential to produce additional results and insights within limited time and resource frames. However, the data still need to be complemented, the different datasets have to harmonised, and the methodology must be developed further to exploit fully this potential.

(iii) Sectorial integration for assessing district heating

District heating (DH) for building heating has strong growth potential in many European countries and can be considered as an important energy infrastructure component in a sustainable energy system (see Chapter 32 in *European Energy Pathways* book). Therefore, the development of the European DH sector is of crucial importance to the pathways towards a sustainable European energy system. DH allows for efficient use of energy resources, for instance, the utilisation of waste heat from industrial processes, electricity production, and incineration of municipal solid waste. In these ways, DH can form linkages between different sectors to increase the efficient use of energy resources. These linkages imply that the DH sector interacts with many other sectors (e.g., the residential and service, electricity, and industrial sectors), and that developments of the interacting sectors are crucial for the development of the DH sector.

The development of the sectors that interact with the DH sector has been acknowledged by integrating the results of the sectors concerned in the assessment of the development of the DH sector. This integration has been performed through interaction and soft-linking with the groups responsible for the concerned sectors (Figure III.10). Below, the interactions with the different groups are described in brief.

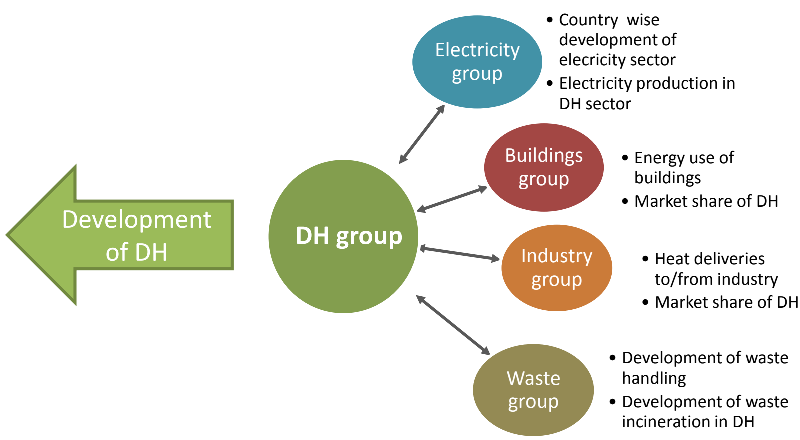


Figure III.10. Example of the interactions between the DH group and other research groups that were needed to assess the development of the DH sector.

The district heating group in the Pathways project

The district heating group within the Pathways project consists of mainly three sub groups. One subgroup affiliated to Halmstad University is dealing with detailed analysis of the DH market (see Chapter 25). A second subgroup, from Physical Resource Theory at Chalmers, has investigated the opportunities for combined heat and biofuel production in Europe's DH systems, see Chapter 21. The third group, from the research and consulting firm Profu, is responsible for synthesis of the DH results and for proposing scenarios for DH development, see Chapter 26.

Interaction with the buildings group

The development of the market share of DH is an important parameter for describing the development of both the DH sector and the energy demand of buildings. Moreover, market share development is dependent upon the development of both these sectors. Thus, there has been close co-operation between the buildings group and the DH group in establishing this development for eight selected EU countries and a region that includes the remaining countries of the EU27 (see Chapters 23 and 26). An approach to assessing market development is described in Chapter 26. One important input parameter for this assessment is the development of the energy use in buildings, since the heat density of an urbanised area is decisive for DH development. In turn, the energy use in buildings depends on the development of energy markets. Consequently, close co-operation and iteration between these groups are essential to establishing reliable development of the DH market share (see Figure III.11). Moreover, other aspects of the development of the DH sector (e.g., concerning CO_2 emissions and renewable DH) are of interest for evaluating progress of energy use in buildings.

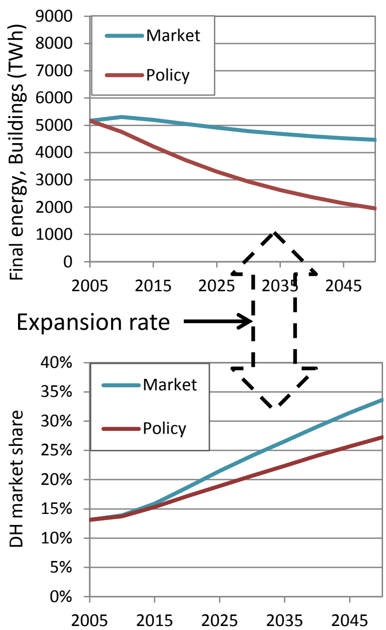


Figure III.11. Development of the DH market share and energy use in buildings are inter-related (shown for EU27).

Interaction with the industry group

The development of the market share of DH has also been an issue for interactions with the industry group of the Pathways project. This concerns industry both as a supplier and a user of DH. Co-operation similar to that described above for the buildings group has taken place between the industry group and the DH group. Moreover, the potentials for using industrial waste heat, from both the industrial and DH points of view, have been analysed in this inter-sectorial co-operation.

Interactions with the waste management group

With appropriate waste management, the environmental impact of waste handling can not only be decreased significantly, but waste can contribute to achieving the sustainability targets. For instance, energy utilisation from waste incineration can contribute to the renewable energy target, since a significant part of municipal solid waste (MSW) is biological material, see Chapter 29 in the *European Energy Pathways* book. Incineration of MSW is very suitable for combination with DH and for combined heat and power plants. Thus, the development of waste handling is important for assessing the development of DH and vice versa, and interactions between the DH group and the waste management group in the Pathways project were essential. In this interaction, the following types of questions were posed: "How can the development of waste generation be facilitated?"; "How large a share of the waste is suitable for incineration?"; and "Can the DH sector absorb the combustible waste?". In the end, it was ensured that the waste management development matched the development of waste incineration for DH (Figure III.12).

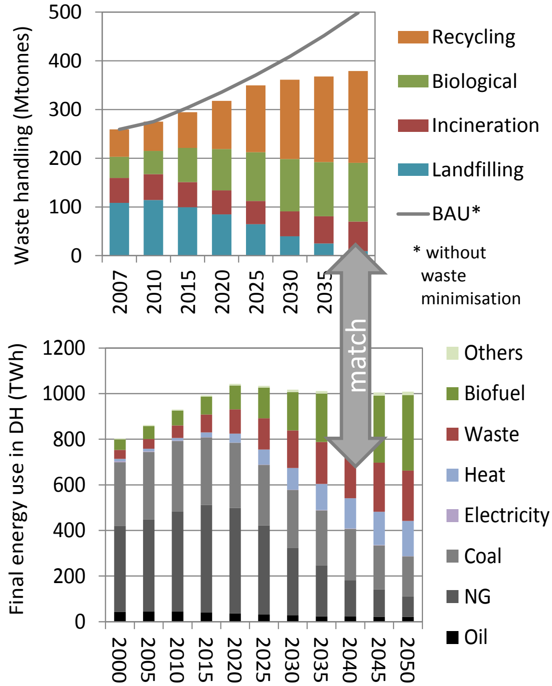


Figure III.12. A match between the development of waste management and waste incineration in the DH sector is assured through inter-group interactions (shown for EU27).

Interaction with the electricity group

There has also been close co-operation between the electricity group and the DH group. The research conducted by the elec-tricity group includes a simplified development of DH production. This simplified picture and the model results for electricity production obtained from the elec-tricity research group were important aspects that were considered for the development of DH production units in the different countries. Such aspects may include e.g. prospects and poten-tials for biomass and CCS. Moreover, the knowledge built up in the electricity group, e.g., concerning country-wise opportunities for renewables and CCS, could also be applied to the DH sector. The benefit for the electricity group was a more detailed analysis of the DH sector, which could be used for describing European electricity production.

Interactions with other groups

The above-mentioned interactions were the most active ones between the DH group and the other groups within the Pathways project. However, there have been less extensive interactions between many other parts of the project. For instance, the availability of bioenergy (obtained from the biomass research group) and the results regarding the proactive strategies of DH companies (obtained from the social-science researchers) have been considered when establishing the development of the DH sector.

1 The Chalmers Fuel database

The Chalmers Fuel database (Chalmers FU db), which is included in the Chalmers Energy Infrastructure database (see Chapter I), covers the fossil fuel sector. The FU db was developed partly because no such database was available in the public domain and partly so as to provide a comprehensive and detailed overview of fossil fuel resources and capacities, as well as some notions of the dynamics of fossil fuel markets. The primary objective of the FU db is to track future global production capacities at the country level for oil, gas, and coal, and current and future capacities of the transport infrastructures and contracted transport flows. The overall goal is to provide a solid basis for formulating realistic near-term scenarios for development of the energy system.

The Chalmers FU db (Figure 1.1) contains field-specific data on oil, gas, and coal fields, including production and reserve data, as well as data related to fuel infrastructures, for example, pipelines, ports, LNG plants, and gas storage sites. The database includes both existing and planned capacities. Linked to each entry is information on geographical location, operational status, ownership etc. Although the focus of the Pathways project is on the EU27 countries, the FU db has global coverage, since an understanding of the fuel markets and its infrastructures must be based on an analysis of the international market.

Currently, the Chalmers FU db comprises the Coal database (Coal db), the Oil database (Oil db), and the Gas database (Gas db), together with associated sub-databases (Figure 1.1). The database is managed in Windows Access with linkage to the Excel software and, when relevant, a Geographical Information System (GIS).

This book describes the methods and models used to achieve the results presented in the **European Energy Pathways** book.

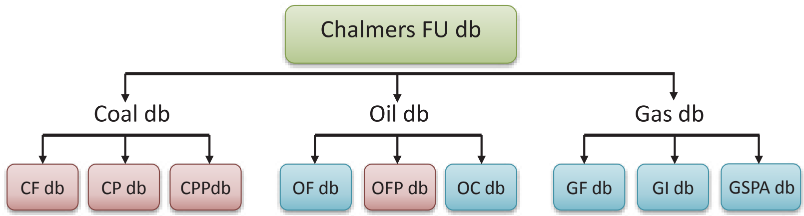


Figure 1.1. The structure of the Chalmers fuel database (Chalmers FU db). The colours in the Figure denote whether the data are continuously updated (blue) or whether the sub-database was established for a specific analysis and is therefore not updated (red).

The Coal database

The Coal db includes databases concerning coal mines and coal fields (CF db), coal ports (CP db), and coal-based power plants (CPP db) in key coal-producing countries. In total, almost 200 lignite fields and 580 coal fields in Europe, Australia, China, Colombia, Indonesia, India, Russia, South Africa, and the USA are registered in the CF db. The CF db contains mainly steam coal and lignite fields, although it also has some fields with combined production of steam and coking coal. For each field, if the information is in the public domain, coal reserves, coal resources, and coal production data have been collected along with quality parameters, such as calorific value, ash, and content of sulphur, moisture, and volatiles. Current status, owner, and location data, i.e., national and global region and co-ordinates, have been collected, as well as planned expansion projects in existing and planned mines.

The CP db contains almost 100 coal ports in the most important coal-exporting countries, i.e., Australia, China, Colombia, India, Indonesia, Russia, and South Africa. The CP db includes information on throughput capacity, expansion plans, export history with respect to coal volumes, location, including co-ordinates as well as data about the owner and the port's website. The CPP db comprises 530 coal plant projects at various stages of development between January 2007 and August 2008 in China, India, Indonesia, Pakistan, Russia, South Africa, the USA, and Vietnam (to August 2009 in the cases of India and the USA). The combined power generation capacity of all the power plants in the CPP db is 465 GW, including more than 80 coal plants in the USA with a combined capacity of around 60 GW of projects which have been abandoned.

The data in the Coal db are derived from coal companies, national agencies and institutions, power utilities, and news agencies, as well as from various publications from the IEA's Clean Coal Center (IEA CCC) and Euracoal. For the CPP db, considerable effort was put into verification of the data tracking each plant individually during the various development stages. In China, this direct approach was not always feasible, so the collected data were confirmed on an aggregated level by the IEA CCC (IEA CCC, 2009). In addition, personal communications with personnel within different institutes, such as the US Geological Survey (USGS) and the Polish Geological Institute (PGI), and contacts with the Minerals Bureau in South Africa, Geoscience Australia, BGR, WEC, IEA CCC, and the US Energy Information Agency, provided important information regarding the interpretation of data related to resources and reserves.

The Oil database

The Oil db is constructed of three databases: the Oil Field database (OF db); the Oil Field Project database (OFP db); and a database that contains statistical data for some forty-five international and Russian Oil Companies (OC db).

The OF db includes around 3,200 oil fields worldwide and contains historical and current production and reserve data. For some oil fields, particularly those located in the Middle East and Russia, it was considered vital to also include various reserve estimates. The database also contains parameters that enable sorting by global region, specific location (i.e., onshore, offshore, shallow-water, deep-water, and ultra-deep-water), and size (for instance giant field, super-giant field, and ordinary field). The fields registered in the database account for roughly 60% of global reserves and 60% of global production. One difficulty encountered in gathering field reserve data was that various sources quote different data (e.g., AAPG, 2003; IEA, 2005; Horn, 2008). However, in many cases, the quoted estimates originate from the same company, IHS Energy, which is generally considered to have the world's most comprehensive oilfield database. It should however be noted that IHS Energy cites 2P reserves (i.e., proven plus probable reserves) rather than proven only or URR (Ultimately Recoverable Reserves).

The OFP db, contains some 520 announced oil projects worldwide, adding almost 33 million barrels per day (mmbd) gross to the global liquids production capacity, most of which either came online in 2007 (around 5 mmbd) or will come online between 2008 and 2012 (around 28 mmbd). It should however be noted that due to the economic recession in 2009, a large number of the announced projects were either cancelled or postponed, see for instance IEA (2009). Efforts to collect data for the OFP db met the same problems encountered when compiling data for the OF db, in particular, that a large number of various sources quote different data, both with regard to start-up year and plateau production levels. Therefore, as much information as possible has been drawn from the source closest to the information, usually the operator of the project. One issue that was consistently observed while compiling the data for the OFP db was the increasing rate of projects that are being deferred, often because these projects are large-scale, complicated, deep-water or Arctic projects (for instance, Thunder Horse in the USA, Kashagan in Kazakhstan, Sakhalin 2 in Russia, and Snöhvit in Norway).

As mentioned above, the OC db contains statistical data from some forty-five international and Russian oil companies on production, reserves, resources, reserve replacement, acreage (developed, undeveloped, regional location), and wells (exploratory, under development, production). Although International Oil Companies (IOCs), as opposed to National Oil Companies (NOCs), only own a small share of global reserves, they account for an impressive share of global oil production. The information contained in the OC db has been derived mainly from annual reports, annual upstream reports and, in the case of Russian companies, exclusively from reserve data audited by well-known auditing companies, such as DeGolyer and MacNaughton or Miller & Lentz.

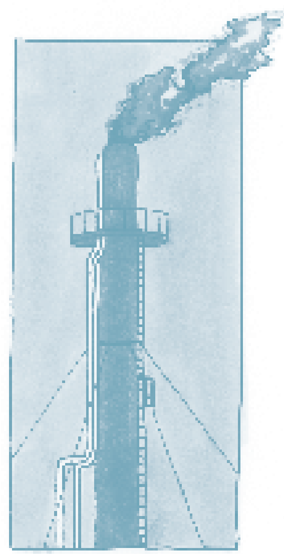
The data have been compiled from a large variety of sources, of which the most prominent are the American Association of Petroleum Geologists (AAPG), including their series on the world's giant fields, the Oil and Gas Journal, in particular their annual coverage of worldwide field production, and IHS Energy, including the International Oil Letter (IOL) and numerous conference presentations available on their website (energy.ihs.com). Other important sources, in particular those with past field production data, are the Department of Trade and Industry in the UK (formerly DTI, now DBERR), the Norwegian Petroleum Directorate (NPD), the US Minerals Management Service (MMS), the States of California, Alaska, and Texas, Canada's National Energy Board (CNEB), the Nigerian National Petroleum Company, and Pemex, the Mexican state-owned oil company. Danish, Dutch, and German authorities and institutions also provided field production data (and in the case of Denmark, reserve data). The 2005 and 2006 editions of IEA's World Energy Outlook, which cites IHS Energy, provided reserve data for some of the world's largest oil fields in MENA (Middle East and North Africa) countries and Brazil. Detailed field information has also been found in annual reports, investor presentations, and the websites of numerous IOCs, including the six majors in the USA and Europe, as well as the four largest Russian companies (Rosneft, Lukoil, TNK-BP, and Gazprom) and some NOCs, such as Petrobras and Saudi Aramco. Valuable information has also been found on the websites of several industry consulting groups, such as CSIS, CGES, Global Insights, and CERA. Specific perspectives on Russian and Saudi Arabian oilfields were provided by Grace (2005) and Simmons (2005), respectively.

The Gas database

The Gas db consists of three sub-databases that contain field-specific data on gas fields, including: 1) production and reserve data (in the Gas Field database, GF db); 2) data related to major external and internal transport facilities, such as pipelines and LNG and re-gasification terminals but also including data related to gas storage sites (in the Gas Infrastructure database, GI db); and 3) information about long- and medium-term gas sales and purchase agreements (in the Gas Sales and Purchase Agreement database, GSPA db)(Figure 1.1).

The GF db corresponds roughly to the OF db and contains information on 2,300 gas fields worldwide accounting for around 60% of global reserves. Annual production is registered if the data exist in the public domain. The fields are classified according to size and location, e.g., onshore, shallow-water, deep-water, and ultra-deep-water.

The GI db provides global coverage of all LNG plants and re-gasification terminals and includes information on capacity, current status, and exact location. Currently (December 2010), 102 LNG trains that are in operation worldwide with a capacity of 278 million tonnes per annum (Mtpa), roughly 370 billion cubic metres (bcm), and 79 operating re-gasification terminals with a nominal capacity of around 820 bcm are included. In addition, the database contains around 110 LNG trains and 120 re-gasification projects (new terminals plus expansions on existing terminals) that are currently under development or have been proposed. The GI db also contains major global and national European gas pipelines and includes information on capacity and exact location, using both geographical co-ordinates and name. Moreover, it includes all European gas storage sites and includes withdrawal and injection capacities, and working gas and cushion gas levels.



Information on global gas sales and purchase agreements (SPA) for LNG and pipelines is gathered in the GSPA db. Presently, long-term LNG contracts covering an annual global supply of around 425 bcm, as well as long-term contracts for the supply of piped gas of around 335 bcm to Europe are to be found in the database.

As is the case for the Oil db, the data in the Gas db have been compiled from a large variety of sources. With respect to analyses of the global gas markets, various updates from the IEA and EIA (as well as US Federal Energy Regulatory Commission) on the global and US gas markets, including lists of worldwide LNG plants and re-gasification terminals, have provided valuable inputs on the gas supply infrastructure, along with of course the GIE (Gas Infrastructure Europe). The annual report of the IEA on natural gas markets and the websites of the main gas companies have provided initial data for setting up the GSPA db which thereafter has been updated mainly through press announcements from the companies involved. Tusiani and Shearer (2007) also provided data specifically on sales contracts for LNG. On the natural gas resource side, the main sources have been the AAPG, including their series on the world's giant fields, the Arab Petroleum and Resource Center, IEA's World Energy Outlook, in particular the 2005 edition which provided field specific data in MENA countries, the Oil and Gas Journal, in particular their annual coverage of worldwide field production, and IHS Energy, including the IOL and conference presentations available on their website. Furthermore, various governmental bodies have provided data on natural gas resources, e.g., the Department of Trade and Industry in the UK (formerly the DTI, now DBERR), the Norwegian Petroleum Directorate (NPD), the Danish Energy Agency, and German and US federal and state bodies. Detailed field information has also been found in annual reports, investor presentations, and the websites of numerous IOCs, including the six majors in the USA and Europe, as well as the four largest Russian companies (Rosneft, Lukoil, TNK-BP, and Gazprom). Information has also been gathered from the websites of several industry consulting groups, such as CSIS, CGES, Global Insights, and CERA. Finally, EIA's Country Analysis Briefs (CABs) have provided valuable background information.

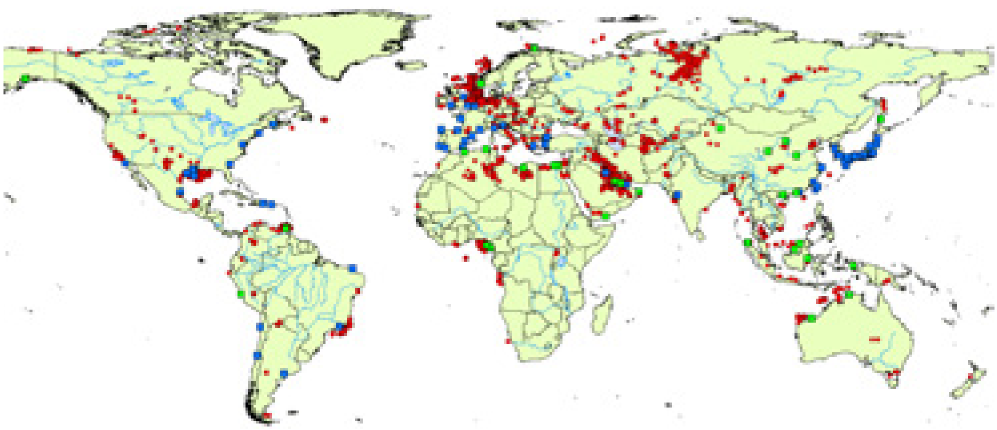


Figure 1.2. LNG plants (green squares) and regasification terminals (blue squares) in operation as of December 2010 and gas fields (red circles) using data from the Chalmers FU databases. Notice the LNG plants located in China (onshore and offshore). These are small plants, usually with a capacity of 0.2 Mtpa or less, being utilised for domestic supply.

Application of the Chalmers Fuel database

The Chalmers FU db, and the associated sub-databases, have been applied both for investigations of specific issues, such as an analysis of coal quality in different regions or an evaluation of current and future coal export capability, as well as for a broader analysis of the development of the fossil fuel markets, both on the European and global levels, see Chapters 21-24 in the *European Energy Pathways* book. Figure 1.2 is an illustrative example of how the databases have been applied to analyse the gas infrastructure in Europe.

For more information:
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Further reading:

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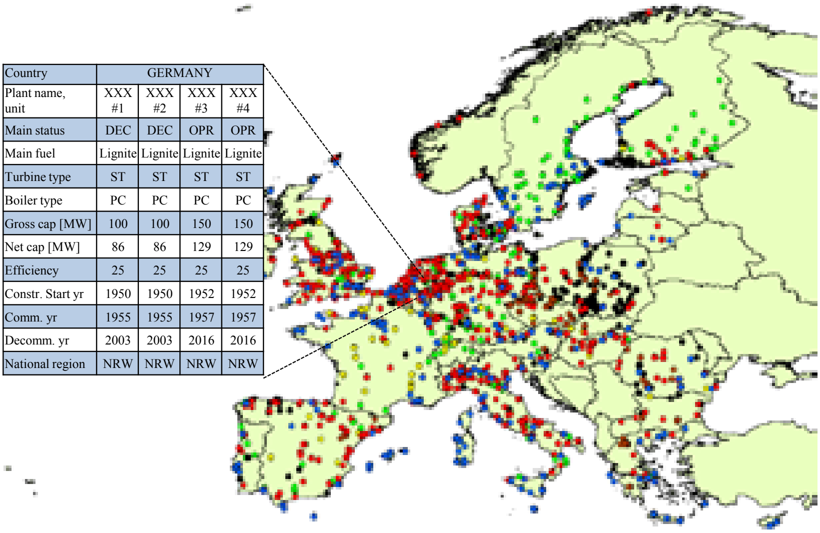
The Chalmers Power Plant database

2

The Chalmers Power Plant database (PP db) is a part of the Chalmers Energy Infrastructure database, as described in Chapter I. The Chalmers PP db describes the power generation structure in the EU27 countries, Iceland, Norway, and Switzerland. This comprehensive database was established partly to support a detailed analysis of developments of the European energy system, with special focus on the electricity generation system, and including consideration of the turnover in capital stock of the existing system and the limitations and possibilities imposed by the infrastructure of the energy system.

The Chalmers PP db includes information on all thermal, hydro, solar and geothermal plants with power output capacities exceeding 10 MW, and all off-shore wind farms. Plants with a capacity less than 10 MW and on-shore wind farms are combined on a regional basis for each fuel or technology. With respect to conventional thermal power plants, the total net capacities of plants in operation within the EU27 currently amounts to 456 GW, which is comparable to the total thermal capacity of 458 GW at the end of 2008 reported by Eurostat (Eurostat, 2010), i.e., the coverage is almost complete if Eurostat is used as reference. In addition, 131 GW of nuclear power capacity and 131 GW of hydro power capacity are recorded in the Chalmers PP db.

All thermal and hydro plants are registered to block level with respect to age, capacity, fuel, technology, present status, and where relevant, installed scrubbers, such as flue gas desulphurisation (FGD) and DeNOx units. Moreover, data on CO_2 emissions are provided for most plants while data on production and load hours are provided for around 45% of the power plants. The location of each unit is registered using geographical coordinates together with the name of the location on four levels: *locally*, town or community; *regionally*, administrative province; *country*; and *globally*, global region, such as the EU. Figure 2.1 shows the geographical distribution by fuel of thermal plants that are currently in operation in the EU27, Norway, and Switzerland, including an example of the information available in the Chalmers PP db. In addition to the power units in operation, 235 GW of thermal power plants are registered as being under construction or planned, of which about half are gas-fuelled (Figure 2.2).



Country	GERMANY			
Plant name, unit	XXX #1	XXX #2	XXX #3	XXX #4
Main status	DEC	DEC	OPR	OPR
Main fuel	Lignite	Lignite	Lignite	Lignite
Turbine type	ST	ST	ST	ST
Boiler type	PC	PC	PC	PC
Gross cap [MW]	100	100	150	150
Net cap [MW]	86	86	129	129
Efficiency	25	25	25	25
Constr. Start yr	1950	1950	1952	1952
Comm. yr	1955	1955	1957	1957
Decomm. yr	2003	2003	2016	2016
National region	NRW	NRW	NRW	NRW

Figure 2.1. Geographical distribution by fuel of operating thermal plants in the EU. Key to dots: red, gas-fuelled plants; black, coal; brown, lignite; blue, oil; yellow, nuclear; green, biomass/waste plants. The figure is simplified, since a significant number of the symbols represent several blocks. Inset: An example of data registered in the Chalmers Power Plant db for a plant in Germany.

75 GW of operating wind power is registered in the Chalmers PP db, which corresponds to the value reported by the EWEA (2010) for installed wind power by the end of 2009. The Chalmers PP database also includes 96 GW of wind power capacity under construction or planned, whereby more than 80% of this capacity is projected to be constructed off-shore. As for thermal and hydro plants, plant-specific data and geographical locations are given. In addition to wind power and biomass power, the Chalmers PP db also includes other renewable energy power capacities, such as those of power plants based on solar thermal, photovoltaic or geothermal technologies, although the registered, as well as the installed capacities are currently small (12 GW in operation, corresponding roughly to 1.5% of total capacity in operation). Most of the data in the Chalmers PP db have been collected through direct contact with each utility, although other sources, such as national authorities, RenewableUK (formerly BWEA), and IAEA, have also provided important information.

Application of database

The Chalmers PP db has been applied to analyse developments in the power generation sector and the impact on future fossil fuel demand (see, e.g., Chapter 22 in the *European Energy Pathways* book), and to estimate the potential of bridging technologies, such as co-firing of biomass with coal (Chapter 12 in the *European Energy Pathways* book) or the CCS technology (see Chapter 16 and 17 the *European Energy Pathways* book). The database is also integrated with the ELIN/ELOD model (see Chapter 11), so as to account for the influences of existing and planned energy infrastructures on possible future pathways of the European energy system.

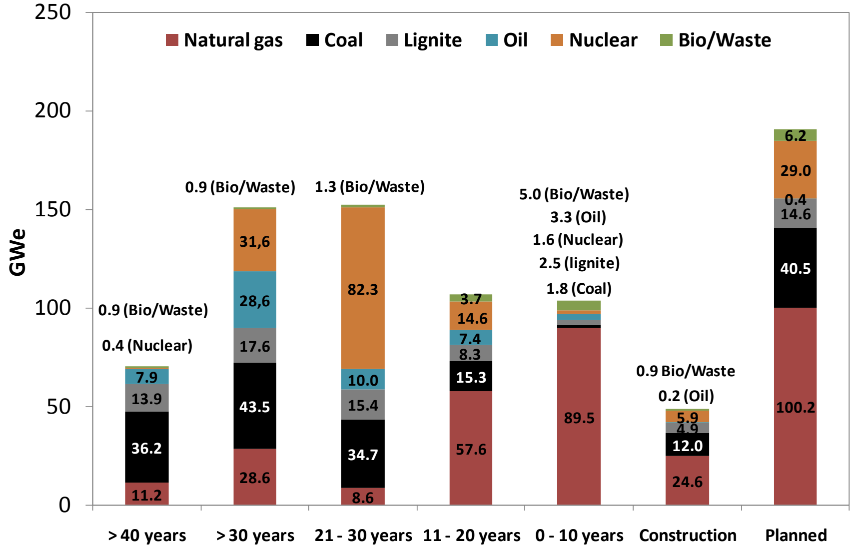


Figure 2.2. Thermal power capacities sorted by fuel and age within the EU27, as included in the Chalmers Power Plant database.

For more information:
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Energy Technology, Chalmers

Further reading

Kjärstad, J., Johnsson, F., 2007. The European power plant infrastructure — Presentation of the Chalmers energy infrastructure database with applications, Energy Policy, 35 (7): 3643-3664.

Assessments of CO_2 emission trends and abatement options for the EU stationary sector

3

Aims and research question

An aim of the Pathways project is to identify and analyse opportunities and challenges associated with efforts to reduce CO_2 emissions from the EU stationary sector. The approach described in this chapter is used in an ongoing project that has the following specific aims: 1) to provide a thorough description of the current industry structure and available CO_2 abatement options; 2) to analyse trends in CO_2 emissions and allocations of emission allowances; and 3) to evaluate how the challenges associated with emission reduction vary between member states and across industry sectors.

Methodology

To analyse the possibilities and limitations imposed by the present energy infrastructure, a database, the Chalmers industry database including facility-level data on key processes and plant components related to energy use and CO_2 emissions has been established. This sub-database, which is an add-on to the Chalmers Energy Infrastructure database (see Chapter I), has the following features:

- Comprises the EU27 countries plus Norway and Liechtenstein
- Covers eight industry sectors, including power and heat plants, mineral oil refineries, coke ovens, metal ore roasting or sintering installations, installations for the production of pig iron or steel (including continuous casting), installations for the production of cement clinker or lime, installations for the manufacture of glass (including glass fibre), installations for the manufacture of ceramic products, and industrial plants for the production of pulp, paper or board.
- Contains the exact locations (country, city, address and geographical co-ordinates) of plants with CO_2 emissions exceeding 0.5 $MtCO_2$/year.
- Specifies emissions and allocated emission allowances, with the verified CO_2 emissions and allocated emission allowances for the period 2005-2009 and the allocated emission allowances for 2005-2012.

• Describes plant-level characteristics; installations are classified according to the type of production process, e.g., integrated steel plants (Blast Furnaces) and Minimills (Electrical Arc Furnaces). For large emission sources (>0.5 $MtCO_2$/year), the database carries information on process technologies, production capacity, fuel mix, and age of capital stock.

By combining the information in the database, which describes the current status of the EU stationary sectors, with the relevant CO_2 emission reduction targets, the potential, timing, and deployment of different abatement options are explored. An important element of this approach has been to consider how aspects such as age structure, fuel mix, and spatial distribution of the plant stock contribute to facilitating or hindering the shift towards less-emission-intensive production processes. Figure 3.1 provides an overview of the general methodological approach.

Figure 3.1. The main elements of the methodological approach.

Validity and reliability of the approach

The most important characteristic of the methodological approach described above is the detailed description of the EU stationary sectors. In its present form, the database includes information on more than 12,000 stationary CO_2 emission sources in the energy and industrial sectors. Together, these installations account for more than 40% of the EU's total GHG emissions (~2,100 $MtCO_2$ in 2008). Installation-level data on annual CO_2 emissions and allocated emission allowances have been compiled using publicly available data sources (CITL, 2010; EPER, 2009; E-PRTR, 2010). The only major stationary CO_2 emission sources currently not covered in the database are petrochemical and other chemical industries and ammonia production plants, which together emit approximately 180 $MtCO_2$/year (Ecofys, 2006).

A relatively low number (~800) of large emission sources (>0.5 $MtCO_2$ /year) is collectively responsible for more than 80% of the CO_2 emissions covered in the database (~30% of total GHG emissions in the EU). For these installations, the database includes information on, process technologies, production capacities, fuel mixes, and age of capital stock (data sources include: CEMBUREAU, (2001); GCD, (2009); IEA GHG, (2006); Steel Institute VDEh, (2006) for the industry branches and the Chalmers Power Plant database for the power sector).

The Chalmers industry database are being continuously updated to ensure validity and reliability. Figure 3.2 provides an overview of the distribution of CO_2 emissions between the different sectors included in the database.

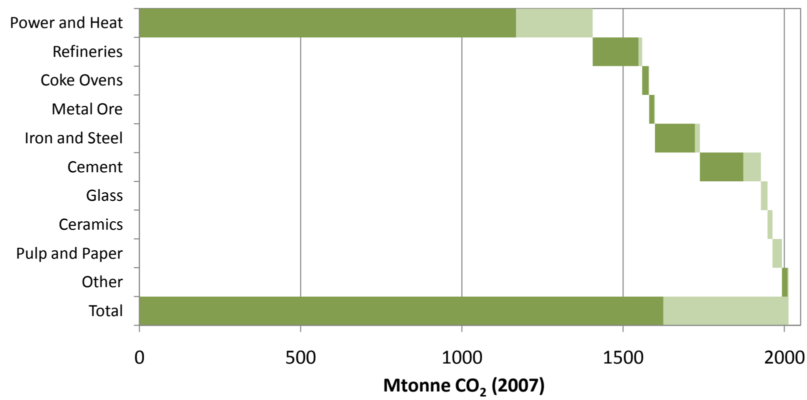

Figure 3.2. Illustration of the sectors covered by the Chalmers industry database. The shares of the total emissions for the sectors are indicated for large emission sources (>0.5 $MtCO_2$/year) (green) and for smaller emissions sources (<0.5 Mt CO_2/year) (light-green). A relatively low number of large emitters dominate the overall emissions.

Applications

Examples of applications of this methodological approach include assessments of:

- The prospects for CO_2 capture in European industry (see Chapter 18 in the *European Energy Pathways* book)
- CO_2 abatement options in the European petroleum refining industry (see Chapter 42 in the *European Energy Pathways* book)
- Challenges and opportunities associated with CO_2 abatement under the EU Emission Trading Scheme (see Chapter 15 in the *European Energy Pathways* book).

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Energy Technology, Chalmers

Further reading:

Rootzén, J., Kjärstad, J. and Johnsson, F. (2010), "Prospects for CO_2 capture in European industry", accepted for publication in Management of Environmental Quality, 22 (1).

Path dependence and the ordering of expectations

4

The law, economy, politics, and technology are embedded in social relationships and structures that build on the norms, expectations, traditions, and conventions that serve to stabilise and order human interactions to give them form and substance. It is precisely because society is ordered that individuals have a good idea of what is reasonable and realistic to expect from others. That we can form stable expectations about other peoples' actions, intentions, and understandings, is both a condition and a product of social organisation, collaboration, and co-operative planning. Social ordering makes life with other people reasonably predictable and over time creates institutions that are resistant to change. Therefore, a planned change of policy can be difficult to achieve.

Centre for Public Sector research

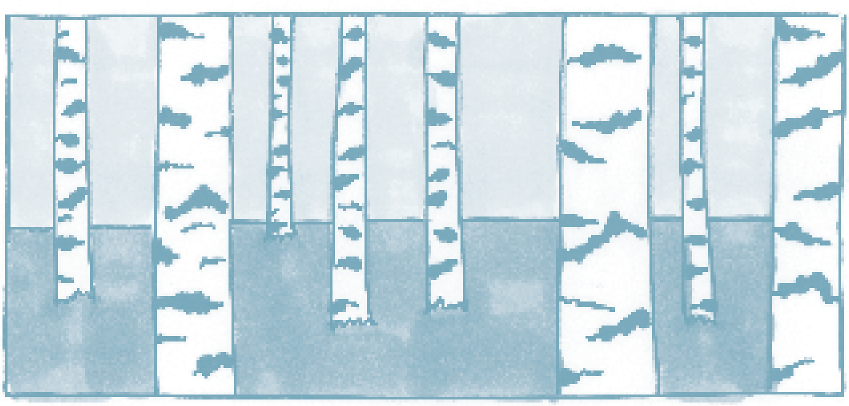
CEFOS (Centre for Public Sector research) at the University of Gothenburg, has long research experience of infrastructure facility siting and planning within the energy and transportation sectors.

The results of this research draw on experiences from a number of empirical case studies conducted over a period of 10 years within various research projects located at the Centre for Public Sector research, University of Gothenburg, and from collaborations with the School of Public Administration, University of Gothenburg, King's Centre for Risk Management, King's College, London, and the Department for Service Management, Campus Helsingborg, Lund University. The research methodology is dominated by case studies to account for the complex interaction of many context-dependent variables. Several of the case studies have been conducted in real time, following the processes as they occur and develop, with the aim of procuring insight into the systemic complexities of the interaction.

Social science research within Pathways uses the concept of "path dependence" as a unifying analytical term to describe the structural and historical continuities that characterise decision processes and organisational arrangements within the energy sector. The concept of path dependence is used in economics (Arthur, 1994; North, 1990), historical sociology and political science (Mahoney, 2000, Pierson, 2004), and organisation studies (Schreyögg and Sydow, 2010). It considers system inertia, change, and adaption, and the role of standardisations (David, 1986, Liebowitz and Margolis, 1995), and it aspires to explain historical trajectories of "reform" or policy making implementation, nested decision making, and co-operation among institutional actors. The concept can be understood to belong to the wider area of theorising that focuses on "bounded rationality" (Simon, 1991) in economics, administration, and policy studies.

Path dependence can be understood as an analytical lens that enables a focus on problems derived from the temporal sequencing of events, resulting in "lock-ins" (which result from combinations of technical, legal, economic, political, and social factors) that restrict future choices or decision paths (Arthur, 1994). It addresses change and stability in decision making by taking into account the constraints on choice imposed by earlier decisions. The concept, which is not without critique, has been elaborated in a number of disciplinary or inter-disciplinary directions (Kay, 2005). A major objection is that it is theoretically vague, even devoid of content, and that it says little more than "history matters" (ibid).

However, given that path dependence is used to "deepen […] theoretical and empirical understanding of a larger set of historical dynamics that may occur in policy development" (Kay 2005: 561), it has a broad potential to explore how "the order of events makes a difference" (Mahoney, 2000: 511). Mahoney (2000), for example, distinguishes between two types of path dependence: self-reinforcing sequencing; and reactive sequencing. A self-reinforcing sequence



of events reproduces institutional patterns by "increasing returns", i.e., some form of utility or benefit at work. Thus, for the system, it becomes beneficial to continue along a set path, since "… initial steps in a particular direction induce further movement in the same direction such that over time it becomes difficult or impossible to reverse the direction" (Mahoney, 2000: 512). In contrast, a reactive sequence follows a different pattern in which events react to previous events and "…whereas self-reinforcing sequences are characterized by processes of reproduction that *reinforce* early events, reactive sequences are marked by a backlash processes that *transform* and perhaps *reverse* early events" (Mahoney 2000: 526). Examples of reactive sequencing can be found in societal planning, in which earlier planning decisions can become obstacles at a consecutive later stage, introducing new and unforeseen planning realities. Reactive path dependence acts through re-framing and re-negotiation of an earlier decision, providing it with some new meaning or de-coupling it from the planning process (Boholm, 2010).

To summarise, the concept of path dependence highlights:

- Developments and chains of events having an inbuilt tendency to continue along already established patterns
- Earlier decisions in a historical sequence exerting decisive influences on what decisions are possible subsequently
- Technological systems and artefacts with "lock in-effects", such as the QWERTY key board or rail track gauge
- "Increasing returns" as a result of following an established path rather than shifting to a new and less familiar one
- Shift of path connected with costs in terms of economic resources and loss of skill, and increased uncertainty about outcomes and procedures
- The role of expectations in decision making and planning: beliefs about a certain technology and its potential, certain policy objectives or in the effectiveness of particular steering mechanisms

A path dependence perspective could be especially fruitful for the development of insights into "pathways to a sustainable energy system" if it is linked to decision making in the public domain, which is shown to depend on inter-organisational communication, as well as on the co-operation and co-ordination of administrations and organisations (O'Toole Jr, 2003; Pressman and Wildavsky, 1973). Societal and urban planning exemplifies a complex joint action (Pressman and Wildavsky, 1973) that engages stakeholders, local communities, citizens, and authorities with diverse sector responsibilities, power resources, and organisational logic (Boholm and Löfstedt, 2004; Suchman, 2003; Flyvbjerg, 1998). The complexity of joint action involves many critical decision points at which decision-related problems, alternatives, benefits, and risks are negotiated. The sequencing of critical decision points according to an "assembly line structure" of interdependence (O'Toole Jr, 2003: 147) offers veto points for key agents. Decisions are nested in past decisions, which condition commitments and thereby specific which new decisions can or cannot be taken. Therefore, policy implementation and planning have an in-built "path dependence" (Kay, 2005) derived from the inter-dependence of actors, the need for co-ordination of action, and the role of the actors' "adaptive expectations", in that they have to plan their own action vis-à-vis a prospected future, in the light of how they understand the planning of other actors (Pierson, 2000).

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In search of legal pathways to a sustainable energy supply: the method of constructive jurisprudence

5

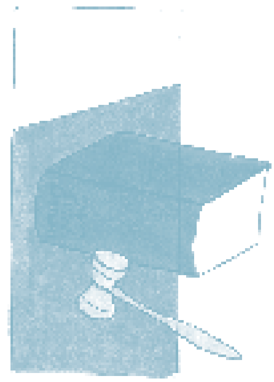
Aims and research question

The legal studies performed under the Pathways umbrella were primarily aimed at describing and analysing the function of the Swedish law in the implementation of renewable energy policy objectives, with a major focus on the development of wind power. In tangible terms, this means that the legal rules governing, for example, the planning, location, and operation of energy installations are evaluated in relation to their capacities to facilitate or impede the development of renewable energy sources. A second aim was to compare the Swedish legal functions with the corresponding functions in foreign legal systems, so as to identify legislative measures that could be used to promote increases in the installed capacity for renewable energy in Sweden.

Methodology

Achievement of the aims of these legal studies requires approaches to determining and comparing valid law. The basis for the determination of valid law is the theory of the sources of law. In keeping with this theory, it is primarily legal rules that are considered formally binding. However, in practice, this source alone is often insufficient in the application of law. "Valid law" in relation to the planning, installation, location, and operation of, for example, windmills is therefore determined not just on the basis of law, but also upon supplementary, non-binding legal sources, in particular case law and preparatory works. Furthermore, EU law is relevant for the application of law on a national level, sometimes with direct legal effect or as a result of interpretation consistent with Treaty rules ("fördragskonform tolkning"). Since the core of the analyses is the function of the law in relation to the development of renewable energy and the preconditions that the law provides in this respect, the purpose of these studies reaches beyond the determination of valid law as the traditional juridical method prescribes. Therefore, it is probably more appropriate to refer to the method as 'constructive jurisprudence'. Constructive jurisprudence is perhaps best described as being problem-oriented, which essentially means that it is the research question that should determine how the problem is approached.

Accordingly, it is not just the interplay between different legal rules that is considered, but also the connection between the legal rules and their social functions (Agell, 1997; Westberg, 1992).



Legal comparisons normally involve comparisons of a substantive character. This means that the subject of the comparison typically is the content of the legal rules, for instance, how a particular issue has been dealt with in the foreign legal system. It is thus not the terminology or the legal concepts that is compared, but the corresponding situations that the rules aim to regulate, that is to say, the function of the rules. The indispensable tertiumcomparationis (common ground for comparison) is therefore typically formed by the rules' social functions (Bogdan, 2003). The comparisons performed in the present study rely on the presumption that the legal rules involved in the establishment of energy installations in all of the examined countries have the authority to hinder as well as to facilitate the development of renewable energy.

From a methodological point of view, it is important to point out that the comparative analyses undertaken in these studies are restricted in the sense that they do not – in any sense – aspire to encompass the entirety of the legal systems involved. Instead, it is the function of the law vis-à-vis wind power development in each country that is analysed, and the purpose of the subsequent comparison is to deduce "better" ways to meet the challenges posed by, not only the environmental issues per se, but the energy policy objectives laid down to solve or mitigate these problems.

Validity and reliability of the method

The validity of applying constructive jurisprudence (as opposed to the more traditional juridical method) is that the method is problem-oriented rather than rule-oriented. The rule-oriented approach typically deals with questions that have to do with, for example, the relationship between different legal rules and their positions in the legal system, whereas a problem-oriented method addresses questions concerning, for example, the social issues related to a particular regulation or the social consequences that the regulation implies. To analyse the function of the law vis-à-vis an external factor, in this case, the development of renewable energy sources, it is imperative to go beyond the borders prescribed by the traditional juridical method and examine the legal system from the perspective of its performance with regard to this development.

The reliability of the study lies in the stringency of the line of reasoning that is allowed by the analysis. In other words, the strength of the analysis, which in turn derives from the method used to examine the legal rules, will determine whether or not reliable arguments can be made.

Application of the method

The method of constructive jurisprudence is applied in Chapter 7 in the *European Energy Pathways* book.

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Gabriel Michanek, Faculty of Law, Uppsala University

Further reading

Pettersson, M., 2008. Renewable Energy Development and the Function of Law. A Comparative Study of Legal Rules Related to the Planning, Installation and Operation of Windmills. Doctoral Dissertation, Luleå University of Technology, Luleå, Sweden.

Identifying pathways of sustainable development in energy companies: case study approach

6

Aim and research questions

The aim was to explore proactive strategies for ensuring the environmental sustainability of municipality-owned energy companies, so as to create an understanding of these strategies and the mechanisms that facilitate their implementation. This gives rise to two research questions, which are investigated in the above context.

1. What do proactive strategies for environmental sustainability involve?
2. What are the key mechanisms that facilitate the implementation of such strategies?

Method

Qualitative research methods commonly start from the perspective of actions taken by the subjects studied (Bryman, 1989). Consequently, it is important that the research method reflects the nature of the study object and the purpose of the investigation (Sayer, 1992). For the study of corporate strategies and practices related to environmental sustainability, a close-up investigation is essential to allow for the knowledge of practitioners to be captured. Nevertheless, acknowledging that organisations are open systems (Scott, 2003), it is desirable that contextual factors be taken into account to create a better understanding. A convenient methodology to capture the larger picture while simultaneously facilitating detailed observations is the case study approach. It is suitable for studies in which a holistic, in-depth investigation is needed (Feagin et al., 1991). A strength of the method is that it enables the researcher to study the dynamics at play in a specific setting. These unique characteristics seem to be very valuable for the project at hand, given its ambition to investigate strategies for environmental sustainability as they unfold in practice. To sum up, a case study methodology was chosen as the research approach for this study owing to its substantial potential to generate interesting and novel findings that are grounded in a real-life setting.

A multiple case design was followed, involving three companies. Given the need to create an understanding of what proactive strategies for environmental sustainability entail, the case studies were of an exploratory nature. Three companies with proactive approaches to the environment were selected based on an emerging framework of activities for environmental sustainability, which is derived from an initial study of fifty Nordic and European energy companies. A particular focus was placed on finding companies that recently implemented or were in the process of planning investments in renewable power. In addition, other corporate initiatives or activities that contribute to environmental sustainability were taken into account, as was the carbon intensity of the current energy generation portfolio.

Data were collected through semi-structured interviews with employees from the different corporate areas engaged in developing or implementing environmentally sustainable strategies and practices. Key informants included members of the management committee, environmental specialists, and engineers. The number of interviews per case depended on the company size and complexity. The total interview time was 22 hours, and all the interviews were transcribed in full. Secondary data from the public domain and company documents supported the interview preparations and complemented the findings from the interview study.

Data analysis – an abductive approach

In summarising the dominant processes surrounding the data collection and analysis in the current project, the concepts of 'abduction' and 'constant comparison' are particularly relevant. Following an abductive approach, the researcher constantly switches between the theory and the empirical findings during the research process, interpreting both in the light of each other (Alvesson and Sköldberg, 2009). 'Constant comparison' refers to an analytical process of comparing and contrasting across cases to establish significant patterns (Berkowitz, 1997). The overlap of data analysis with data collection is a prominent feature of case study research (Eisenhardt, 1989), which also permeates this study.

Model of analysis

In framing strategy as a pattern of actions (Mintzberg and Waters, 1982), environmental strategy can be seen to manifest itself in the discrete activities performed that lead the company towards environmental sustainability. The activity-based view of strategy (Porter, 1985; Johnson et al., 2003) can thus be conveniently applied in an environmental strategy setting. Thus, by studying corporate practices and activities aimed at mitigating the environmental impact, a better understanding can be gained of what a strategy for environmental sustainability involves in the context of a municipal energy company. Following this reasoning, corporate activities and practices that promote environmental sustainability have been systematically mapped and organised. A model of analysis that reflects an energy business setting has been constructed based on the concepts presented by Hart (1995) and Hart and Milstein (2003). To analyse the diverse activities performed under this type of strategy, it is useful to think in terms of four conceptual areas that represent important dimensions for companies working with the transition to sustainable business (see Figure 6.1).

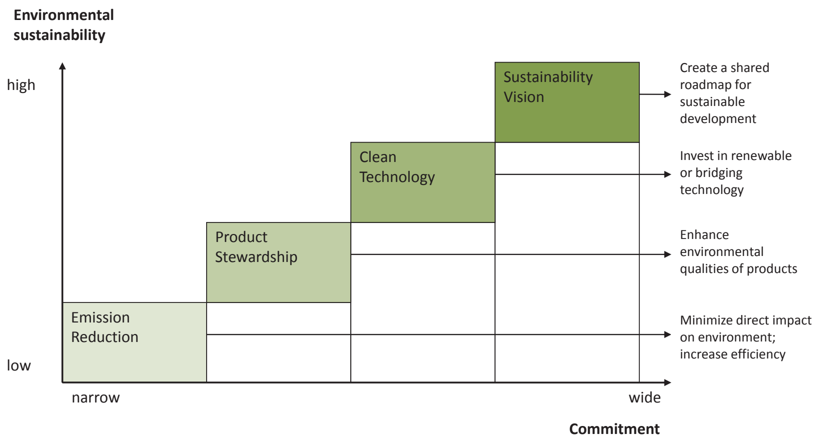

Figure 6.1: Framework of conceptual areas of strategies for environmental sustainability. Source: Adapted from Hart (1995) and Hart and Milstein (2003)

Emission Reduction refers to activities that minimise the emissions associated with conducting business or that increase (energy) efficiency. Product Stewardship encompasses the development of new sustainable products and services or the enhancement of the sustainability of existing products and services. Activities conducted under Clean Technology relate to investments in renewable and bridging technologies. The fourth area, Sustainability Vision, aims at creating a shared roadmap for sustainability within the firm and with its stakeholders, which reconciles value creation for the company with the wider goal of creating a sustainable society. According to the framework, moving up the 'ladder' of an environmentally sustainable strategy requires wider commitment and leads to improved environmental sustainability.

After the discrete activities and practices were organised with the help of the model, the underlying dynamics were examined, searching for mechanisms that enabled these companies to strengthen environmental sustainability and to contribute to the sustainable development of the stationary energy system. Analytical induction (Manning, 1982) was applied to identify the factors that facilitate the effective implementation of sustainable practices. Crossing back and forth between the collected data and developing hypotheses for the potential mechanisms allowed for the emerging theories to be modified and re-assessed. From the analysis, five prominent mechanisms were defined (see Chapter 34 in the *European Energy Pathways* book). The *European Energy Pathways* book presents the case study findings in a descriptive style and describes the relevance of these mechanisms in an empirical context.

Validity and reliability

To strengthen the validity of the case studies, data from several sources were used in a triangulation, as recommended by Yin (2003). Regarding the conceptual validity of emerging theory, George and Bennett (2005) have suggested that contextual factors be taken into consideration, and this advice was followed as closely as possible. Repeated discussions and presentations of emerging findings throughout the research process strengthened the validation. In addition, ample time was allowed for reflection, as suggested by Alvesson and Sköldberg (2009), to ensure that the research aim achieved more than mirror reality. To ensure reliability, the procedures applied for collecting and analysing the data were rigorous and consistent.

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Further reading

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A method for techno-economic comparisons of integrated biomass-fossil plant options

7

Aims and research question

In the Pathways project for which the methodology was developed, new and conventional ways to improve biomass conversion efficiency are presented and compared to support investment decisions in new technologies. The aims are to: 1) show potentials for improved energy-/cost-efficiency in biomass conversion; and 2) present results for efficiency, costs, and risks, with clear connection to factors such as heat to power ratio, renewable fuel share, fuel moisture, gasifier/boiler type, and fuel cost.

Method and modelling

The main part of the work involves simulations with the advanced heat balance software Ebsilon Professional (Evonik, 2009), which in some cases was soft-linked with the chemical equilibrium software Aspen Plus (Aspentech, 2009). An example of the simulation layout is shown in Figure 7.2. The results of these simulations are re-calculated to certain key values, the most important being the specific efficiency of biomass (n_{bio}), which, as suggested by Korobitsyn et al. (1999) and Petrov (2003), is determined from the formula:

$$\eta_{bio} \equiv \frac{P - \eta_{ref} \cdot \dot{Q}_{NG}}{\dot{Q}_{bio}},$$

where P is the total net production of power, n_{ref} is the efficiency of a reference fossil-fuelled (natural gas) plant, Q_{NG} is energy fed to the plant as natural gas, and Q_{bio} is energy fed to the plant as biomass.

Cost assessments are performed on the basis of levelised cost of electricity (LCoE), as defined by the IEA (2005). Size-dependent costs of key components, such as boilers and steam turbines, are calculated using relations developed within the project, based on the manufacturers' information (Figure 7.1).

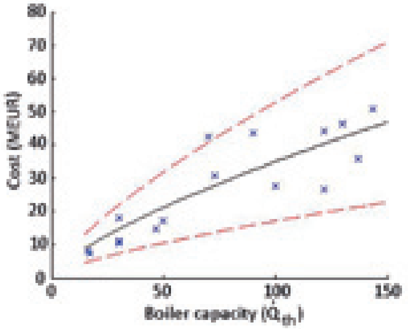

Figure 7.1. Cost relationships (solid black line) with 90% confidence intervals (slashed red lines). Blue crosses indicate input data.

Within the project, a qualitative risk assessment approach is used. Risk is determined component-wise, based on how commercialised and crucial each component (C) is, and summed to give a total risk (R) for a process with *n* components as follows:

$$R=R_{C1} + R_{C2} + \ldots R_{Cn}$$

Validity of results

The methodology used is similar to that used in other power plant assessments and is relatively well-tested. Uncertainties in the results mainly stem from:

- Non-universal (site-specific) input cost data with large variations (±50%, as seen in Figure 7.1), which affect cost assessment.
- Limited information on how input cost data are broken down to individual components, which affects the cost assessment.
- Limited information on the risk/reliability of novel technology, which affects the risk assessment.

Application of the method

The methodology is applied to achieve the results presented in Chapter 13 in the *European Energy Pathways* book.

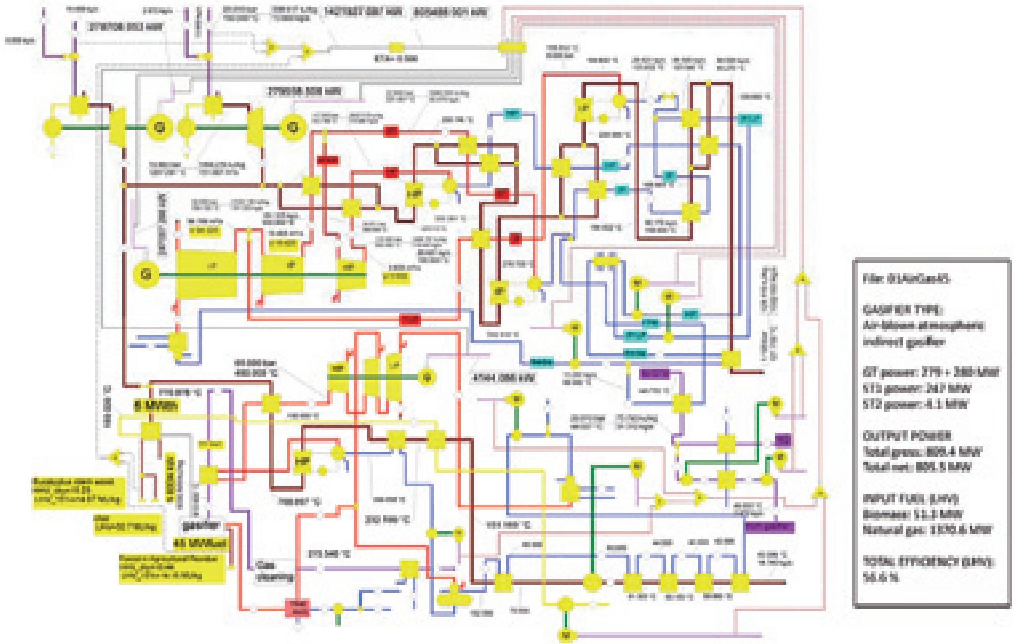

Figure 7.2. Example of an Ebsilon Professional simulation set-up. This exemplifies a case in which a 50 MWth air-blown indirect atmospheric biomass gasifier is integrated with an 800 MWe CCGT power plant. Biomass syngas is cleaned, pressurised, and fed to one of the gas turbines, at a heating value (LHV) of 13.7 MJ/kg. The gasifier components (shown by arrows) are simulated in Aspen Plus.

For more information:
Erik Pihl and **Henrik Thunman**
Energy Technology, Chalmers

Further reading:

Pihl, E., 2010. Integrating biomass in existing natural gas-fired power plants, Licentiate Thesis, Department of Energy and Environment, Chalmers University of Technology.

Methodology for assessing process integration of new technologies in the oil refining industry

8

Aim and research question

Assessing process integration of CO_2 mitigation technologies into energy-intensive industry in Europe is one part of the Pathways project. The aim of this work is to analyse pathways that would enable this industrial sector to reduce its CO_2 emissions and includes the investigation of the possibility for fossil fuel-based industries, e.g., the oil refineries, to increase their use of biomass. The research questions posed using this methodology were:

- What is the CO_2 consequence of implementing a biomass gasifier for H_2 production in an oil refinery compared to a conventional steam reformer?
- What is the energy balance for the emerging technologies, in this case, different gasification concepts?
- Can the excess heat from the current process and/or from the new technologies be used for process heat integration?
- What are the carbon-balances for the different process integration alternatives given the different future energy market scenarios and in comparison to the conventional technology?

Methodology

The methodology used is based on three methods and steps:

- Simulation of new process equipment to achieve energy balances
- Pinch analyses of the current refinery process and the new process
- Evaluation of CO_2 emissions using future energy market scenarios

The basis for the process integration work is energy balances, which are calculated using the Microsoft Excel program.

First, models of the new technologies are constructed in the optimising model tool Aspen Plus. Using this tool, energy balances from the different cases were calculated and served as inputs for process integration analyses of the total system, including the gasifier, drying, upgrading and cooling of the syngas, and the refinery process.

Second, process integration opportunities are analysed using the pinch analysis methodology. In the process integration analysis, the Pinch analysis methodology, which was first developed by Linnhoff and colleagues in the late 1970's, is used. A thorough description of the methodology can be found in several editions; one of the most recently updated is Kemp (2007). Pinch analysis enables the designer to identify energy targets that minimise the use of hot and cold utilities by maximising internal heat recovery in the process. Moreover, the curves constructed in the Pinch analysis are used for identifying possible steam production, as well as opportunities for energy efficient integration of energy-intensive process units, such as the drying of biomass. In Figure 8.1, one example from the results of the Pinch analysis is shown.

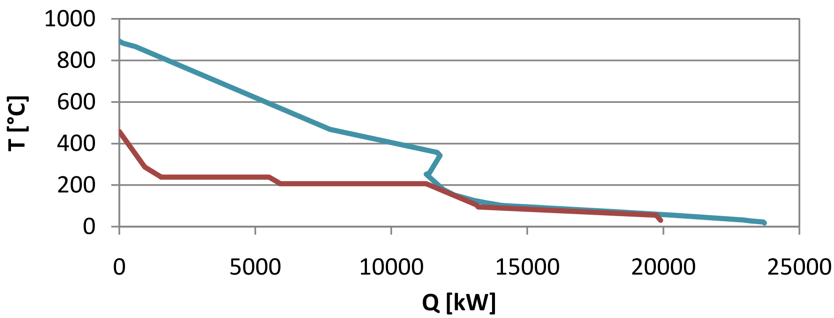

Figure 8.1. Shown are the Background/Foreground curves in the Pinch analysis, which are used to identify heat integration possibilities. The blue line indicates the surplus heat created by the new technology. The red lines represent possibilities for steam production and heat integration, i.e., the redline is constructed of streams that have a heating demand (e.g., pre-heating of air for the gasification process, heat for district heating) and streams that can be used for steam production.

Third, to evaluate the CO_2 consequences of integration of new technologies, the different energy market scenarios developed by Axelsson and Harvey (2010) are used (see also Chapter 20.) Biomass gasification is still under development and is not likely to be implemented before 2020. However, using a number of different possible cornerstones of the future energy market, robust investments can be identified.

Validity and reliability of the methodology

Figure 8.2 shows a typical output from the use of this methodology. This indicates how the CO_2 balance changes when new technologies are installed under a given scenario. Using this methodology to calculate the CO_2 effect or the profitability of energy investments in the industry, the performances of future or long-term energy investments at industrial sites can be evaluated and robust solutions may be found.

This methodology gives a theoretical result for CO_2 emissions. In this case, all theoretically usable excess heat can be used in practice. However, for a more thorough analysis, all the parts must be studied in detail and all of the special conditions must be taken into account.

The reliability of the outcome is linked to the Pinch analysis. If only the theoretical result from the pinch analysis is used, the result is less reliable than if all specific conditions for all streams are considered. However, since this methodology evaluates future investment options and their impacts on the CO_2 balance, there are many uncertainties. The aim is not to find an exact answer but to judge whether a robust solution can be found. For details of the analysis of the validity and reliability of the energy market scenarios, see Chapter 20.

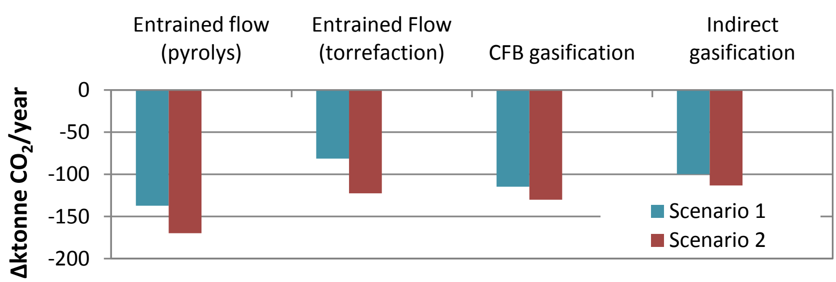

Figure 8.2. Representative results from the analysis. On the x-axis are several gasification options for H_2 production. The y-axis shows the CO_2 effect of process integration of these gasification options, as compared to the conventional technology for H_2 production (a steam reformer). In this example, compared to production of H_2 with a steam reformer, gasification of biomass leads to a decrease in CO_2 emissions from the refinery process. It also clear that the largest reduction is in both scenarios true for the entrained flow gasification technology with pyrolysis oil as feedstock.

Application of the methodology

This methodology was used in the project Biomass gasification for hydrogen production in refineries (see Chapter 43 in the *European Energy Pathways* book).

For more information:
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Heat and Power Technology, Chalmers

Further reading:

Johansson, D., Franck, P-Å., Berntsson, T., 2010. A process integration analysis of hydrogen production from biomass in the oil refining industry, Proceeding of the 19th International Congress of Chemical and Process Engineering and 7th Congress of Chemical Engineering 2010.

Design of a large-scale CO_2 transport and storage infrastructure

9

Aim and research question

The aim has been to investigate the potential for carbon capture and storage (CCS) within each EU Member State (MS) and to identify obstacles and possibilities with regard to the establishment of a large-scale CO_2 transport and storage infrastructure. The key research themes were: 1) an investigation of the CO_2 storage capacities within each MS; 2) utilisation of the results from to assess the different conditions for CCS within each MS; and 3) the evolution of a large-scale CO_2 infrastructure.

Methodology

The methodology comprised: 1) an evaluation of the relevance of the CCS technology; 2) an investigation of CO_2 transport and storage cost levels; and 3) case studies to assess potential CO_2 infrastructures.

To evaluate the relevance of CCS within the power and heat sector in each EU MS, the Chalmers Energy Infrastructure database (CEI db), comprising the Chalmers CO_2 storage database (see page 80) and the Chalmers Power Plant database (Chapter 2), were applied in a Geographical Information System (GIS) to derive parameters such as source and/or sink clusters, distances between plants and storage sites, ownership concentration, fuel distribution, and the phasing out or in of old or new plants, respectively (for a description of the CEI db, see Chapter I). The data obtained in this investigation together with other parameters, such as the share of CO_2 emissions from the power and heat sector in total GHG emissions, CO_2 storage potential, and storage site location (onshore/offshore), were compiled and analysed, to classify the relevance of CCS within each MS as either poor, moderate or good. It should be noted that the Carbon Sequestration Leadership Forum (CSLF, 2008) has recently recommended methodologies to calculate the storage capacities of aquifers, oil and gas fields, and coal seams, and these methods deviate somewhat from the methods used in the previous studies of Joule II (1996) and Gestco (2004), which are applied in this work. However, application of the new methods will require detailed knowledge of each specific reservoir, whereas most of the estimates quoted to date have been rough approximations on the basin or regional scale.

The Chalmers CO_2 storage database (CS db)

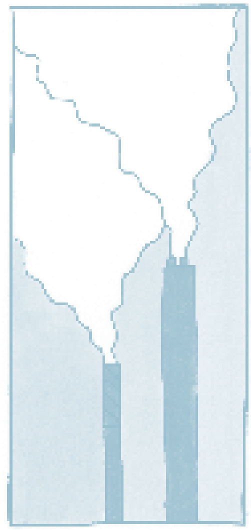
The Chalmers CS db is a part of the Chalmers Energy Infrastructure database, and contains information on CO_2 storage reservoirs in Europe with storage potentials exceeding 1 $MtCO_2$, i.e., gas and oil fields and aquifers. There are presently almost 1,200 different reservoirs registered in the database, of which about 600 have a technical storage potential of at least 10 $MtCO_2$. Overall, some 200 reservoirs, with a combined storage potential of 112 GtCO2, have an individual storage potential of at least 100 $MtCO_2$ (technical). The technical trapped storage potential of all the reservoirs amounts to 125 $GtCO_2$, of which almost 100 Gt in aquifers. The total storage potential is roughly equally divided between onshore and offshore sites. Assuming that CO_2 does not need to be trapped within an offshore aquifer, it may be possible to utilise the entire aquifer volume for storage, which would greatly increase the storage potential. A large part of the storage potential is concentrated in the British and Norwegian part of the North Sea.

A significant part of the data in the Chalmers CS db has been collected through direct contact with the various oil companies or from their annual reports and press releases, as well as through contacts with the responsible ministries in the countries involved. Additional sources for the Chalmers CS db are the Millennium Atlas (GSL, 2002), GeoCapacity (2007), SEI (2008), the Joule II study (Joule II, 1996), technical reports from Getsco (2004), various issues of the Oil and Gas Journal, and various papers released online by the Society of Petroleum Engineers.

To classify and assign a cost level to the transport and storage of CO_2 within each MS, three different cost levels (€5, €7.50, and €10) per tCO_2 were applied. In deciding the cost levels, particular emphasis was placed on plant clusters, ownership concentration, source-sink distance, and site location (onshore or offshore), since these parameters to a large extent determine transport and storage costs. The different cost levels were subsequently used as inputs for the modelling work using the ELIN model (see Chapter 11).

The last part of the analysis involves the design of a large-scale CO_2 transport and storage infrastructure in Germany and UK. The input, i.e., captured CO_2 over time, was provided through modelling of the European electricity system up to 2050 (using the ELIN model) based on strict CO_2 emission reduction targets (more specifically, a 30% reduction in 2020 and an 85% reduction in 2050, in both cases relative to the levels in 1990) (Odenberger and Johnsson, 2009 and Chapter 1 in the *European Energy Pathways* book). The characteristics for the modelled CCS plants, with block capacities of 600 MW (coal) and 1000 MW (lignite), were obtained from the ENCAP project (ENCAP, 2008). Each block is assumed to generate in base load with an efficiency of 37%, increasing to around 43% by the end of the period.

For the transport and storage infrastructure, it has been assumed that CCS plants are being erected on existing sites following: 1) the volume of captured CO_2 over time, as envisaged by the model results; and 2) the phase-out of existing plants. All transport of CO_2 takes place via pipelines and the system has been designed already from the start to accommodate the expected peak transport volume. In practice, this may not happen, since each utility may choose to phase in new plants according to its own requirements. Furthermore, it has been assumed that Collecting Pipelines (CPL) at nearby power plants transport the CO_2 to large regional Bulk Pipelines (BPL). Around 30 km from the reservoir, the bulk pipeline is divided into Reservoir Pipelines (RPL), each carrying 10 million tonnes per annum (Mtpa) to selected sites with storage capacities of at least 400 Mt, thereby ensuring a 40-year lifetime for all system components (in subsequent studies, the assumed average storage potential per reservoir in Germany has been lowered to 100 Mt due to a new study published by the BGR in April 2010). Finally, at 2 km from the reservoir, each RPL is divided into Injection Pipelines (IPL) based on an assumed injection capacity of 0.5 Mtpa and 1.0 Mtpa per well. Each segment of the onshore pipeline is assumed to be 20% longer than a straight line measured in the GIS between the same two segments. The corresponding increase in the length of offshore pipelines was set to 10%.



The CO_2 is assumed to leave the power plant at a pressure of around 110 bars and is re-pressurised in booster stations located 200-km apart. Energy consumption for re-pressurising the CO_2 was set to 1.9 kWh/tCO_2 per 200 km (IEA, 2005), while the cost of electricity was set as being equivalent to the average marginal cost of electricity production according to the model results (i.e., €0.056/kWh). The sizing and costs of pipelines and the cost of drilling are calculated according to equations taken from the IEA (2005). A terrain factor of 1.2 was applied to all onshore pipeline costs, apart from IPL's, to account for difficult terrain or densely populated areas. All pipeline costs were subsequently scaled up by a factor of 2, to account for the substantial increases in the costs of steel and other construction materials observed over the last three years (the scale factor was determined based on a comparison of costs and applying IEA's equations for pipelines specified by Pöyry (2007) and Vattenfall (2007)). Likewise, the costs related to site development, booster stations, onshore surface facilities, and monitoring were taken from the IEA (2005). The costs for offshore platforms were taken from the BERR (2007), assuming a maximum of 20 injection wells per platform. Transport-related investments have been assumed to materialise at equivalent annual levels over three years, the commissioning year and the two preceding years, while storage-related investments have been allocated to the year of commissioning. Thereafter, investments have been annuitised based on an economic lifetime of 20 years and 8% discount rate, to derive annual capital costs. Annual costs include the capital cost, a 3% annual operation and maintenance cost (based on total investments), and the cost of electricity. Finally, all the annual costs between 2020 and 2050 have been summed and divided by the amount of CO_2 transported and stored over the same period, to derive the cost per tCO_2 stored.

Validity of the method

Apart from the smallest MS of Cyprus, Luxembourg, and Malta, most MS have identified structures that potentially may be used for subsurface storage of CO_2. Estonia and Finland are the only MS that are completely without suitable reservoirs, while Lithuania appears to have very limited storage potential apart from the trapping of CO_2 through dissolution in aquifer brine. All the remaining MS had, at the end of 2008, identified potentially suitable reservoirs. However, the estimated storage potential in Germany and Spain are rough regional estimates that refer to onshore sites only, and the storage potential in the Netherlands is dominated by the Groningen field, which will not be available for storage until after 2040. Public acceptance may represent a barrier to onshore storage of CO_2, and to date only eleven MS have identified offshore storage sites. Clusters of large plants (≥ 500 MW) are found in most MS, and perhaps more surprisingly, most countries also have a considerable concentration of plant ownership, either locally/regionally or nationally. In fact, only two countries, Slovenia and Sweden, have no particular plant clusters and a poor concentration of plant ownership. Plant clusters and ownership concentration are two factors that are likely to facilitate cost-efficient build-up of a CO_2 transport and storage system. Six countries have transport distances of less than 100 km between large sources and potential sinks; in general, transport distances are likely to lie in the range 100 km to 300 km. In summary, from our analysis, we conclude that CCS is a relevant domestic CO_2 mitigation option in twenty-one MS, and cost estimations for the transport and storage of CO_2 are allocated to each MS, as explained above.

Application of the method

The cost estimation for the transport and storage of CO_2 for each individual MS has been integrated into the ELIN model and is therefore an integral part of the analysis of Europe's electricity sector performed within the Pathways project (see for example Chapters 1 and 17 in *European Energy Pathways* book). The methodology has been applied to discuss a possible ramping-up of CCS in Europe, as described in Chapter 16 in *European Energy Pathways* book.

Further information:
Jan Kjärstad and **Filip Johnsson**
Energy Technology, Chalmers

Further reading:

Kjärstad, J., Johnsson, F., 2009. Ramp-up of large-scale CCS infrastructure in Europe. Proceedings for the 9th Conference on Greenhouse Gas Technologies. Energy Procedia 1(1): 4201-4208.

Odenberger, M., Kjärstad, J., Johnsson, F., 2008. Ramp-up of CO_2 capture and storage within Europe. Int. J. Greenhouse Gas Control 2 (4): 417-438.

This book describes the methods and models used to achieve the results presented in the **European Energy Pathways** book.

10

Analysing the potential for different technology pathways within the European pulp and paper industry

Aim and research questions

The aim is to examine how the European pulp and paper industry (PPI) can contribute to a more sustainable European energy system through the implementation of different technology pathways. To elucidate the potential for, and effects of, implementation of different technology pathways within the PPI, two main questions are addressed:

- What will be the most profitable pathway(s) and which pathway gives the largest reductions of CO_2?
- Are all mills capable of implementing all of the different studied pathways?

Bottom-up approach combined with potential on a European level

To answer the first research question, the impacts of future development in the energy market and different policy schemes on the economic performances and CO_2 emissions consequences of the different pathways need to be studied. To answer the second research question, the implications of, or limitations imposed by, external preconditions, such as geographical location and existing and new infrastructures, need to be studied for the different sub-sectors of the pulp and paper industry. Thus, knowledge and data on different system levels are needed. Therefore, the analyses are based on research and knowledge obtained in other parts of the Pathways project and previous research, including:

1. Previous research in the form of model mill studies and case studies regarding process steam savings and the effects of different technology pathways on the energy balance in different types of mills (FRAM, 2005; Axelsson et al., 2006; Olsson et al., 2006; Hektor and Berntsson, 2007; Pettersson and Harvey, 2010).
2. Technical and geographical data for the European pulp and paper industry (e.g., CEPI, 2007 and CEPI, 2008 and Chalmers industry database, see Chapter 3.

3. Data for the infrastructure surrounding the European pulp and paper mills (Chalmers Energy Infrastructure database, see Chapter I).
4. Results regarding the future development of the energy market (see page 269 in the *European Energy Pathways* book).

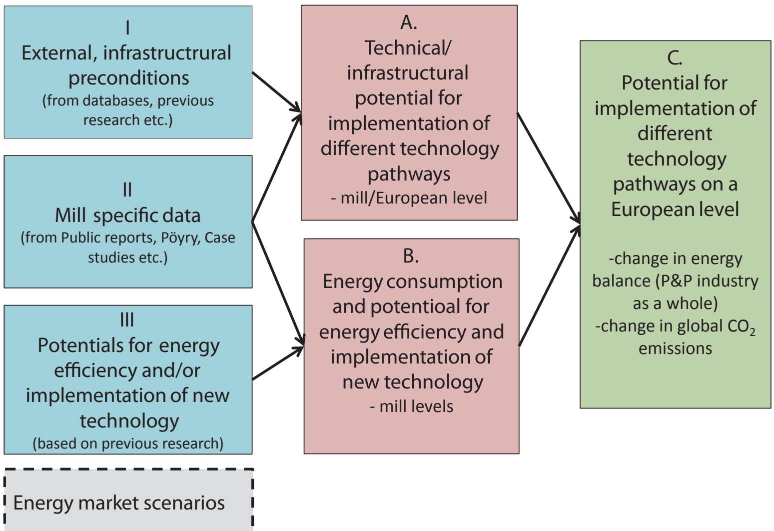


Figure 10.1. An overview of the methodology used.

Consequently, the approach assumes detailed research and is based on a bottom-up thinking combined with estimation of the potential on a European level. An overview of the approach is presented in Figure 10.1. The approach is carried out stepwise, as follows:

I: External, infrastructural preconditions
These are the characteristics of the geographical area surrounding the mills, e.g., information on where potential CCS storage sites and district heating grids are located.

II: Mill-specific data
Mill-specific data refer to the characteristics of the individual mills that constitute the European PPI stock. The included data relate to the technical age of the mill and specific mill equipment, production, fuel usage, process steam demand, CO_2 emissions, and estimates of available amounts of excess heat.

III: Potentials for energy efficiency and implementation of new technology

The potentials for energy efficiency and implementation of new technology pathways on a mill level are based on previous and on-going research conducted by ourselves and others. The results from this part typically show the economic performance and impact on global CO_2 emissions of the implementation of different technology pathways in specific mills.

A. Technical/infrastructural potential for implementation of different technology pathways

In this item, mill-specific data for the individual mills (II) are connected to the gathered data for the surrounding infrastructure (I). The results reveal how the technical potential for implementation of a certain technology is limited (or enhanced) by the location of the mill.

B. Energy consumption and potentials for energy efficiency and implementation of new technology

How the existing energy balance of the individual mills that constitute the European PPI stock can be altered is determined by fitting the potential for energy savings known for some mills (III) to the mill-specific characteristics (II). The results from this step typically show how the potentials for energy savings and implementation and integration of different technology pathways depend on mill-specific characteristics, such as the technical age of process equipment and the type of production process.

C. Potential for implementation of different technology pathways on a European level

When the effects of the surrounding infrastructure (A) and the mill characteristics (B) on the potentials for implementation and integration of different technology pathways have been determined, these two factors are brought together, and the final overall potential for implementation and integration of different technology pathways is estimated for the entire European PPI stock.

Energy market scenarios

The future economic performance and global emissions of CO_2 associated with different technology pathways are dependent upon the development of the energy market. To depict various possible future energy market conditions, energy market scenarios are used. The scenarios are based on different fossil fuel price levels (low and high) and CO_2 emission charge levels (low and high), which are combined into different scenarios (see Chapter 20). The benefit of using these scenarios, which reflect the strong connection between different energy market parameters, is that a packaged sensitivity analysis of the energy market prices is conducted.

Validity and reliability

As described above, most of the inputs regarding possible energy projects in pulp mills originate from previous studies. The previous studies on kraft mills are mainly in the form of thorough investigations of model mills that accurately describe existing mills (FRAM, 2005). For mechanical mills, a more general approach is used, while retaining a good match to real mills (Jönsson et al., forthc.).

To assess the pathways for mills within the EU, a selection was made so that kraft mills, TMP mills, and newsprint mills in the EU are well-represented. Although the coverage on CTMP and other mills is not as good, the contributions of these mills to the energy use of the pulp and paper branch are negligible.

Application of the methodology

The methodology described here was applied to the European pulp mill stock to assess the different technology pathways for the European PPI (the first research question mentioned above). The results are presented in Chapter 39 of the *European Energy Pathways* book. In addition, the potential for CCS in PPI was assessed to address the second research question. The results of this assessment are presented in Chapter 19 of the *European Energy Pathways* book.

For more information:
Johanna Jönsson and **Thore Berntsson**
Heat and Power Technology, Chalmers

Further reading:

Jönsson, J. and Algehed, J., 2010. Pathways to a sustainable European kraft pulp industry: Trade-offs between economy and CO_2 emissions for different technologies and system solutions, Applied Thermal Engineering, 30 (16), 2315-2325.

Jönsson, J. and Berntsson, T., 2008. Analysing the Potential for CCS within the European Pulp and Paper Industry, Congress Proceedings of ECOS 2008, Krakow, Poland, June 24-27.

The ELIN and ELOD models

11

The ELIN and ELOD models are two versions of the same approach. The sole difference is that ELOD is a refinement of the ELIN model, which was the original model formulation. In particular, ELOD includes a more detailed time resolution and the interconnectors between countries. ELIN was applied during the initial years of the Pathways project, and ELOD was deployed during 2010. In the present book (and in the accompanying *European Energy Pathways* book), the terms "ELIN" and "ELOD" are used separately, although they should be regarded as describing the very same model approach. However, from the model perspective, the refinements that were made during the development of ELOD are significant and therefore, a "new" model name is warranted.

Aim

The ELIN/ELOD model is a techno-economic investment model developed within the Pathways project to analyse the long-term development of the European electricity system. The model applies scenario analysis and generates cost-efficient investment strategies for the European electricity supply system over the coming 40-50 years, with resolution on the annual level.

An important aim of the ELIN/ELOD model is to describe and visualise how the present electricity supply system can be transformed in the future, in terms of the timing of investments for different pathways. Thus, a principal objective of the model is to describe the electricity supply system with a high level of detail in a transparent modelling framework that focuses on the electricity sector. This is important when assessing the timing of replacements for the present power plants, which is described in the model down to single power plant/block level.

For more detailed analyses of the electricity system, e.g., intra-annual features or intermittency issues, other models are linked to the ELIN/ELOD model, including EPOD (for more detailed intra-annual analyses, see Chapter 12) and BALWIND (for a more thorough analysis of wind power, see Chapter 15).

Model specification

The model is designed to:

- have a time scope from the present day until 2050, with an annual time resolution;
- assess net electricity generation;
- include a detailed description of the present electricity supply system, as derived from the Chalmers Power Plant database (see Chapter 2) ;
- calculate cost-efficient investments necessary to meet the demand for electricity under stringent CO_2 emission reductions while the present power plants are phased out;
- be regionalised down to the level of an EU Member State. Thus, model calculations are possible for single Member States as well as for multiple regions or the entire EU; and
- be easily linked to other model approaches of the Pathways project.

The model is governed by the following set of conditions and assumptions:

- Estimates of the availability of the existing capital stock (on a plant-by-plant basis) over time are based on the current age structure of power plants and assumptions of technical lifetimes.
- Electricity generation technologies are aggregated to technology classes that are differentiated by fuel type (e.g., natural gas, coal, lignite, biomass etc.) and generation type (e.g., condensing power, combined heat and power, industrial back-pressure, wind power on-shore/off-shore etc.), and whether or not they represent residual capacities from the existing system (as derived from the Chalmers Power Plant database) or new investments that are obtained from the model.
- New investment options are limited to presently known technologies, i.e., conventional thermal technologies, CCS, solar PV, tidal barges, wave power, and geothermal power.
- Technology change is provided exogenously in the form of increased efficiencies for thermal technologies and increased annual load factors for intermittent electricity generation.
- Costs included are limited to technology costs and costs arising from the applied CO_2 targets. Taxes or support schemes linked to electricity supply are not included in the modelling.

Model description

The objective of the ELIN/ELOD model is to minimise the total system cost for the electricity generation system. This is done over the entire period investigated, i.e., the sum of all annual costs of generating electricity until

2050 as obtained by applying optimisation that includes perfect foresight. As described above, inclusion of the existing energy system, in this case the electricity generation system, is an essential feature of the model as well as part of the reason for developing the model. The existing system is taken from the Chalmers Power Plant database and the work of Kjärstad and Johnsson (2007). The development of the electricity supply system over time is based on phasing out existing electricity generation capacities with respect to assumed technical lifetimes, combined with investments in new generation capacity to meet the demand projections, given a number of constraints, such as emission caps. Therefore, each model run is preceded by the definition of a scenario, which comprises three main parameters that shape the development of the electricity supply system. First, an annual growth rate in total electricity demand, which may vary over time, is assumed. This growth rate is applied to the net electricity generation from the present system to determine the demand for each year in the period investigated. Presently, the growth rates for electricity demand are taken from other studies, which projects electricity demand from a macro-economic perspective. Second, an assumed CO_2 emission cap is introduced to limit emissions. Third, assumptions regarding technical lifetimes determine the availability of existing generation capacities over time, i.e., the phase-out pattern. In addition, a number of technology-specific parameters (e.g., thermal efficiencies) and boundary conditions (e.g., national renewable energy source potentials or national strategies on nuclear energy) are applied. A schematic description of the modelling procedure is shown (Figure 11.1). Thus, when the development of the present system is estimated, in terms of residual capacities, electricity generation is determined using a cost-minimising procedure that yields the net present value of the total system cost over the entire period. Consequently, the development of the present system (point 1 in Figure 11.1) and policy targets (point 2 in Figure 11.1) are taken into account and any shortfall in generation is covered by additional investments according to the least-cost criteria (point 3 in Figure 11.1).

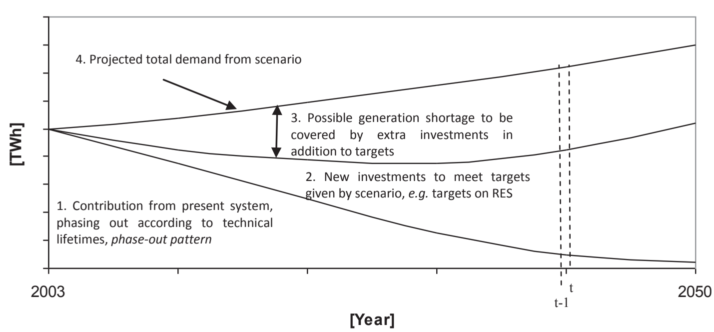


Figure 11.1. Schematic of the modelling procedure in the ELIN model, which is used to determine a development pathway for a given set of assumptions in a scenario.

In Figure 11.2, results from the ELOD model are shown. Once again (as in the previous principal figure), existing capacity (in grey) has been separated from new investments.

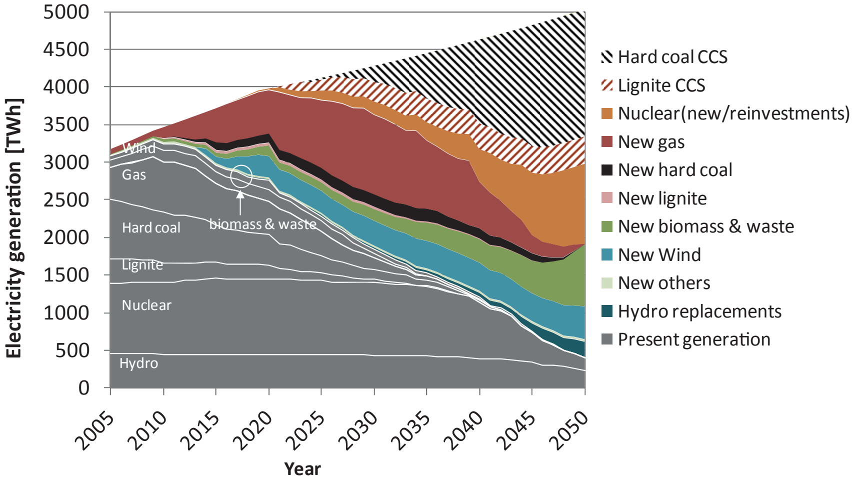


Figure 11.2. European (EU27 countries plus Norway) electricity generation in the Market scenario. ELOD model results.

While the existing capacity is described on a single-block basis, investments in new capacity are made through annual capacity investments aggregated into specified technology classes, e.g., nuclear power, lignite condensing power, and on-shore wind power. However, to preserve the level of detail, as in the detailed database (current system description) used as the input to the model, the aggregated output of new investments is compared with current capacities in terms of required numbers of sites for current and future electricity supply systems. This provides a first estimate of whether there is a need for new sites. Obviously, wind power requires new sites, whereas the need for replacements and expansion of centralised electricity generation is less obvious. Moreover, the development of new sites for large power plants should be difficult in most parts of Europe.

Since power demand shows seasonal variations and since the calculations are made on an annual basis, a simplified load curve is included to eliminate under-investments (in ELIN). Thus, to capture the need for investment in capacity that is sufficient to meet peak demand, a boundary condition is included based on annual mean capacity utilisation. Statistics on the historical relationships between total capacity and electricity generation give a capacity utilisation factor, which is the generation level in any year divided by the installed capacity for that year. The default is to keep this factor constant over time, yielding a system with a ratio of base to peak load capacity that is similar to the one in the present system. In contrast, in ELOD, a more detailed load curve is implemented. In this model formulation, a year is divided into 16 time-steps with respect to season (winter, spring, summer, and autumn), week (weekday and weekend), and time of day (day and night).

Thermal power plants are assigned a thermal efficiency, which remains constant over the technical lifetime for a specific power plant (or new investment), based on the year of commission. Thus, as mentioned previously, the average thermal efficiency for a class of thermal power plants (e.g., coal condensing plants) depends on the amount of power remaining from the present system, as well as on the extent and timing of new investments, since new power plants generally have higher efficiencies than older plants. Development of thermal efficiencies for specific thermal power plants is provided from an S-shaped exponential function derived from a least-square curve-fitting process applied to the historical statistics and future projections of total thermal efficiencies for each power plant technology (Thorén, 1999; Strömberg, 2005; OECD/IEA, 2006; Thunman, 2006). The reason for using an S-shaped exponential curve is that it provides a realistic asymptotic development that approaches the assumed Carnot efficiencies for thermal power plants.

A more in-depth presentation of the ELIN model methodology is given in Odenberger (2009).

Model inputs and outputs

The main inputs to the model include a description of the existing electricity supply system and the projections for electricity demand and overall economic parameters (e.g., technology costs and fuel costs; Table 11.1). A major source of fuel prices and electricity demand is the Energy and Transport Trends to 2030 (European Commission, 2008). Electricity load curves are derived from the EPOD model and based on data from ENTSO-E. The Chalmers Power Plant database provides almost complete coverage of European grid-connected power plants with rated net capacities greater than 10 MW. Smaller installations, such as individual wind turbines, are included as regionalised aggregates.

Table 11.1. Cost assumptions for new power plants. The values for fuel-based power plants are valid for condensing power plants. The CHP schemes in the model are assumed to have the same costs but different efficiencies (generally somewhat lower electric efficiencies but high total efficiencies). The efficiencies are shown as a range depending on the year of commissioning (between 1960 and 2050). O&M: Operation and maintenance

	Investment cost (€/kW el.)	O&M cost (€/MWh el.)	Efficiency (%, 1960-2050)
Lignite	1,337	5	31-56
Hard coal	1,023	4.5	31-56
Natural gas	630	3.8	36-70
Oil	630	4.5	36-70
Peat	1,725	5.2	20-50
Biomass	2,500	5.6	20-50
Nuclear	3,000/2,000[1)]	8	31-42
Wind on-shore, lowland	1,075	9.5	n.a
Wind, off-shore, highland	1,290	11	n.a.
Wind off-shore	1,600	16	n.a
Hydro (large-scale)	1,000	8.8	n.a
PV	2,940	4	n.a
Tidal/Wave	1,700	15	n.a
Geothermal	2,550	20	n.a
Lignite CCS	2,548/1,960[1)]	7	37-43[2)]
Hard coal CCS	2,097/1,613[1)]	6.5	37-43[2)]
Natural gas CCS	1,404/1,080[1)]	5	47-53[2)]

[1)] Market/Policy scenario assumptions
[2)] Available from year 2020

The main outputs from the model are the generation mix for the region studied until the year 2050 (capacity and generation). In the case of multi-regional scope, the development results for each Member State are included, as well as the aggregate results for the entire region. Model results may also provide cost data, e.g., marginal electricity generation cost, system cost, and marginal CO_2 abatement costs for meeting the cap, CO_2 emissions from the system, and fuel consumption.

Validation

Validation of the ELIN/ELOD model involved comparisons with statistics and other model approaches, mainly the EPOD model. These comparisons are shown for the case of Northern Europe in 2005 (Figure 11.3, left panel). While the ELIN model run covers 2003-2050, EPOD is run only for a single year at a time. It is clear that ELIN over-estimates coal power and under-estimates gas power when production data are displayed. This is also clear in the comparison for a future year for ELIN and EPOD (Figure 11.3, right panel). In this case, it is assumed that EPOD captures production adequately (based on EPOD validation with statistics). However, since EPOD takes its capacities from an ELIN (and ELOD) model run, it seems that the best approach is to use ELIN/ELOD in combination with EPOD. However, the deviations shown in Figure 11.3 spurred the refinement of ELIN into ELOD, whereby the match (reported as electricity production) between the statistics and ELOD output was significantly improved.

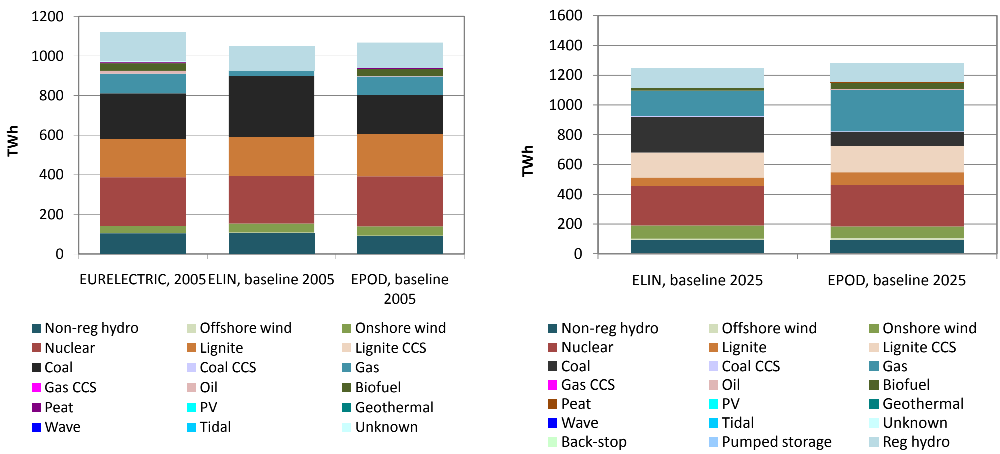


Figure 11.3. Electricity generation in the Nordic countries, Germany, and Poland (statistics taken from EURELECTRIC, and as estimated by ELIN and EPOD) in 2005 (left panel) and in model year 2025 (right panel).

Application of the model

The ELIN/ELOD model has proven to be an essential tool for analyses throughout the Pathways project. Issues that have been dealt with include:

- Co-ordinated modelling work within the electricity-supply model package together with the EPOD and DC Power Flow models (see Chapter III);

and as reported in the *European Energy Pathways* book:

- Analysis and visualisation of different scenarios under given CO_2 constraints (Chapter 1);
- Analysis of the effects of different policy instruments (Chapter 11) ;
- Estimation of the need for new interconnector capacity in the future (Chapter 4);
- Analysis of the impact of an ageing capacity stock (Chapter 2).

For more information:
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Thomas Unger, Profu

Further reading

Odenberger M., 2009. Pathways for the European electricity supply system to 2050 – implications of stringent CO_2 reductions, Thesis for the degree of doctor of philosophy, Chalmers University of Technology, ISBN 978-91-7385-297-5.

Dispatch modelling of the European electricity supply:
the EPOD model

12

Aim and research question

The EPOD model is only one component in the electricity-supply model package used in the Pathways project, the aim of which is to generate and analyse long-term development paths for the European electricity system. This involves several model approaches that are linked together. Due to reasons of transparency and computational limitations it is more efficient to use several models, each addressing specific issues, rather than one "super" model that attempts to incorporate "as much as possible". The aim of the EPOD model is to provide the research group with a better description of the seasonal, daily, and hourly variations in electricity production for a given year. The model may be applied to most Member States of the EU27, either in a "single-country" mode or in a "regional" mode (including several countries). Important outputs from the EPOD model include annual electricity production by fuel and technology, annual CO_2 emissions from electricity supply, capacity utilisation, and marginal cost for electricity.

Methodology

The EPOD model is an optimisation model in which annual electricity production costs are to be minimised for a selected region in Europe (consisting of a selected number of European Member States) or a single country. For this purpose, the model considers, among others, electricity demand and seasonal variations in hydro power, wind power, and combined heat and power. Installed electricity supply capacities by country, technology, and fuel are obtained from the ELOD model (see Chapter 11) and the Chalmers Power Plant database (see Chapter 2). Electricity demand and fuel and CO_2 prices are also synchronised with ELOD assumptions. Running the EPOD model in hourly mode (for a fraction of a year) incorporates further considerations, such as hourly regulation of base-load power plants. The EPOD model is strictly supply-oriented. Thus, end-use measures (e.g., as a response to a sudden increase in electricity price) are not included. Demand is given and fixed for each time step. Interconnector capacities between European countries are also included, both in terms of existing (based on ENTSO-E data) and estimated future investments (taken from the ELOD model). Therefore, the marginal costs for electricity production may differ between countries as a result of bottlenecks.

The use of the EPOD model is tightly linked to the use of the ELOD model. The prime difference is that ELOD uses a broad time horizon in terms of years (2003-2050) while EPOD uses a more detailed time resolution within each year (hourly segments, weekly or diurnal, as compared to 16 time steps per year for ELOD). The more thorough intra-annual analyses obtained from EPOD are a feasible supplement to the somewhat rougher outputs provided by ELOD.

In EPOD, electricity demand and wind-power fluctuations are included on an hourly basis (Figure 12.1); these data have been taken from the European Network of Transmission System Operators for Electricity, ENTSO-E (https://www.entsoe.eu) and the TRADEWIND project (along with estimates from the Pathways project), respectively. The TRADEWIND project has also been the primary source of production data concerning non-regulatable hydro power (seasonal fluctuations).

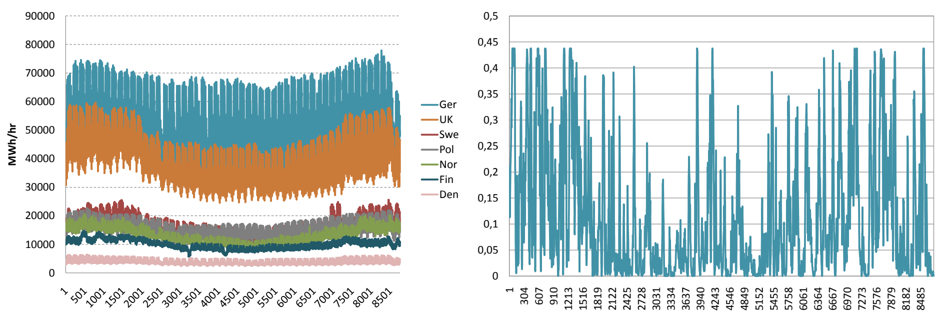

Figure 12.1. Hourly fluctuations included in the EPOD model. Electricity demand (shown for seven North European countries; left panel) and aggregated national wind power production (shown for low-land category in Sweden and expressed as hourly fractions of 1000 units per annum; right panel).

Finally, combined heat and power (in district heating and in industry) is modelled as electricity-only supply. Thus, demand for district heat or industrial process heat is not included in the model. However, a typical heat-load profile for each country (derived from EUROSTAT statistics on heating-degree days) is used (on a monthly basis) for estimating seasonal electric efficiencies for combined heat and power. High demand for heat (in winter) implies high efficiencies due to electricity and district heat production. Low heat demand (in summer) implies low electrical efficiencies, mimicking condensing power plants, due to no or little district heat production. This means that fuel use in CHP schemes is only associated with the production of electricity; fuel assigned to heat production is entirely excluded from the model. Electrical efficiencies in industrial back-pressure electricity production are assumed to be relatively high over the entire year due to the (almost) constant need for process heat.

Output examples

Important EPOD outputs include electricity production, annual CO_2 emissions, marginal costs for electricity, cross-border electricity trade, and supply system costs. A typical EPOD model result for weekly electricity production is shown in Figure 12.2 (model year 2025). In the left panel, the electricity generation for a single country, in this case the UK, is shown. In the right panel, the corresponding pattern for a larger region, in this case Western Europe (see Chapter 1 in the *European Energy Pathways* book for our definition of Western Europe), is reported. The seasonal variations in electricity demand and wind power are clearly shown. Since, according to the figure, production exceeds demand in Western Europe, electricity is exported (net export) to neighbouring regions.

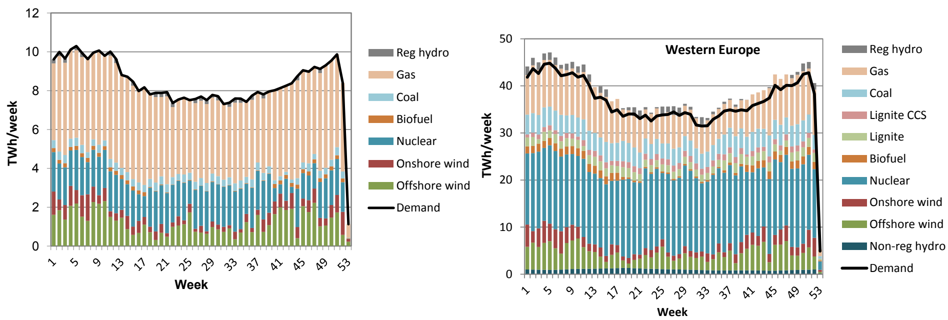

Figure 12.2. EPOD model results for the UK (left) and Western Europe (right) in 2025 (Market scenario).

Furthermore, EPOD may be used for sensitivity analyses for a given year and given capacity stock (e.g., for testing different CO_2 prices or analysing the impact of selected power supply outages). Such annual sensitivity runs are more difficult to handle with a dynamic optimisation model, such as ELOD, when minimising costs over 50 years.

The output of an hourly EPOD model run focusing on, for example, the top-load segment of a year, is used as input for the DC Power Flow model (described in Chapter 13). Thus, the hourly electricity production can be put into an electricity grid context to identify, for example, bottlenecks within a country. An example of hourly output (48-hour load block during winter) from EPOD in the case of Germany (Market scenario in 2025) is shown in Figure 12.3. Fluctuations are significantly more pronounced than in the previous weekly display regarding both demand and supply, especially for wind power production. Furthermore, variations in marginal costs are also apparent.

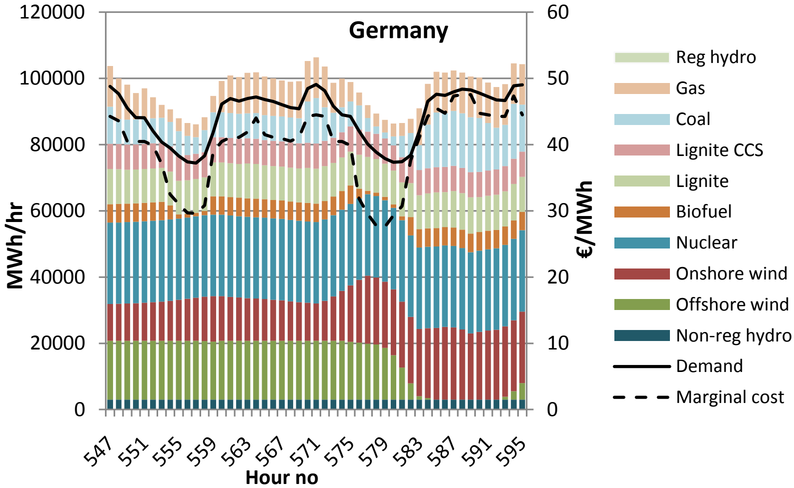

Figure 12.3. Hourly EPOD model results for two winter days in Germany in 2025 (Market scenario).

Validity and reliability

The EPOD model results have mainly been validated by comparing model results for past years with statistics on electricity supply. This type of comparison has also been useful in validating the quality of the ELOD model. Figure 12.4 shows such a comparison for the German electricity supply (left panel) and the North European electricity supply (Germany, Sweden, Finland, Denmark, Norway, and Poland; right panel) in 2005. Statistics are taken from EURELECTRIC (2007). It can be seen that there is good correspondence between EPOD output and the statistical values in both cases (the close agreement between the model results and statistics for hydro power should not come as a surprise, since in this case, the statistical outcome for hydro production, averaged over several years, was used as input for the EPOD model). This is also generally true for single countries (and not only Germany). Most of the deviations that are observed may be explained by the fact that installed capacity in EPOD is not entirely in accordance with actual installed capacity in 2005. This is due to the fact that the installed capacity used as input for EPOD is taken from the ELOD model output. Since 2003 is the starting year for ELOD calculations, investments may occur in 2005 that do not fully coincide with the actual investments carried out between 2003 and 2005. Furthermore, the electricity demand values are not entirely in agreement, since EPOD (and ELOD) uses sources other than EURELECTRIC. Moreover, normal-year conditions are used, which not only affect hydro power but also, as a result, other power supplies. Finally, the limited scope of Northern Europe in this case neglects the trade in electricity with other regions, which might have had some impact on the actual outcome in 2005.

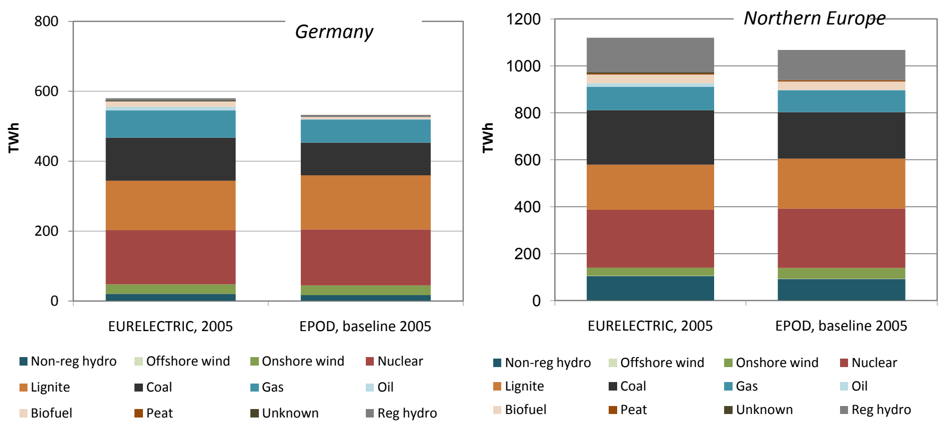

Figure 12.4. Comparison between EPOD model results and the statistics taken from EURELECTRIC for 2005 in the case of Germany (left panel) and Northern Europe (Germany, Sweden, Finland, Denmark, Norway, and Poland; right panel)

The close interconnection between the EPOD and ELOD (and the preceding ELIN) models provides validity in both directions. The results from one model have in many cases been confirmed by the use of one of the other models. Thus, both model approaches support one another.

Applications of the model

EPOD has been used to:

- Improve the electricity-supply model package by including it with the ELIN/ELOD and DC Power Flow models (see Chapter III).
- Analyse the seasonal impact of large shares of wind power (see Chapter 9 in the *European Energy Pathways* book).
- Assess the impact on climate of European electricity and elaborating on the concepts of average and marginal electricity (see Chapter 10 in the *European Energy Pathways* book).

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13

Modelling of the European power transmission network:

the DC Power Flow model

Aim and research question

Within the Pathways project, a modelling package has been developed for the complete generation of a power generation-delivery system, comprising the ELIN, EPOD, and DC Power Flow models. ELIN models the future development of the EU electricity supply system by 2050, while the EPOD model allows a more detailed analysis of electricity production for a given year in the future. An important task of the DC Power Flow model in this context is to represent the electrical transmission network that connects the generation facilities and loads considered in both the ELIN and EPOD models. One research aim is to assess the interactions between the future pathways for power generation systems and power delivery systems, so as to identify major bottlenecks in the systems and measures to overcome such bottlenecks in the future.

Description of the model

The DC Power Flow model gives a detailed representation of the high-voltage transmission network for European power systems. This model requires large amounts of data from the network companies, which are difficult to obtain due to confidentiality issues. To overcome this problem, the initial model and data, which were made available by Zhou and Bialek (2005), were used. The model deals with only active power and ignores transmission-related losses. The reactive power is also neglected due to lack of availability of data on reactive power generation and reactive power demand, as well as on the reactive power consumption devices in the system. The network model is implemented using PowerWorld Simulator, a standard power system and analysis software by Power World Corporation (2010). This model is an efficient tool to evaluate the grid-associated challenges and adjustments required for the transformation of the electricity production system according to the results obtained using the ELIN and EPOD models. The DC Power Flow model takes its inputs from the ELIN and EPOD models. These inputs include investment plans for new generation capacities of different types from the ELIN model and the generation dispatch schedules for the peak load hours, i.e., a snapshot, for different years, that allows calculation of the power transfer in the entire transmission network.

Application of the model

One of the important outcomes from the DC Power Flow model is the identification of grid bottlenecks and necessary grid reinforcements (or alternative production siting). The model, in combination with ELIN and EPOD, can be used to perform various analyses of future-generation transmission systems. The model can be used to study the whole network or part of the network, i.e., a region or a country. For the latter, the part of the network has to be isolated from the rest of the network. The rest of the network has to be made equivalent with extra nodes in the system. To accomplish this, the steady-state power system equivalence technique is used.

The DC Power Flow model has been used to evaluate the effects of the future generation plan on the transmission network in Germany. However, the model can be used for the same purpose for different countries, groups of countries or the whole EU network. An example of the application of this model to Germany for the baseline scenario and for a peak load hour in 2015 is given in Figure 13.1. More about the scenarios can be found in Chapter III.

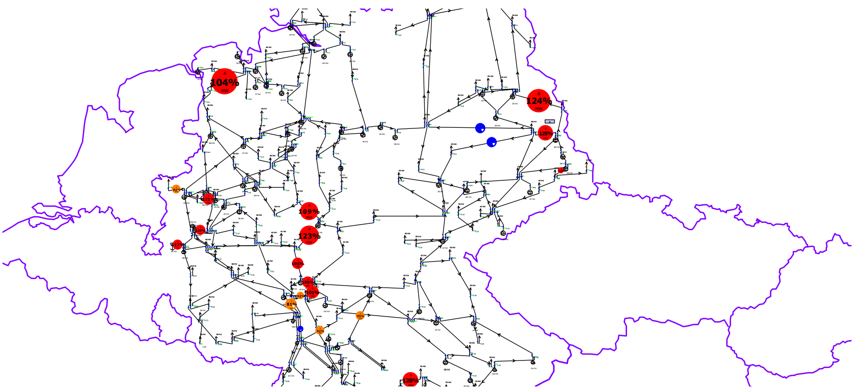
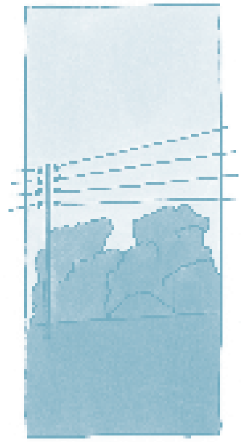


Figure 13.1. Power flow for Germany for a typical peak load hour in the baseline scenario (2015).

The DC Power Flow model is also used to represent the simplified EU transmission network, so as to evaluate the power exchanges between the EU countries and the required investments in cross-border interconnections. In addition, the DC Optimal Power Flow model has been to evaluate the investment scenarios for the interconnections between countries using a Cost-Benefit Analysis. Further information on this form of application can be found in the Chapter 3 in the *European Energy Pathways* book and in Papaemmanouil et al. (2010).

Validity and reliability of the model

The initial model and data were validated against the published data on cross-border power flows with a correlation exceeding 90% (Zhou and Bialek, 2005). It showed that the model and the data were rather accurate. In subsequent developments of the model, different assumptions for the data regarding generation and loads were made to accommodate the new investments in generation from the ELIN and EPOD models. The reliability of the model is rather dependent upon these assumptions and the input data transferred from ELIN/EPOD to this model. In addition, when making the system equivalence of isolate individual or regional system, a commonly used method has been used.



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A bottom-up model for energy, carbon, and costs assessment of building stocks

14

Aims and research question

To develop energy efficiency strategies for building stocks, there is a need for simplified methodologies and tools for assessing different options and selecting the best option. Bottom-up modelling of buildings, whereby each building is modelled separately, is required to determine the impacts of new technologies or retrofit measures with appropriate spatial and time resolutions. In addition, in developed regions, such as the EU (the main application of the present work), most buildings are already built, which means that the main challenge in the coming decades is to improve the existing building stock. Therefore, a bottom-up modelling methodology has been designed to assess energy efficiency and CO_2 mitigation strategies in the existing building stock. The model meets the following objectives:

- to be simple with respect to both the descriptions of the buildings and model complexity, so as to reduce computational time and the amount of input data;
- to allow modelling of the building stock of an entire region or country on a level that allows aggregation for Europe as a whole;
- to allow assessments of the effects of different energy efficiency measures, including market realism, when it comes to the achievement of the potentials;
- to include behavioural issues;
- to allow assessments of the direct and indirect costs per unit of energy and CO_2 saved (meeting certain criteria, e.g., discount rate, baseline year, target year); and
- to allow for easy and quick changes of inputs and assumptions in the model.

Method description

The ECCABS (Energy, Carbon, and Costs Assessment for Building Stocks) model was developed to comply with above-mentioned objectives. The model is described in detail by Mata et al. (2010a). The simulation model consists of two parts: 1) a Simulink model, which solves the energy balance for buildings; and 2) a code written in Matlab, which handles the input and output data from the Simulink model (Mathworks, 2010). The model uses a bottom-up engineering approach in which the energy demand of individual buildings is calculated based on the physical and thermal properties of the buildings, existing heating and ventilating systems, type of building (i.e., single-family houses or multi-family houses), and climatic conditions. The analysed buildings can be either existing sample buildings or so-called archetypes, i.e., representative of a group of buildings with similar structure, service systems, and purpose as the building stock to be investigated.

The model provides two energy outcomes: 1) end-use demand, i.e., the energy demand for heating, ventilation, and hot water in buildings; and 2) the final energy demand, which takes into consideration the efficiency of energy supply systems to the buildings. The results for individual buildings are then scaled-up to represent a country´s building stock by multiplying the results by the number of buildings that fit the description of each building modelled. The potential energy savings from various energy efficiency measures are always related to a reference energy demand, which is calculated and recorded for a certain year for the existing buildings of the stock to be analysed.
In addition, the model results include estimates of costs and carbon intensities of

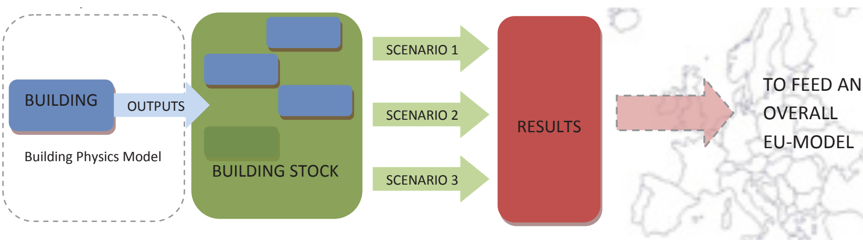

Figure 14.1. Overview of the calculation steps in the ECCABS model.

fuels and the estimated direct costs (i.e., investments, operation and maintenance costs) for the efficiency measures. Input data regarding future energy prices and CO_2 emissions are provided by scenarios for world wholesale energy prices for the industrial sector (Axelsson and Harvey, 2010; see also Chapter 20), future electricity prices (see Chapter 1 in the *European Energy Pathways* book) and CO_2 emissions from electricity production (see Chapter 10 in *European Energy Pathways* book). The input data are complemented with information on distribution costs and excise taxes from the IEA (2009), and VAT rates for the residential sector based on current rates (EC, 2010). The inclusion of indirect costs is currently under development.

Obviously, the results obtained depend on the characteristics of the buildings, as well as on the energy/carbon intensity of the building sector studied. Thus, although the model was applied using a relatively high number of residential buildings in Sweden and validated as described in the next section, it is dependent upon the inputs. Therefore, the possibility to apply this model to countries and regions other than Sweden will depend on the availability of data on buildings (i.e., data for a sufficiently high number of sample or archetypal buildings).

Validity and reliability of ECCABS

The accuracy of the energy balance model (in Simulink) was tested and validated for two buildings: an office building located in Barcelona, Spain; and a residential building in Köping, Sweden. For the Spanish office building, for which the cooling demand is covered by natural ventilation only, the indoor temperature during a warm week was calculated and compared to the measured indoor temperatures. The modelling results were reasonable, albeit not in full agreement with the measurements. This discrepancy is partly explained by uncertainties regarding some of the input values, given the characteristics of the building (i.e., large glass façades, ventilated basement, natural ventilation, and extensive exposure to the sun). However, the discrepancy is also due to the simplified nature of the modelling approach. The latter explanation was verified by comparing the results from the ECCABS model to results obtained using another model, DesignBuilder (DB, 2010), which performs a more detailed simulation of natural ventilation. In the comparison between the more simplified ECCABS model and the more complex DesignBuilder model, the latter provided results that were closer to the measured values. Nonetheless, the ECCABS-modelled heating demand was within the range of measured heat consumption, as described by Mata et al. (2009). As for the Swedish residential building, the calculated heat demand was in a good agreement with the measured values (within 1% difference) (Mata et al., 2009).

The simulation of energy consumption for the baseline year serves as a large-scale validation of the model. The results of the ECCABS model relate energy efficiency measures to a baseline energy use (also referred to as "useful energy") in the year 2005, while the statistics only report final energy use (also referred to as "delivered energy"). The difference between the statistics and the total energy use resulting for this work, recalculated as delivered energy, was 5% (taking into account the types and efficiencies of the heating and electricity systems in the housing stock, i.e., the percentages of oil, gas, pellets, wood, electricity and district heating for heating and hot water demand). Thus, the baseline energy use is considered validated. The modelled final energy by fuels was also validated against data available in the ODYSSEE and GAINS databases (Enerdata 2010; IIASA, 2010).

The modelling results for the Swedish case have been compared to the results of previously published studies on the topic. This is not a straightforward task, since the studies differ in terms of assumptions, possible efficiency options and approaches in the modelling. To start with, there are several definitions of "energy-saving potentials"; in Sweden they are generally related to the definition of cost savings (see box below).

First, the total technical potential derived in the present study is up to 65% higher than that reported by other sources (Sandberg, 2007), while our calculated techno-economic potential saving is 30%-50% lower than those previously reported (BFR, 1996; Dalenbäck et al., 2005, Pettersson and Göransson, 2008). Second, bottom-up modelling approaches generally tend to provide higher potentials than top-down assessments (see Swan and Ugursal, 2009). Third, the number of measures studied influences the total potential (e.g., some studies do not include reduced indoor temperature as an efficiency option). In addition, the interest rate used obviously influences the results (in the present case, 4% was applied). Finally, the data used for the description of the building stock influence the results. Our work is the first assessment based on a description of the Swedish buildings as they were in year 2005, while all the other studies are based on the Swedish building stock in 1995. For a detailed comparison of the present and other reports and models, see Mata et al. (2010b).

The investment required to implement all the measures assessed in the present work is much lower than that estimated in a previous national report (BFR, 1996). A possible reason for this discrepancy is that in the present study, some investment costs have been set at zero when the measure is assumed to take place in any case (mainly due to regulation/standards), e.g., changes in lighting and some appliances. In addition, there have been developments in technologies

DEFINITIONS OF ENERGY-SAVING POTENTIALS

The most common distinctions in the definition of the costs for energy savings have been found to be:

The *technical potential*, which is defined as the amount by which it is possible to reduce energy demand or CO_2 emissions by implementing already demonstrated technologies and practices without specific reference to costs.

The *techno-economic potential*, which is the cost-effective (i.e., profitable) technical potential to reduce energy demand or CO_2 emissions. The costs are calculated as the net annual cost to apply the measure minus the cost of the energy saved, divided by the energy saved or CO_2 avoided due to the application of the measures.

IN SWEDEN:

Cost savings are defined as the sum of the investment and the present value of the annual maintenance cost of the efficient alternative, divided by the present value of the cost of the annual energy savings (GB, 1977). These savings were used as the basis for the first Swedish energy-saving plan, and have subsequently been used in all Swedish energy efficiency assessments.

(and costs) since 1996. As for the assessment of CO_2 abatement opportunities, none of the other available studies details the methodology used and the specific measures that were included.

Application of the tool

The ECCABS model has been used to assess the energy savings and CO_2 mitigation of retrofitting measures in the Swedish housing sector (see Chapter 45 in the *European Energy Pathways* book and Mata et al., 2010b,c). The model has also been used together with two top-down models (see Chapters 19 and 23) to provide a comprehensive overall assessment of energy efficiency and CO_2 mitigation strategies in the existing European building stock under different scenarios up to the year 2050 (see Chapters 44 in the *European Energy Pathways* book). The end-use energy model was initially developed under the name ”Energy Assessment of Building Stocks - EABS” (Mata and Sasic, 2009) to estimate the effects of a number of measures for reduced energy use in the Swedish residential stock, as represented by a number of buildings. That task was commissioned by Boverket and the results are published in part in Boverket (2009).

For more information:
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Angela Sasic Kalagasidis
Building Technology, Chalmers

Further reading:

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Mata, É., Sasic, A. and Johnsson F., 2010. Energy, Carbon and Cost Assessment for Building Stocks: Description of the bottom-up model ECCABS, Report A 2010-01, Chalmers University of Technology, Gothenburg.

The BALWIND model:
modelling the integration of intermittent electricity generation

15

Aim and research question

The BALWIND model is a tool that is used to analyse interactions between intermittent wind power and thermal power plants in a regional electricity grid system. The model uses a mixed integer programming approach to determine the power plant dispatch strategy that yields the lowest system costs. In the model, each large thermal plant is described separately in terms of start-up cost, part-load cost, and minimum load level.

As large-scale wind power is integrated into a power system (typically 20% wind power grid penetration), the intermittent nature of wind power will result in an increase in variations in load on the other units in the system (e.g., thermal power plants). The BALWIND model is designed to investigate and quantify the consequences of the wind power variations on thermal power systems. Several strategies have been suggested to reduce the impact of wind power variations, including storage technologies and demand-side management. It is possible to integrate such active variation management strategies in BALWIND and to evaluate their influences on the power generation system.

Model description

The BALWIND model was first developed as a stand-alone optimisation model of the electricity generation sector (Göransson and Johnsson, 2009). However, in its latest versions it is an add-on to the more established BALMOREL model, and as such it also includes the heat generation sector (see box below for a description of the BALMOREL model).

With the BALWIND add-on, each power generating unit with an electric capacity above a certain size (e.g., 80 MW) is treated separately. Modelling of individual plants is necessary in order to include variation management in the optimisation. Thus, this is a development of the original BALMOREL model in which heat and/or power generation technologies are aggregated based on technology, fuel, and geographical location on an area level.

The least-cost variation management strategy depends on the properties of the thermal units available for management and the duration of the variation. If no active strategy for variation management is in place, variations can be managed by:

- part-load operation of thermal units;
- starting/stopping thermal units; or
- curtailing wind power.

BALMOREL

BALMOREL is a linear programming model that was originally designed for the countries around the Baltic Sea. It optimises electricity and heat production over a specified geographical scope, taking into account costs and utility (maximising consumer utility, i.e., the willingness to pay for heat and power minus production costs) under the assumption that there is perfect competition in the heat and power markets. In BALMOREL, the geographical scope is managed at the levels of country, region, and area, i.e., each country is made up of one or several regions, which in turn consist of one or several areas. The heat generation and heat demand should be balanced in each area, whereas electricity generation and electricity demand should be balanced over each region. Electricity can also be exchanged between regions to the extent that the defined transmission capacity allows. Regions within the same country share policies and regulations. The simulated countries can trade electricity with each other. Electricity can also be traded with countries outside the geographical scope of the simulation, in which case the amount of exchanged capacity is based on assumptions regarding price relations or total traded capacity. BALMOREL is developed and distributed as an open source code; a detailed description of the model is provided by Ravn (2001).

The costs of these strategies, separately and in combination, can be compared by defining the start-up costs and part-load costs, as well as the running costs of the power-generating units. For example, if a high level of wind power production persists over a long time period, it can be economically advantageous to shut down some of the other units taking part in the dispatch of the system. In contrast, if the high level of wind generation has a short duration, the shut-down and start-up costs of the thermal plants might be higher than the losses experienced (the value of the curtailed wind power) if the thermal plants were kept in operation, even if the production cost exceeds the spot price. The overall objective of the model is to combine the production patterns of the power-generating units so that the electricity and heat demand is satisfied with the lowest total system costs. When assessing the production patterns with BALWIND, add-on running costs, start-up costs, and part-load costs are taken into account. The aim of the modelling is thus not only to find the optimal combination of units that satisfies the production need at each time step, but also to minimise costs while considering optimal combinations of units over several time steps, including start-up costs and part-load costs. Figure 15.1 shows a schematic of the model, comprising parts of BALMOREL and the BALWIND add-on.

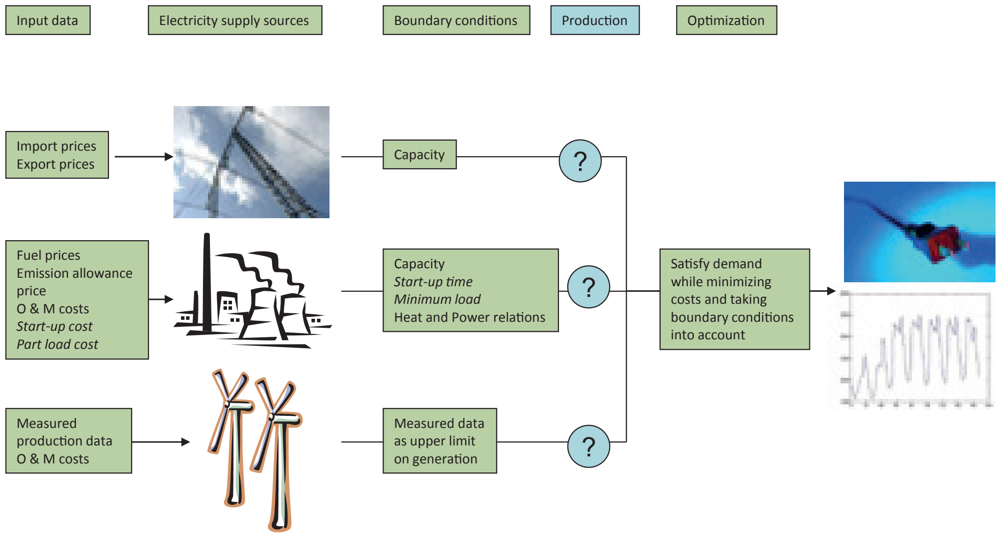
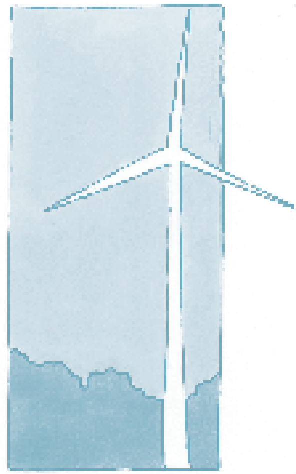


Figure 15.1. Schematic picture of the model. Contributions of the BALWIND add-on are indicated in italics.

The start-up costs and minimum load-level limitations of the large thermal units are included in the model using a binary variable, as explained by Göransson and Johnsson (2009). The concept is based on the work of Schaeffer and Cherene (1989), who included "spinning reserves" in an investment and simulation model for electricity generation, so as to investigate the influence of varying demand on a power generation system. The BALWIND model takes their concept one step further, as it includes wind power production variations, reserve requirements in accordance with these variations, and combined heat and power generation.

Wind power variations occur continuously. To capture the frequency of these variations, the time resolution of the model has to be sufficiently high. However, there is a trade-off between scope and exactness and a very high time resolution will drastically limit the scope of the simulation (i.e., the number of individual power plants that can be taken into consideration or the number of time periods that can be evaluated with reasonable computational times). Due to differences in the local conditions at each wind turbine, the production variations with the highest frequency will be smoothed out over large wind farms. Taking the aggregated wind power production of an entire region, the smoothing effect will be even more pronounced. This effect, referred to as power smoothing, can be observed from statistics on wind data and is explained in detail by Manwell and co-workers (2005). Based on these observations, a time resolution of 1 hour is used in BALWIND. It is assumed that this resolution will capture the most important features of the interaction between power-producing units (i.e., the unit commitment decision) in a power system as long as there is a reasonable amount of wind power capacity installed within each region in the simulation. However, with a 1-hour time resolution, the model cannot be used to estimate the need for reserves to balance generation within the hour. Reserve requirements are instead taken as fixed requirements for available capacity based on previous studies by other authors (e.g., Holttinen and Pedersen, 2003 in the western Denmark case). To limit the computational time and allow for a wider geographical scope, the simulation results for one representative week (i.e., based on weekly wind power production) per season (Summer, Autumn, Winter, Spring) are weighted together to represent a full year. Thus, in the model, 1 year is represented by a total of four "seasonal" weeks.



Limitations

The focus of the model is on production strategies rather than on investment strategies, and total costs are minimised for a power system with fixed configuration (i.e., the model does not include investments). The model is therefore not intended to serve as a direct basis for decisions related to investment in wind power. Instead, it is designed to investigate how the wind power that results from the investment can be handled by the system in place. The model is designed to indicate the possibilities for a power system to manage variations based on physical limitations rather than mimicking the actual production patterns, which are determined to a large extent by market conditions.

The simulations have been subjected to some limitations, so as to decrease the complexity. Limitations on transmission and distribution of electricity within a region are not considered. Thus, the modelled region should not encompass any important bottlenecks but should be one for which a dispatch curve can be drawn. Wind power forecast errors are only taken into account when determining the size of the required secondary reserve (based on studies by other researchers, e.g., Holttinen and Pedersen, 2003), and they are not considered when planning future power generation. Finally, to obtain reasonable computational times, the time resolution of the calculations was limited, as indicated above.

Validation

Evaluation of the model is carried out by comparing the true power production and the simulated power production in the large thermal units of an existing power system for the amount of wind power present in the system today. This type of evaluation was carried out for the western Denmark system in its present configuration, with the western Denmark wind power production data as the input for the simulations. However, there are some important differences between the model and reality. First, the model considers physical limitations of the system to manage variations rather than market conditions, such as time between plant scheduling and hour of production. Second, in the optimisation process, the wind power production data for the whole year are known (perfect foresight), whereas the true production levels are set according to wind power forecasts for a limited time period. Therefore, the comparison of true and simulated power production only indicates the extent to which the simulated production level is reasonable. In a previous study (Göransson and Johnsson, 2009), it was shown that the model could describe the western Denmark system in a satisfactory way.

Applications

The model has been applied using a simplified description of the power system of western Denmark as the starting point for the simulations. The western Denmark power system is a wind-thermal power system with 11 thermal units, having an electrical capacity of more than 80 MW (Eltra, 2005), which are described

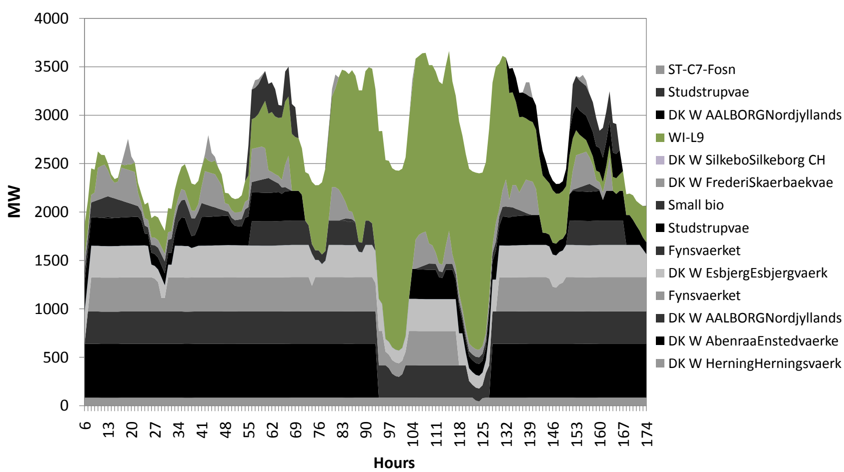


Figure 15.2. The operational pattern of the generation units in the wind-thermal system based on western Denmark for one week in Spring, as generated by the model. Thermal units are indicated in grey and wind power is indicated in blue.

individually. Nine of the eleven units deliver heat to respective district heating systems. The total electric capacity of these large units is 3,500 MW; the system also contains smaller thermal units (mainly CHP) with a total electrical capacity of 1,600 MW and wind power with a capacity of 2,400 MW. The wind power generation corresponds to 24% of the total demand for electricity in the region (Eltra, 2005). Hourly wind power production and load in the model are based on data from western Denmark in 2005. Reserve requirements are set based on the work of Holttinen and Pedersen (2003).

Examples of the results from work with the model, applied to western Denmark, can be found in Chapter 6 in the *European Energy Pathways* book. Results are generally aggregated from the weighted results of separate runs for four seasonal weeks, as explained above. In order to develop a good understanding of the investigated system, the operational pattern of the generation units derived from the weekly runs can also be useful. Figure 15.2 illustrates the operational pattern of the generation units in the wind-thermal system, based on western Denmark, for one week in Spring.

For more information:
Lisa Göransson and **Filip Johnsson**
Energy Technology, Chalmers

Further reading:

Göransson, L., 2008. Wind power in thermal power systems. Licentiate thesis, Department of Energy and Environment, Chalmers University of Technology.

Top-down modelling of energy use and CO_2 emissions in the industrial sector of the EU25 countries

16

Aim and research question

The purpose was to estimate the energy use and CO_2 emissions in the industrial sectors of the EU25 countries to the year 2030, assuming policy-induced increases in the costs for emitting CO_2. Thus, the overall research question was: How might energy use and CO_2 emissions in EU industry develop in the short-to-medium term under different climate policies?

Model and data description

To assess the policy-induced changes in energy use and carbon emissions, a top-down model was developed. In this model, energy use in each industry branch is calculated as a function of production (in terms of value added), energy prices, energy price elasticities, and an autonomous efficiency improvement constant (i.e., independent of energy prices). The model is disaggregated into five energy types, i.e., coal, gas, oil, electricity, and other (biomass, heat), for ten industry branches and two geographical regions (the old member states [EU15], and the new member states [NMS10]).

For fossil fuels and electricity generation, the assumed values for energy price elasticities and autonomous efficiency improvement constants were based partly on the data from the literature (e.g., Kratena and Wäger, 2003; Enevoldsen et al., 2007) and partly on regression analyses, carried out within this study, of time series data of energy use per added value and energy prices. The time series data on energy use and added value were taken from the Odyssee database (Odyssee, 2008), and the data on energy prices were obtained from the IEA database (IEA, various years). Assumptions regarding price-driven substitution from fossil fuels to solid biomass fuels and heat (i.e., plant surplus heat or district heating) were based on estimates of the temperature structure of the heat demand in each branch; these estimates were made in a related study within the Pathways project (see Chapter 25 in the *European Energy Pathways* book).

Validity and reliability of the model

Overall, the regression analyses did not yield results of good statistical significance, due to limitations associated with the data. First, the level of branch aggregation in the Odyssee data is relatively high, which means that a possible correlation between energy price and energy use may be obscured by structural changes within the branch. Second, the length of the time series data in Odyssee is about 25 years for EU15 and only 10-15 years for NMS10, which is probably insufficient, since information on the impact of price on energy use in industry is outdated, especially for capital-intensive industrial branches, in which capital lifetime may exceed 30 years. Third, the IEA energy price data contain only the average prices for the entire industry, which obviously is a source of inaccuracy since energy prices, particularly those for electricity, may vary substantially between industrial branches.

Another observation from the statistical analyses is that the regressions that included the autonomous efficiency improvement parameter yielded results of higher significance (r^2) than those that excluded this parameter. The reason for this is that this parameter represents trends that are not directly related to energy price levels, which include (at least):

- Increasing value added to industry, due to structural changes (growth of branches with greater added value per energy use) and product development
- More efficient technologies due to improved knowledge

In the present study, the autonomous efficiency improvement parameter was found to have a greater impact than energy prices on the future carbon intensity of industry, and this was especially so in the NMS10, where the trends for structural changes and technological improvements towards higher efficiency are stronger than in the EU15 (see Figure 16.1). For most branches and energy types, the autonomous efficiency improvement parameter was estimated at about 0.7% per year in the EU15 and 1.5% per year in the NMS10.

This book describes the methods and models used to achieve the results presented in the **European Energy Pathways** book.

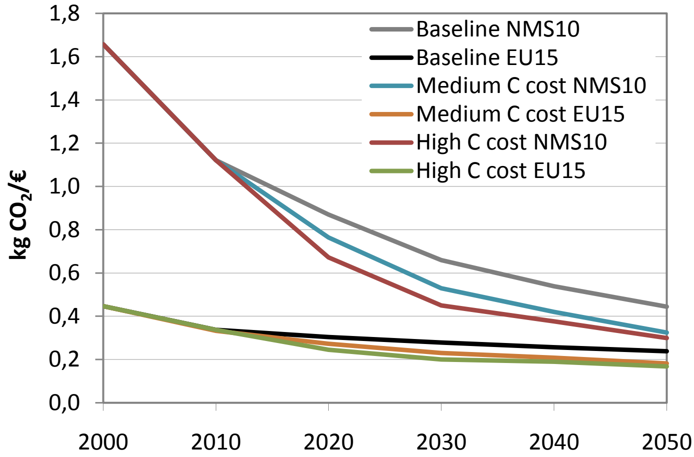


Figure 16.1. Examples of carbon emissions per value added (average for all industry sectors) for all scenarios.

Application of the model

The top-down model developed as part of this study was used as the basis for creating the Market and Policy scenarios for the entire industry sector (see Chapter 24).

For more information:
Stefan Wirsenius
Physical Resource Theory, Chalmers

Further reading:

Wirsenius, S., Algehed, J., Jönsson, J., 2010. Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent climate policies: Evaluation of top-down, bottom-up and hybrid approaches. Accepted for publication in Energy Efficiency.

Capital vintage modelling of energy use and CO_2 emissions in the pulp and paper industry

17

Aim and research question

The aim was to estimate future energy use and carbon dioxide emissions in the pulp and paper industry of the EU15 countries, assuming the implementation of different policy options aimed at reducing CO_2 emissions in this sector. Thus, the overall research question was: How might energy use and CO_2 emissions from the EU pulp and paper industry develop in the short-to-medium term under different climate and industry policies?

Model and data descriptions

To assess the policy-induced changes in energy use and carbon emissions, a capital vintage model of the EU pulp and paper industry was developed. Capital vintage models are dynamic models that capture the age structure of the capital stock and its associated age-specific attributes, such as size, rate of replacement, input efficiency, and input substitution possibilities. In the model used in the present study, the capital vintage modelling was carried out in a top-down framework rather than in a bottom-up framework, since most of the parameter values are derived from econometric analyses of aggregated data related to production, prices etc.

In the model, carbon emissions are calculated as a function of paper demand, the aggregate energy efficiency of the capital stock, and the fuel mix. The model captures changes in the age distribution and size of the capital stock over time, which means that the future size and structure of the stock is a function of new capital investments and the retirement of aged equipment. Estimates of existing capacity structure for each vintage class were based on Pöyry data (Pöyry, 2009). The capacity and efficiency of each vintage class were traced over time to calculate aggregate efficiency improvements resulting from new investments and the retirement of old capital. More specifically, the energy efficiency of each new capital vintage class was calculated as a function of the aggregate average efficiency of the existing capital stock and the parameter "relative energy intensity" (REI) of new to old capital. The fuel mix of gas, oil, coal, and electricity in the model was calculated as a function of energy prices. The relationships between paper production, energy prices, and fuel mixes for the industry were quantified using multiple regression analysis of historical time-series (1990-2005) data, compiled mainly from CEPI (CEPI, various years) and IEA (IEA, various years). Due to limitations in the dataset, the use of biomass- and self-generated energy is not based on econometric relations, but is defined exogenously.

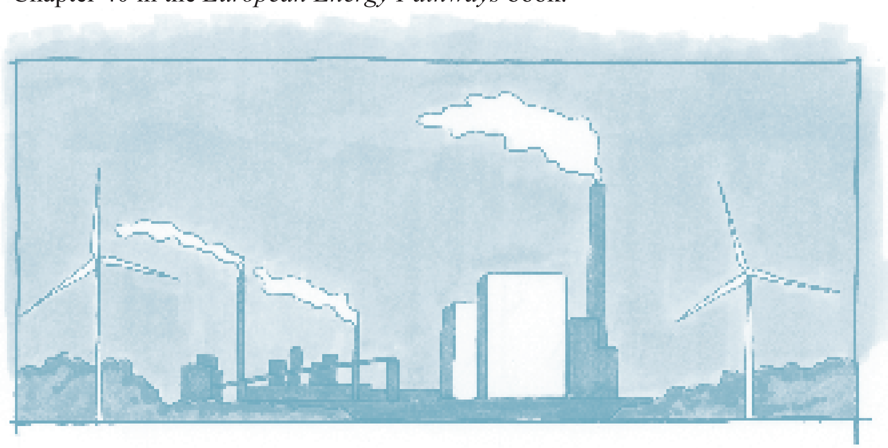
Validity and reliability of the model

Many of the regression analyses did not yield results of statistical significance, due to several limitations in the dataset, which mainly involved short (in some cases, around 10 years) and/or incomplete time series. These limitations are largely related to the fact that the investigated region consists of many countries, among which the quality and length of the time-series data vary substantially. In addition, the IEA energy price data contain only average prices for the entire industry, which obviously is a source of inaccuracy, since energy prices, particularly for electricity, may vary substantially between industry branches.

Application of the model

To assess the potential for energy intensity and CO_2 mitigation, five scenarios were investigated in this study: a baseline scenario, in which carbon costs are assumed to remain at current levels in the EU ETS (i.e., around 25 €/tCO_2); and four policy scenarios in which carbon costs are assumed to increase and/or a higher energy efficiency of the new capital relative to the existing capital is assumed.

The model generates a multitude of process and industry-wide outputs that aid in the analysis of energy efficiency and CO_2 mitigation potential. Representative outputs are presented in Figure 17.1. More detailed results can be found in Chapter 40 in the *European Energy Pathways* book.



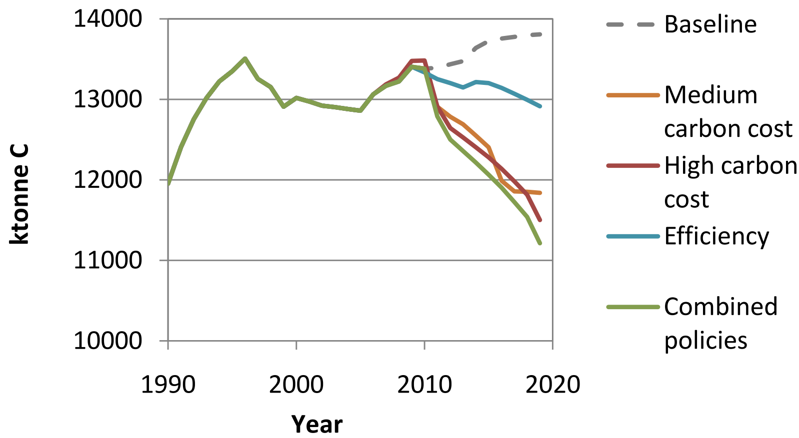


Figure 17.1. Scenarios for carbon emissions in the EU15 pulp and paper industry.

In the baseline scenario, carbon emissions increase slightly compared to the current level (Figure 17.1). All of the simulated policy options reveal reduced carbon emissions compared to the baseline conditions. The Efficiency scenario results in a much lower level of emission mitigation, 8% below the baseline in 2020, compared to all the other scenarios. The Combined policies scenario, which combines the Medium carbon cost and Efficiency scenarios, generates the most impressive emission mitigation, cutting emissions by 22% below the baseline level by 2020.

For more information:
Stefan Wirsenius
Physical Resource Theory, Chalmers

Further reading:

Gasper, R., Ruth, M., Wirsenius, S., 2010. Short-term Emissions Reduction Potential in the EU Pulp and Paper Industry. In review at Energy.

Wirsenius, S., Algehed, J., Jönsson, J., 2010. Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent climate policies: Evaluation of top-down, bottom-up and hybrid approaches. Accepted for publication in Energy Efficiency.

Capital vintage modelling of energy use and CO_2 emissions in the iron and steel industry

18

A dynamic model that captures the main production stages and technologies was applied to assess energy intensity reductions and CO_2 mitigation potential in the EU15 iron and steel industry. The model uses econometric forecasting techniques coupled with capital vintage modelling of the production stock, to produce scenarios for energy use and CO_2 emissions until 2030. Scenarios reflecting high or low future energy prices and lax or stringent CO_2 emission reduction policies have been adapted from the Pathways energy market parameters.

Aim and research question

The aim of this study is to assess the energy intensity reduction and CO_2 mitigation potentials of the European iron and steel industry (for full details see Torén, 2010). The overarching purpose can be broken down into two specific questions: 1) How will energy use and CO_2 emission from the EU iron and steel industry develop in the short-to-medium term under specific scenario assumptions?; and 2) What are the likely structural developments in the EU iron and steel industry arising from various scenario assumptions? The present study covers the EU15 countries, representing roughly 85% of total steel production in the EU27, until the year 2030.

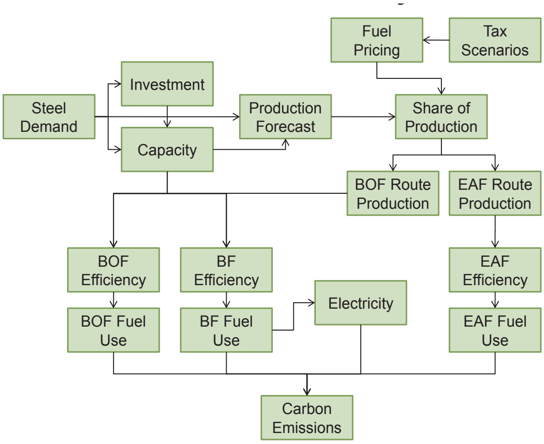


Figure 18.1. Basic model layout

Method and Model

To assess the energy intensity reductions and CO_2 mitigation potential in the EU15 iron and steel industry, a dynamic model that uses econometric forecasting techniques has been applied. The model captures the two main production routes, primary and secondary production, and the main production processes for these routes, the blast and basic oxygen furnaces (BF and BOF) and the electric arc furnace (EAF), respectively. The model incorporates technology-specific engineering information to specify material and energy use efficiencies for the modelled technologies at each point in time, limits to these efficiencies, and conversion factors. To quantify the rates of change for the technical coefficients that describe the industry econometric time series analysis was used. Embedded in the overarching econometric model is a capital vintage module that explicitly accounts for the age structure of the stock, including age-specific efficiencies, production levels, and capacity utilisation. Furthermore, economy-wide steel demand, industry steel production, and dynamic capacity levels for the primary and secondary routes are modelled (Figure 18.1). The model is based on previous work by Ruth et al. (2000; 2004) and Ruth and Amato (2002), which assessed the US iron and steel industry.

To assess the potentials for energy intensity and CO_2 mitigation, several scenarios for energy prices and cost of carbon were adapted from Pathways energy market parameters (for further details see Chapter 20) (Axelsson et al., 2009; Axelsson and Harvey, 2010).

Example of Results

The model provides a multitude of process and industry-wide outputs that aid in the analysis of energy intensity reduction and CO_2 mitigation potential; two representative outputs are presented in Figure 18.2. These results are to be considered as preliminary, as refinement of the model parameters is ongoing. The left panel of Figure 18.2 depicts the shares of secondary (electric arc furnace) production for the different energy price and tax scenarios. The share of secondary production is specified as a function of the relative price of electricity to the primary energy price and cumulative secondary route production. The production share is used to calculate ideal production capacities, which in turn govern capital investments. The production shares have a major influence on the energy use and CO_2 emissions profile for the iron and steel industry, as evidenced by the average CO_2 emissions per tonne steel for the Baseline scenario (Figure 18.2, right panel). All the factors in the model influence the average per tonne CO_2 emissions, from cumulative production for the two steel-making routes and carbon price-induced fuel switches to process-specific efficiency gains and replacement of ageing production capital.

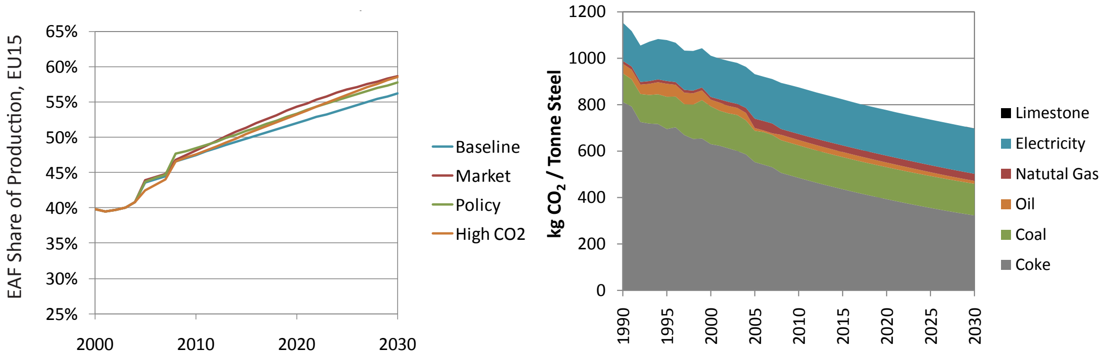


Figure 18.2. Examples of model outputs.

Validity and Reliability

Capital vintage modelling is an attempt to avoid the pitfalls of more traditional bottom-up and top-down modelling. It does this by incorporating both technological descriptions of the capital stock and top-down representations of the economies that stimulate change in the capital stock. It also captures more adequately the inherent inertia of capital investments, thus mirroring the real world more accurately. However, since the model is based heavily on econometric time series analysis, the effects of radically new techniques and technologies and of policy measures, inducing fuel and CO_2 costs substantially different from historic values, cannot be captured with any accuracy. This effectively imposes a limit as to how far into the future capital vintage models can provide useful insights into the development of the sector under study.

A comprehensive sensitivity analysis has been performed in addition to the inherent sensitivity analysis that the different fuel and CO_2 price scenarios provide. Departing from the cumulative emissions from 2010–2030 for the Baseline scenario, six of the most important variables have been varied: (1) the relative energy intensity (REI) of new EAF capital; (2) yearly BF technology learning rate; (3) GDP; (4) Euro effective exchange rate (EEER); (5) steel price; and (6) the maximum allowable market share of the EAF. These six variables were allowed to fluctuate ±5% to ± 20% around their original values (Figure 18.3). It is clear that the single most important parameter is the yearly learning rate for the blast furnace process, whereby minute changes in the variable value have a substantial impact on the overall results. In contrast, the macro-economic variables scarcely affect the results.

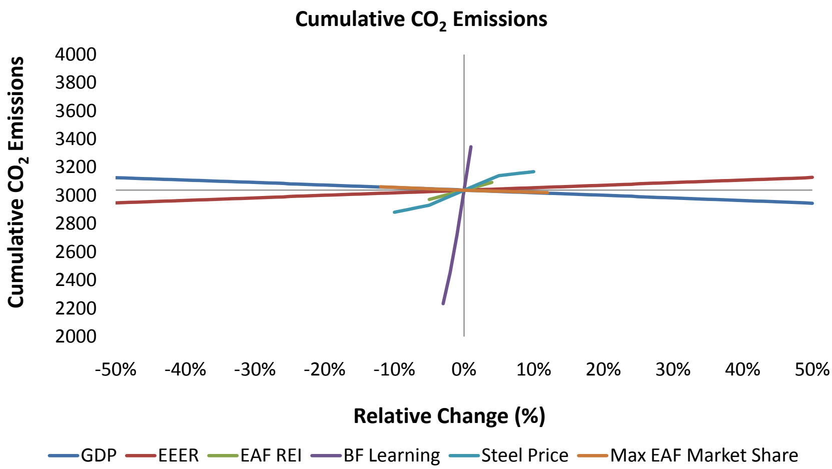


Figure 18.3. Sensitivity analysis for baseline cumulative emissions for the period 2010 – 2030.

Application of the model

The model has been used to produce a set of scenarios for the EU15 steel industry until 2030 (see Chapter 41 in the *European Energy Pathways* book). The scenarios are used to assess how the iron and steel industry reacts to high or low future energy prices, and how lax or stringent CO_2 emission reduction policies affect industry structures, fuel mixes, CO_2 intensities etc.

For more information:
Johan Torén and **Stefan Wirsenius**
Physical Resource Theory, Chalmers

Further reading:

Torén, J., 2010. Scenarios to 2030 of Energy Use and CO_2 Emissions in EU Steel Industry - An Application of Capital Vintage Modeling Technique. Thesis for the Degree of Master of Science in Industrial Ecology, Department of Energy and Environment, Chalmers University of Technology.

A top-down approach to modelling national energy demand:
example of residential sector space heating

19

Decomposition and econometrics are used to model future energy demand for residential sector space heating, in the context of the development of the economy. The objective of this modelling work is to assess the roles of national trends in personal income, energy prices, carbon taxes, and general energy efficiency improvements. The outputs should provide an alternative yet complementary perspective on the development of energy demand to that obtained from models that focus on bottom-up technologies, se e.g., Chapter 14.

Aim

The aim is to establish a methodology for arriving at a macroeconomic focused prognosis for energy demand for space heating in the dwellings of any given country. The method should allow the use of exogenous inputs, including future prices, future income levels, and future population sizes, to calculate future space heating demands. It should also allow for an analysis of the influences of both efficiency and structural effects on space heating demand.

Method and model

Three equations are used in this model. Equation (1) is similar to the IPAT formula (Chertow, 2001), in that it divides total energy use for space heating in the residential sector into three sub-components. Equations (2) and (3) describe two of these sub-components.

$$E_t = A_t S_t I_t \qquad (1)$$

where E is the total use of energy for space heating (in TWh), A is population in millions, S is the residential sector floor area per capita (in m^2), I is the unit consumption for energy use for space heating per year, measured (in $kWh/m^2/yr$) and t is time (in years).

The first component of Equation (1), population, is an exogenous model input that is available from various sources, e.g., Eurostat (2009). The second component of Equation (1), floor space per capita, is calculated as follows:

$$S_t=(1/Y)_t\,\delta+c \qquad (2)$$

where Y is income per capita (in €), and δ is a coefficient relating floor area per capita to the reciprocal of income and is calculated using time series data for the parameters S and Y and regression software.

The third component of Equation (1), unit consumption for energy use for space heating, is calculated as follows:

$$ln(I_t)=ln(P_t)\alpha+ln(I_{t-1})\beta+(t)\gamma+c \qquad (3)$$

where P is the weighted average price for energy for a year (in €/unit of energy carrier), α is the price elasticity of demand of I , β is a coefficient of the previous year's I (lag in demand), and γ is an exponential time trend coefficient; its value reflects the percentage change per year in unit consumption due to technological development imposition of regulations and other variables not captured by prices and lag.

The values of α, β, and γ are calculated from year-on-year time series data using regression analysis. The use of the log-log regression form means that α is the price elasticity of demand of I. This is the percentage change in demand for space heating that results from an increase in price. Values of less than 1 for price elasticity are interpreted as indicating that the product is inelastic to price change. To obtain an absolute value for I_t, the exponential of the right-hand side of Equation (1) is calculated.

The rationale underlying Equation (1) is to decompose total energy use for heating into a number of components that have varying degrees of influence. The chosen components have been labelled as activity, structure, and intensity indicators by IEA (1997). In this case, the activity indicator (A) is the act of housing people in heated homes and is represented by total population. The structure of this activity reflects how large these homes actually are and is represented by the parameter of floor space per capita (S). The intensity indicator (I) represents the efficiency of space heating, i.e., the energy required to heat a unit of floor space. Combining these three components of population, floor space per capita, and unit consumption of energy for space heating produces the total energy demand for space heating from a macroeconomic perspective, and it reveals the partial influence and role of each component.

In Equation (2), which allows calculation of S, the floor area per capita (the area of floor space that needs to be heated), it is implied that increasing affluence leads to increases in floor space per capita. The reciprocal of income per capita is used to reflect the assumption that floor area per capita approaches an asymptotic limit or saturation level over the coming decades. The reciprocal function provides an estimation of both maximum floor space per capita, in this case represented by the constant *c*, and δ, the coefficient that relates future income to floor space.

Equation (3), which calculates the unit consumption for energy use for space heating per year (I), is designed to capture a number of parameters that influence consumption. The first of these parameters is energy price (P). Increases in energy prices (whether from market developments or the imposition of carbon taxes) should in theory lead to decreases in unit consumption. In practice, this means that if energy prices increase and a home owner or tenant wants to reduce their energy bill, they can decrease the indoor temperature or shorten the duration of home heating. However, energy prices may increase for a specific energy carrier, say oil, and not another, say biomass, which suggests that a home owner should switch from oil to biomass heating when this occurs rather than changing heating habits. Given the investment and temporary disruption that changing heating systems would necessitate, fuel switching would probably not occur very often and then only if there was long-term evidence that one energy carrier would remain cheaper than another. Decreasing the indoor temperature may not be an option if there are no controlling devices on radiators or if a dwelling is already being heated to the minimal level needed for health and comfort. Factors such as these would cause a delayed reaction to price changes, the second parameter that influences unit consumption, and this is incorporated into Equation (3). In practice, delayed reaction to price change can be represented in such equations by assuming that the energy use of the previous year (I_{t-1}), otherwise known as the 'lag of energy use', has an influence on (I_t). In the long run, there are inevitable technical improvements to building thermal efficiency and heating systems, which improve the efficiency of energy use and thereby lower the unit consumption, regardless of price dynamics. These technical improvements occur not only as a result of stricter efficiency standards, but also due to autonomous technical breakthroughs. As these improvements are typically implemented in a buildings renovation cycle, they only happen in a fraction of the building stock in any given year. Nonetheless, these trends are important in the long term, and thus are the third and final parameter incorporated into Equation (3). In practice, long-term technical trends are represented by the time variable (t).To summarise, combining energy prices (P), the lag of unit consumption (I_{t-1}), and a linear trend that signifies technological development (t), together produce the relationship shown in Equation (3) for unit consumption, which reflects macroeconomic influences and technical trends, as well as the reality of the somewhat restricted user options available for the particular case of space heating.

Validity and reliability of the selected method

The methodology is suitable for use with individual countries for which relevant historic time-series data are available. Ideally, the coefficients α, β, and γ in Equation (3) should be calculated using time-series data dating back to at least 1970, so as to incorporate the price spikes of the 1970's caused by the oil crisis and the relatively low prices that prevailed from the mid-1980´s. This diversity of prices should allow for robustness in the coefficients calculated. In contrast, the data for calculating δ in Equation (2) should be from 1980 onwards, as the high construction rate in Europe during the 1970's may exaggerate subsequent estimations of this coefficient.

In econometric terms, the use of a relatively small number of data-points for calculating coefficients from a regression analysis (α, β, γ, and δ), e.g., 35 yearly data-points (from 1970 to 2005), can make statistical significance of coefficients calculated difficult to achieve. One way to increase sample size is to use a panel of time-series combining data for a number of different countries. Given the inevitable influences of the parameters on the right-hand side of Equation (3) on one another, e.g., increases in energy prices encouraging improvements in technical efficiencies, multicolinearity may be a problem. If the time series data categories used are neither stationary nor co-integrated, i.e., prices and unit consumption or income and floor space, Equations (2) and (3) may have to be reformulated to calculate the annual changes instead of the annual totals. The process of calculating annual change can remove the trends in the time-series data that are causing them to be non-stationary.

No feedback loops are included in the components of Equation (1), such as increased energy prices encouraging the purchase of smaller houses or increased energy savings leading to the purchase of larger dwellings. No separate demand functions for heating in single-family dwellings or multi-family dwellings have been made, although it is acknowledged that there are significant differences in the structures of these subsectors. It must also be borne in mind that the demand for space heating may be proven to be inelastic to price change. In such a case, the influence of the technical trend on demand might be much larger.

Application of the method

Three price scenarios (Baseline, Market, and Policy) have been applied to model the effects of increases in carbon taxes on heating in Swedish dwellings. The basis for the three scenarios is described elsewhere in Chapter I while their application to the building sector is described in Chapter 46 in *European Energy Pathways* book.

To construct a similar top-down approach for the non-residential (service) building sector, the population (P) component of Equation (1) could be changed to the number of employees for the sector in a particular country. Similarly, the reciprocal of income per capita (Y) in Equation (2) could be changed to GDP for the sector. Given that there are few countries for which data on floor space in the service sector are available, a simpler solution is to remove Equation (2) altogether, so as to have only two components in Equation (1), either number of employees and energy per employee or GDP and energy per unit GDP. This can be done not only for the sector as a whole, but also for individual branches, such as commercial, education, healthcare, and hospitality, see IEA, 1997. The difference between the approach described here and the more technology-focused models (e.g. Chapter 14) is that the latter do not usually incorporate price or income elasticities or do not base their outputs on historical trends. Such models, which are usually focused on the potentials of individual technologies, invariably show greater achievable savings than the top-down models, such as the one described in the present work. This is due to the fact that top-down models consider future developments based on historical trends, thereby incorporating all of the delays and hindrances to the achievement of technical savings potentials. For example, householders' lack of knowledge of the fact that the technology choices described in bottom-up models are available to them often leads to energy savings potentials not being realised. This contributes to the so-called 'energy efficiency gap' (Jaffe et al., 1994)

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ENPAC, a tool for constructing energy market scenarios

20

Research question

The industrial sector can become a major contributor to increased energy efficiency and reduced CO_2 emissions provided that appropriate energy saving investments are made. The potentials for profitability and net reductions in CO_2 emissions for investments in the industrial sector must be assessed by quantifying their implications within a future energy market context. However, future energy market conditions are subject to significant uncertainty. One way to handle a decision-making that is subject to uncertainty regarding future energy market conditions is to evaluate candidate investments using different scenarios, including future fuel prices, energy carrier prices, and CO_2 emissions associated with important energy flows related to industrial plant operations. Such scenarios are referred to herein as "energy market scenarios". The construction of these scenarios is described in brief below, and a more detailed description can be found in Axelsson and Harvey (2010).

ENPAC, a tool for construction of energy market scenarios

To achieve reliable results from a scenario analysis, the energy market parameters within the different scenarios must be consistent. This implies that different energy market parameters must be clearly related to each other (e.g., via key energy conversion technology characteristics and substitution principles). For the construction of consistent scenarios, a calculation tool that incorporates these inter-parameter relationships is essential. Thus, the Energy Price and Carbon Balance Scenarios tool (the ENPAC tool) was developed. The ENPAC tool calculates energy prices for a large-volume customer in Europe based on forecasted global market fossil fuel prices and relevant policy instruments (e.g., costs associated with emitting CO_2, different subsidies favouring renewable energy sources in the electricity market or the transportation fuel market), and key characteristics of energy conversion technologies in the electric power and district heating sector (Figure 20.1). Required user inputs to the ENPAC tool include fossil fuel prices, charges for emitting CO_2, and support for the use of biomass. Based on these inputs, the marginal technology for electricity generation can be determined by setting the technology with the lowest cost of

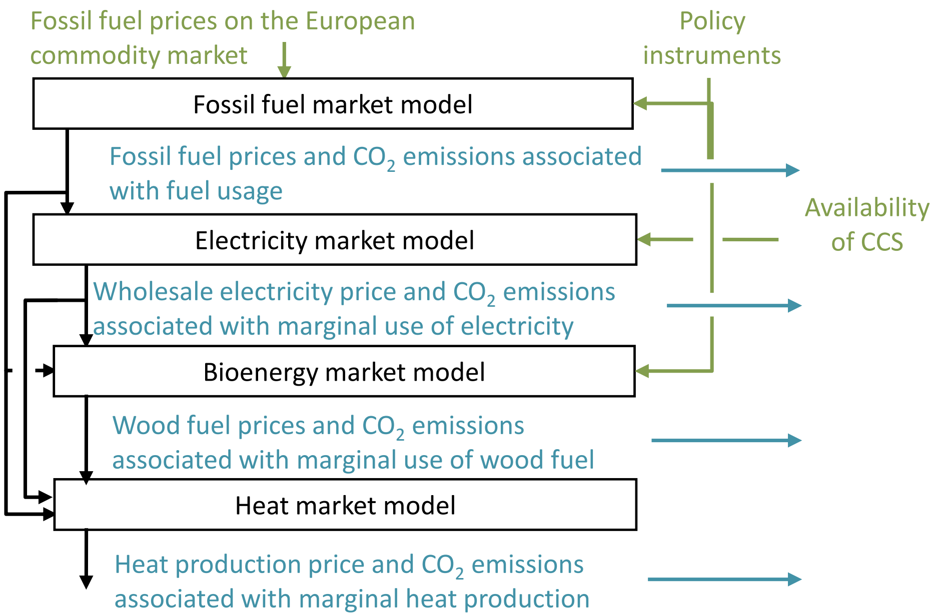

Figure 20.1: Overview of the calculation flow in the ENPAC tool. Green arrows represent required inputs to the tool. Boxes represent calculation units for the different energy markets. Black arrows represent information flow within the tool. Blue arrows represent output from the tool, i.e., energy market parameters.

electricity production as a build margin (box *Electricity market model* in Figure 20.1). The resulting build margin determines the electricity wholesale price and CO_2 emissions associated with the marginal use of electricity. In the next step, the wood fuel market price is calculated based on the willingness to pay for a specified wood fuel user category. Thus, the CO_2 emission consequences of the marginal use of biomass can also be determined by assessing the CO_2 reduction associated with the consumption of biomass for the marginal user (and assuming that biomass is a limited resource). Finally, the willingness to pay for industrial excess heat in the district heating market is determined based on the identified price setting technologies in a representative heat market. Using this procedure, consistent future energy market prices can be determined. Moreover, CO_2 emissions related to the marginal use of energy streams can also be determined.

Validity and reliability of ENPAC

To determine the validity of ENPAC, the resulting energy market parameters have been checked against the statistical data and the results obtained from other groups within the Pathway project. In general, the resulting energy market parameters are in close accordance with the historical values and matching is particularly apparent for fossil fuels. This is not surprising, since the relationships for fossil fuel prices are based on statistical data. However, validation of the tool for biomass fuels is not straightforward, since there is no common European market for these fuel types and there is a lack of reliable statistics. Moreover, recently launched policy instruments that encourage the use of biomass can have a significant impact on biomass prices, and these policy instruments differ across European countries. To cope with this complexity, the tool generates a variety of biomass prices for different marginal users and different policy instruments. With this feature, the biomass prices obtained from ENPAC match the historical values. Price modelling for industrial excess heat is even more complex. Comparison with customer heat prices is not relevant, since these are not directly related to the value of excess heat. Furthermore, the agreed price for industrial excess heat is, in general, a well-kept business secret, making official validation impossible. To overcome this obstacle, ENPAC presents a low and a high market value for excess heat, which can then be used for the assessments.

Above validation against historical data, comparison with results and experiences from more advanced models within the Pathways projects has been done. As an example, the resulting marginal technology and electricity prices from the Pathways ”electricity group” (see Chapter III and e.g. Chapter 1 and Chapter 10 in the *European Energy Pathways* book) have been compared to the corresponding values from ENPAC. In general, the electricity prices resulting from the market simulation calculations conducted by the electric group are somewhat higher than those in ENPAC. However, the difference is small (~10%) and does not necessitate a revision of the ENPAC model. The discrepancy can be explained by the fact that the model, used by the ”electricity group” includes costs for peak load production. For the same reason, these simulations do not identify a single marginal technology, but rather a mixture of marginal technologies. However, the dominating technology in the mixture generally matches the build margin in the ENPAC tool.

The reliability of the resulting energy market parameters is related to the quality of the input values for world energy prices, carbon emission costs, etc. To derive the best available values, IEA (e.g., the World Energy Outlook 2008) and EC (e.g., European Commission, 2008) sources have been consulted. It remains to be seen whether the forecasts from these sources are correct. Nevertheless, the main point of the scenarios is the ability to handle uncertainty by having scenarios that represent different cornerstones of energy market conditions.

Application of the ENPAC tool

The ENPAC tool has been used to produce eight energy market scenarios from 2010 to 2050, with a set of energy market parameters for every decade (see pages 269-270 *in the European Energy Pathways* book). Among others, scenarios reflecting both the Policy and Market Pathways have been constructed. These have been used in the industrial group and building group (see Chapter 37 and 44 in the *European Energy Pathways* book).

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Simon Harvey, Heat and Power Technology, Chalmers

Further reading

Axelsson E. and Harvey, S., 2010. Scenarios for assessing profitability and carbon balances of energy investments in industry. AGS Pathway report 2010:EU1, Göteborg.

The Euroheatspot model:
simulation tool for national district heating analysis

21

Aim

The EU aims to increase the use of bioenergy in all energy sectors. Co-generation of biofuels for transportation and heat and electricity, for example, via biomass gasification, represents an opportunity to increase production and the use of renewable fuels in the transport sector and in heat and electricity generation. To the extent that it replaces fossil fuels (and the biomass has limited greenhouse gas emissions), this will reduce CO_2 emissions in both the stationary and transport energy sectors.

The possibility for biomass-based co-generation of biofuels for transportation and heat for district heating (DH) systems in the EU member states and in the EU25 as a whole has, therefore, been assessed. More specifically, the opportunity for DH systems to act as a heat sink for biofuel production has been estimated.

Model description

The Euroheatspot model is a simulation tool for national DH analyses within the EU. The Euroheatspot model was developed from the Heatspot model (Knutsson et al., 2006) and includes a description of the existing DH systems in the EU25 (represented by the situation in 2003). In the Euroheatspot model, the DH system in each Member State of the EU25 is represented by the aggregated contribution of heat from different energy sources from the individual DH systems of the Member States. The description of the existing DH systems in the Euroheatspot model reflects the assumptions that all the DH systems within a country are connected and thus have the characteristics of this aggregated system.

An input to the model is the description of the DH systems, which includes the sizes of the different heat generation options in the DH systems (in W) and the total national production of DH (in Wh). Data on the existing (i.e., 2003) DH systems in the EU25 was from the compilation made in the EU project ECOHEATCOOL (EHC) (Werner, 2006). When the level of detail required for the Euroheatspot model was higher than that reported in EHC, e.g., concerning which energy source was used, supplementary data were collected from the IEA (IEA, 2005). Energy conversion characteristics for the included heat generation options are also provided. Table 21.1 presents the heat generation options presently available in the DH system.

Table 21.1. Energy conversion characteristics and the order of merit (increase in costs, from top to bottom) for the included heat generation options. The data are based on the description in the Euroheatspot version used in ÖPwC (2005), although some of the values for conversion efficiencies have been updated.

	Total conversion efficiency [%]	Power-to-heat ratio	CO_2 emissions [g/MJ]
Waste CHP	85	0.2	25
Waste HOB (heat only boiler)	85		25
Waste heat (from industries etc.)	100		-
Waste heat from nuclear power, geothermal and solar thermal energy	100		-
Combustible renewables[1)] CHP	85	0.4	-
Coal CHP	85	0.4	93
Combustible renewables[1)] HOB	85		-
Electricity[2)]	300	-0.33	-
Natural gas CHP	90	0.4	56
Petroleum CHP	85	0.4	74
Coal HOB	85		93
Natural gas HOB	90		56
Petroleum HOB	90		74

1) Includes primary solid biomass
2) The use of electricity is assumed to be represented by the use of heat pumps only

The merit order of heat supply options is also included in the model (i.e., the assumed cost relationships between the options) (see Table 21.1) and is most often fixed throughout the modelling. The inclusion of the merit order means that the relative costs of the different heat supply options are taken into consideration. The reasons for not including specific cost estimates are that: (i) cost estimates for emerging heat supply options, which may be assessed in the model, are uncertain because these technologies are not yet commercialised on large-scale; and (ii) future costs for all heat supply options depend to a large extent on the development of new policies, which may differ between countries.

In the Euroheatspot model, the national DH systems are described by a heat load duration diagram, in which the heat supply options in the system are placed in the specified order of merit and are ranked by size (illustrated in Figure 21.1a). The same annual load curve (describing the duration, i.e., hours of use over the year) is used for all countries. The shape of the annual load curve is based on the representation of the Swedish situation used in ÖPwC (2005), as this is considered to be a fair representation of the average situation in the EU. This may over-estimate the base load heat generation in southern EU countries with longer summers and over-estimate peak load heat generation in countries with more even annual heat generation capacity. The maximal annual operation time is assumed to be 8,000 hours. The installed capacity (in MW) for each included heat supply option, corresponding to the compiled production level in each country, is estimated by using an analytical expression that represents the annual load curve.

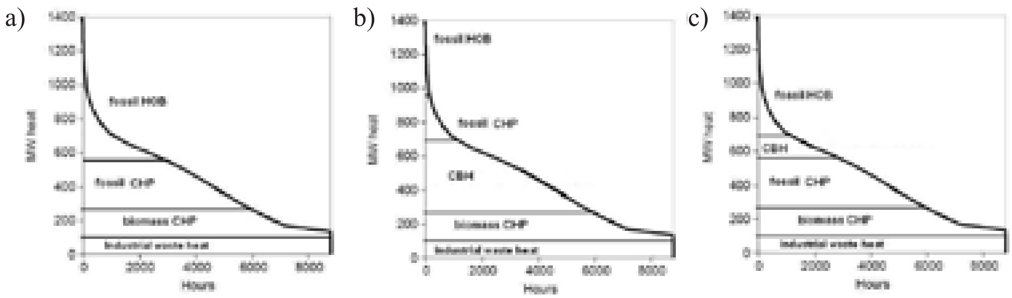

Figure 21.1. The Euroheatspot model. Heat load charts for aggregate heating systems and changes in heat sources for all European countries when a new type of technology (biofuel/heat/cogeneration, CBH) is introduced. (a) An existing DH system; (b) a system in which heat from the CBH is placed before fossil CHP; and (c) a system in which heat from the CBH is placed after CHP. Source: Egeskog et al. (2009).

The Euroheatspot model may be used to analyse the potential for a new technology depending on its merit order ranking, as well as the effects of its introduction on the DH systems production mix and emissions. Figure 21.1 b-c illustrates how the model works, based on the example of the *biofuel/heat cogeneration* (CBH) technology. The CBH option is introduced at two different positions in the merit order:

- *Before the fossil CHP scenario*: CBH is assumed to be more competitive than coal-based CHP, i.e., it mainly replaces fossil-fuel-based heat options. In this scenario, the introduction of CBH affects electricity production from fossil fuels. This is because all fossil CHP heat supply options are pushed upwards in the merit order, which means that they can no longer deliver the same amount of heat as they used to.

- *After the CHP scenario*: CBH is more competitive than fossil-fuel-based HOB only.

When a certain capacity of CBH is introduced into the existing DH systems, the heat supply options with higher production costs will be pushed upwards in the duration diagram, to make space for the specified capacity of the introduced CBH. The heat supply options that are pushed upwards may have the same installed heat capacities as before, although a higher position in the diagram represents a shorter production time.

Application of the Euroheatspot model

In the Pathways project, the Euroheatspot model has been applied to study the possibilities for CBH in the existing and future DH systems in the EU Member States (see Chapter 36 in the *European Energy Pathways* book). The model was used to compare the potentials of the different national DH systems to accommodate heat from CBH plants with a biofuel production capacity that corresponds to the levels stipulated by the EU 2020 renewable transportation target.

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Further reading

Berndes, G., Hansson, J., Egeskog, A., Odenberger, M., 2010, Bioenergy strategies for Europe - synergies and competition between the stationary and transportation sectors.

Berndes, G., Hansson, J., Egeskog, A., Werner, S., 2008. Bioenergy expansion strategies for Europe - Cost effective biomass allocation and biofuel steppingstones. REFUEL WP5 final report. Chalmers University of Technology, Göteborg.

Using the EMER model to merge results from the different research groups into pathways

22

Aim and research question

In the Pathways project, various research groups study the development of a sustainable energy system from different perspectives. These analyses consider, for example, legal and business aspects, as well as possible technology-related developments in different sectors of the energy system. The results of these analyses have been considered when constructing the comprehensive ”Pathways towards Sustainability”, as described in Chapter I. An important building stone of the multidisciplinary syntheses is a more technical synthesis of all the numerical results describing the development of the energy system. The technical synthesis includes means to gather and merge all the technical results into an overall development and to ensure consistency, e.g. between supply and demand.

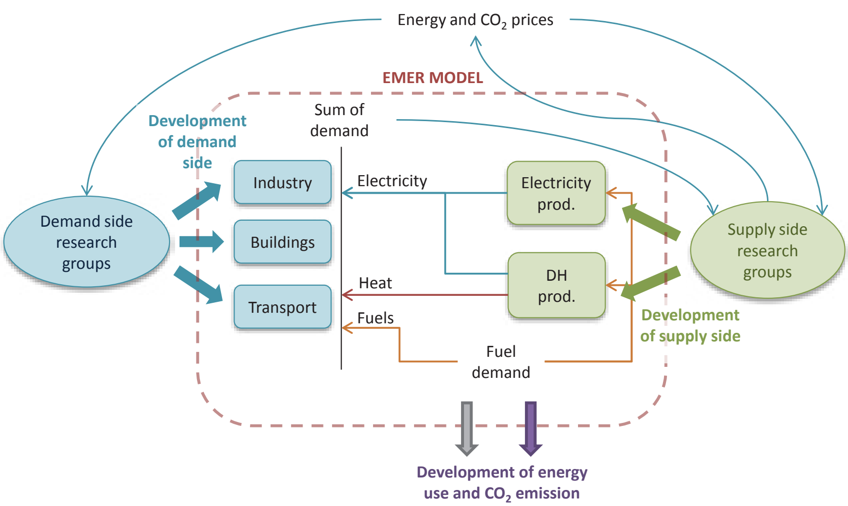

Figure 22.1. Simplified overview of the EMER synthesis model. Development of energy use and production, according to results from the different research groups in the Pathways project, are merged in the model to ensure consistency and to establish an overall development.

EMER, a tool for merging technical results

To gather and merge the numerical results, a spreadsheet model in Excel was developed. This model, the Energy Merge model for Europe (EMER), is a simulation model that administers the production and consumption of energy carriers in the different energy sectors (Figure 22.1). The input to the EMER model consists of the numerical results for the development of the sectors, as obtained from the different research groups in the Pathways project. In the EMER model, total energy use and production are summed and compared, to ensure balance. Any necessary adjustment, for example in electricity production, is done iteratively in close co-operation with the concerned research group. The EMER model also calculates and summarises the total primary energy use (by type and year) and annual CO_2 emissions (considering CCS). This provides an opportunity to follow-up the realisation of the sustainability targets for the European energy system in its entirety. In cases where the results from the research groups were not sufficient to create a complete picture (e.g. the transport sector, for which there is no research group within the Pathways project), the results were complemented using external sources, e.g., results from the Primes model of the European Commission.

Validity and reliability of EMER

The EMER model has played an important role in the soft linking of the research groups within the Pathway project. As already described in Chapter I, there has been a close dialogue with the researchers, and their results have dictated the input data to the EMER model. The output from EMER has in turn been communicated back to the groups. Thus, the construction of the presented pathways has been accomplished in a soft linked iterative way. During this process, the results of the EMER model have been validated against other models and results within the Pathways project. Moreover, the process has allowed for validation of the results from the research group, e.g., concerning cross-sectorial interactions and against the energy system as a whole. For instance, sector-specific questions, such as "Does the development of the electricity and district heating sectors match the development of the demand-side sectors?", and system-specific questions, such as "Are the efforts adequate to reach the overall targets?", could be answered in this process.

The reliability of the resulting pathways is closely related to the quality of the input values from the different research groups. The quality of the individual results as such is not discussed in this section (but can be found in other sections in this book). However, on a synthesis level, another important aspect of data quality is consistency between the sectors concerning the costs and goals of improvement measures. This means that measures to reach the common sustainability target must include balanced distribution between the sectors. In the Market Pathway, the implication could be that all sectors implement the most cost-effective measures to achieve a marginal CO_2 cost that is common to the whole system. To achieve this in the Market Pathway, common energy prices and the CO_2 cost have been used by the research groups (Figure 22.1) for all the included sectors.

Common energy and CO_2 prices are also assumed in the Policy Pathway. In this pathway, strong policy instruments are, in addition, assumed for implementing energy efficiency measures and conversion to renewable energy sources. However, allocation of the common target between the different energy sectors is not straightforward, and it must be assigned by the modeller. In this work, the target is allocated according to the assessed potentials in the different sectors. For instance, it is assumed that a transformation to renewable energy sources requires less effort if it is done in the electricity sector than if it is done in the industrial sector. Therefore, a higher renewable target is set for the electricity sector than for the industrial sector.

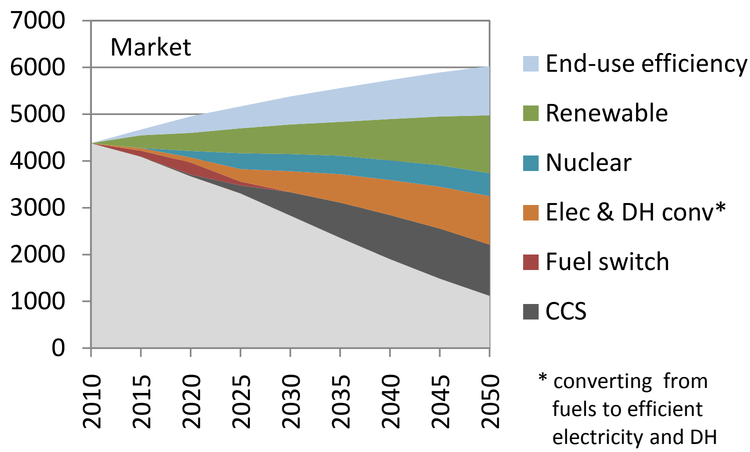

Figure 22.2. Results example: wedges in the Market Pathway.

Application of EMER

The EMER model has been used to produce two pathways towards sustainable European energy systems: the Policy and the Market Pathway, respectively (see page 5 in the *European Energy Pathways* book). Furthermore, a baseline scenario has been established that facilitates the construction of “wedges” (see Figure 22.2) and the follow-up of energy-saving targets.

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Assessing the end-use energy demand in the EU building stock: a top-down technological model

23

Aim

A model has been developed that gives a comprehensive description and calculation for the total building stock in Europe, and its final and useful energy end use over a long period. The model covers dwellings and service buildings (official as well as commercial services).

The Pathways' studies of the building sector use a methodology that combines bottom-up and top-down models to assess the impacts and potentials of end-use efficiency, conservation, fuel switching, and carbon prices on energy use in the EU buildings stock. As the amount of basic data on the total building stocks in all countries is substantial, including their physical properties, equipment, energy end uses, and fuel mixes, an overall "technological" model has been developed that can handle all these datasets and model results, and that allows examination of the results in a comprehensive way.

Method and model

The top-down technological model uses two Excel sheets for each country or group of countries. One sheet contains all the input data, including the properties of the stock in the starting year and the assumed rates of efficiency measures etc. over the calculation period. The input data include:

- Floor areas for dwellings and service buildings in the starting year
- Final energy use per fuel/electricity for space heating, water heating, cooking, appliances, and electrical equipment in the starting year
- Conversion efficiencies, which are used to calculate useful energy from final energy
- Assumptions regarding the rates (percent per year) of future standard increases in energy demand
- Assumptions regarding the rates (percent per year) of future efficiency measures

- Assumptions regarding the future development of the stock (new buildings, demolition)
- Energy requirements for new buildings

Separate values can be introduced for the future development of standard increases in heating and electrical equipment, as well as for annual increases in the energy efficiencies of heating and equipment. All such developments can be assumed to be either the same over the total period or individual assumptions can be made per 5-year period. Energy efficiency measures can be divided into various types with various efficiency improvement rates, if the relevant data are available.

A pronounced feature of the model is that it separates standard increases from efficiency improvements. Standard increase is defined as a higher demand for a service, i.e., higher room temperature or more television sets per m^2, while energy efficiency improvement refers, for example, to insulation that enables a certain indoor climate with less energy, or the same kind of TV with lower electricity use.

The second Excel sheet composed for each country in the model includes the calculations made for the above-mentioned input data, and a presentation of the results. Calculations are made for each 5-year period up to the year 2050, and the results are shown in terms of floor areas and end-use energy for each period. For space and water heating, useful energy is calculated first. Future fuel mixes are then introduced, resulting in the final energy value per fuel and electricity.

Validity and reliability of the model

The model is a tool that allows straightforward calculations of the volume of the stock, the corresponding energy end use, and changes in these parameters over time. The validity and reliability of the model depend on the quality and relevance of the input data and the assumptions introduced for future development. To verify our model, input data for 2005 from GAINS (IIASA, 2010, see also below) was introduced into the model, and the result for the year 2030 was compared to the GAINS results for 2030 (i.e., the final year of GAINS). When comparable assumptions of efficiency rates etc. were employed, the results in terms of total end use energy were very similar.

The model outputs of this "technological" approach can be compared with those from models that use alternative approaches, such as top-down econometric models (see Chapter 19) or bottom-up technology-focused models (see Chapter 14). Although the results from the mentioned studies do not cover all the EU countries in the Pathways project, their results regarding, for example, the rates of efficiency measures in certain countries have been checked against this calculation, revealing similar values.

The advantages of the technological model are that it focuses on the potential of energy efficiency improvements in the context of increasing floor space and standards of living. The model is simple to use, and it offers a complete picture of future energy demand. The disadvantages of the model are that it does not incorporate economic influences or the potentials of individual technologies. Such influences have to be studied separately, and then introduced as, for example, annual changes in specific energy end use.

Application of the model and method

The present calculation was performed for eight individual countries (France, Germany, Ireland, Italy, Poland, Spain, Sweden, and the UK) plus one calculation for the remaining countries, giving results for the EU27 as a whole. The eight countries represent about 75% of the total energy use in the EU. The calculation performed in the Pathways project covers the period from 2005 to 2050 (see results in Chapter 44 in *European Energy Pathway* book).

The basic data are generally taken from the GAINS database (IIASA, 2010), which contains most of the required data for the baseline year (2005), as well as forecasts up to 2030. Developments to 2050 have generally been assumed to follow the trends from the previous decades. In some cases, e.g., Sweden, more detailed data than those in GAINS are available and have been utilised. An advantage with GAINS is that it contains assumptions of future development of standard increases separated from efficiency improvements, which are usually hard to find. In general, the GAINS database has proven to be very useful for the present application.

The model has been used in the calculations of the three scenarios covering all EU27 countries. The scenarios are further defined in Chapter 44 in the *European Energy Pathways* book.

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Synthesising studies of industrial energy use

24

Research question

Analyses of industrial energy use can be based on a wide spectrum of methodological approaches. The challenge is to utilise fully the knowledge gained in a range of such studies, so as to reach a coherent and well-founded synthesis for the entire industry. Therefore, the purposes of the methodology are to synthesise and discuss the results for industry, derived using different methodological approaches, and to relate the results to the overall pathways towards sustainability. Finally, the synthesis provides a basis for future coherent and extensive systems analyses of the entire industrial energy system.

Analysing industrial energy use from two perspectives – the methodology

Within the Pathways project, the development of specific industrial sub-sectors and/or types of measures for reducing emissions is studied in great detail in a number of bottom-up analyses. Furthermore, a top-down analysis of the European industrial sector as a whole has been made. A synthesis concerning the development of industrial energy use has been performed in the following three steps (see Andersson and Nyström, 2010):

- Establishment of a starting point for the development of industrial energy use, based on the results from the top-down industrial model.
- Provision of a coherent overview of potential changes in energy use and CO_2 emissions, based on the bottom-up analyses.
- Correlation of the top-down and bottom-up results, to estimate a development path for each of the pathways used.

The starting point for the synthesis is the results obtained using the top-down model of European industry, in which the contribution of industry to CO_2 emission reductions is estimated (Figure 24.1). This analysis does not take sector-specific constraints and conditions into account, but rather gives a general indicator for the development of industrial energy demand, given certain levels of development of production and energy markets. Furthermore, for the synthesis, it provides a necessary complement to the bottom-up analyses, since the latter do not include all sub-sectors and aspects of development.

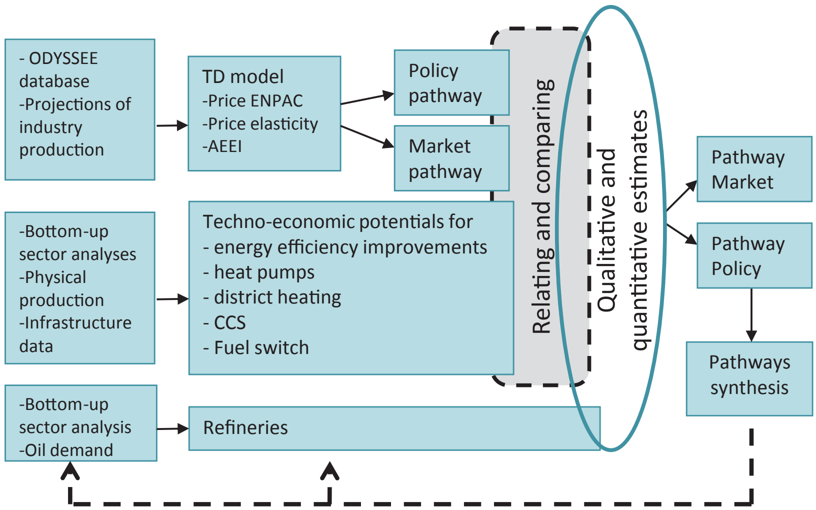

Figure 24.1. Outline of the synthesis methodology.

The other approach used is based on a range of bottom-up (or hybrid) estimates of techno-economic potentials for emission reductions within each single industrial sub-sector. The Pathways results give the basis for this approach, especially for the energy-intensive industrial sub-sectors, and they are complemented with data and results from the literature. The refinery sector is not included in the top-down model and is therefore analysed from a bottom-up perspective only.

For each industrial sub-sector (e.g., the primary metals sector), the contribution to changes in total CO_2 emissions are discussed. The contributions can be divided into the following types of changes:

- Changes in production volume.
- Structural changes – between industrial sectors and within a specific sector.
- Energy efficiency improvements, resulting in lower net energy use per produced unit.
- Decreases in CO_2 intensity of energy use, achieved through increases in the share of less-CO_2-intensive energy carriers or through carbon capture and storage (CCS).

In the final step, the top-down and bottom-up results for each industrial sub-sector are related to each other, and the developments for the Policy and Market Pathways are estimated. The pathways differ in terms of the energy policies implemented, which have direct impacts on the levels and types of measures that can be expected to be implemented, thereby affecting the techno-economic potential.

This industrial synthesis is primarily qualitative, in that it includes a discussion about the orders of magnitude and types of measures included in each of the approaches. The discussion focuses on which principal adjustments of the top-down results are needed to account for the sector-specific results of the bottom-up analyses. Four types of adjustments are discussed: 1) adjustments of the baseline development, in cases with non-realistic development, reflecting the lack of sector-specific constraints in the top-down model; 2) adjustments to the levels of energy efficiency improvements, when technical potentials found in detailed sector analyses are not compatible with the top-down results; 3) adjustments to account for policy effects that are not included in the model, e.g., different types of non-economic policies; and 4) adjustments to account for some specific technological shifts that are less likely to be accounted for by historical values for elasticities and AEEI. Examples include fuel substitution for biomass and the introduction of CCS.

Finally, based on the qualitative discussion, a rough quantitative estimate is made. The purposes of this estimate are to derive the order of magnitude for the industry's contribution as a whole and to provide the input necessary for constructing the Pathway synthesis of the entire European energy system.

Validity and reliability of the industrial synthesis

Even though the methodology described above seems to be fairly straight-forward, in reality it represents highly complex relations. The industrial sector is extremely diverse and heterogeneous, both in terms of products, processes, and the types of energy used. Consequently, analyses of potential future developments of energy use and CO_2 emissions from the industry are complex and the associated uncertainties are significant. Producing valid results from bottom-up analyses for future industrial energy use involves, for instance, relating potential improvements to future production volume and structure and understanding to what extent different measures are additive. To estimate potential implementation, it is also necessary to take aspects, such as the dynamic timing and infrastructure, into account. Synthesising results from different bottom-up analyses amplifies the overall complexity.

Synthesising the results obtained using fundamentally different approaches, such as the top-down model and the detailed bottom-up analyses included in the Pathways project, entails further inherent difficulties (see also Algehed et al., 2009). Two specific aspects that are directly connected to the differences in methodologies are: 1) the development of production volume; and 2) the basis for comparison. The development of production volume in the top-down analysis is based on projections of value added, which it is assumed will continue to increase. However, the implications for physical production are not defined. In contrast, the bottom-up analyses can be related to physical production exclusively. The basis for comparison is a baseline development without sustainability targets. However, energy efficiency improvements would take place also in such a baseline development. In the top-down model, these are included as part of the effects of the AEEI and price elasticities. How these efficiency improvements relate to the bottom-up potentials are, however, not evident.

Aside from the above considerations, the main purposes of the synthesis are to discuss the industry results based on methodological approaches and to describe the types and orders of magnitude of potential contributions to CO_2 reductions from the industry for specific pathways. These purposes are fulfilled. Nevertheless, the final values presented are highly uncertain and should be used with caution.

Application of the methodology

The synthesis methodology was used to describe the overall development of industrial energy use and the industry's contribution to the reduction of CO_2 emissions, see Chapter 37 in the *European Energy Pathways* book. The results are used as inputs to the overall Pathways synthesis, and will be used as the basis for continued coherent and extensive systems analyses of the entire industrial energy system.

For more information:
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Further reading:

Andersson, E., Nyström, I., 2010. Opportunities for reducing CO_2 in European industry until 2050 - a synthesis of industry analysis. AGS Pathway report 2010:EU3, Göteborg.

Evaluating competitiveness of district heating using a distribution capital cost model

25

Aims and research question

The overall research question in the Pathways project regarding district heating addresses in a general way how district heating (DH) can contribute to sustainable development in Europe. The methodology and model description presented below refer in particular to the question of how energy efficiency measures in buildings alter the prerequisites for DH expansion. The full analysis is documented in Persson and Werner (2011).

The central aim was to evaluate the competitiveness of present and future DH systems, as residential and service sector heat demands are expected to decrease in the future. This overall aim was formulated in the following three research questions: (i) What are the current distribution capital cost levels and the possible district heat market shares in European cities; (ii) By how much will distribution capital costs increase when future heat demands decrease; and (iii) How will this increase influence the future heat market shares for DH?

Methodology

The methodology initially involved a theoretical reformulation of the traditional expression for linear heat density (Brachetti, 1984; Frederiksen and Werner, 1993; Schulz, 1933; Simon, 1950), which enabled the modelling of future district heat distribution capital costs through the use of alternative data categories (independent input parameters: population density, specific building spaces, and specific heat demands). Traditionally, linear heat densities (the quota of annually sold heat and the network trench length) could only be established for existing DH networks. Therefore, this initial theoretical approach was important in facilitating linear heat density estimations for future district heat locations.

To produce the final results, complementary input parameters, such as effective width (Persson and Werner, 2010), construction cost levels (Svensk Fjärrvärme, 2007), pipe diameters (Frederiksen and Werner, 1993), and annuity, were estimated based on previously gathered data, statistical information, and assumptions. For the modelling of the four studied countries, independent input parameter information was gathered from the Urban Audit 2001 database (Eurostat, 2009), the IEA energy balances for OECD countries 2006 (IEA, 2008), and other complementary sources on housing statistics in the European Union (e.g., Italian Ministry of Infrastructure, 2006).

Recalculations of the model-derived estimates – based on altered specific heat demands – were performed to assess the consequences of reduced future heat demands. As such, the study of the 1703 city districts in 83 cities in Germany, France, Belgium, and The Netherlands is a descriptive analysis of present demographical and economic conditions for DH establishments, generating somewhat normative results with regard to the relationship between present and future investment conditions.

Model description

The main output parameter of the distribution capital cost model is the annual distribution capital cost, C_d [€/GJ], for DH network investments. In general terms, the distribution capital cost is estimated to constitute more than half of the total distribution cost for a typical DH network. The Excel-based model tool produces additional outputs, among which the total network investment cost levels, total heat demands, linear heat densities, and pipe lengths of target areas are of key interest. An overview of the model is presented in Figure 25.1.

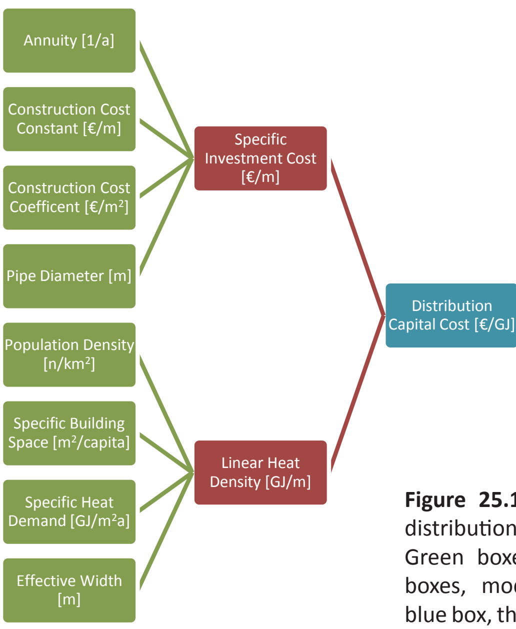

Figure 25.1. Overview of the distribution capital cost model. Green boxes, input data; red boxes, model estimates; and blue box, the output parameter.

Within the model, three determining heat density area characteristics categories are elaborated, i.e., inner city areas (high), outer city areas (moderate), and park areas (low), with the associated residential living area and land area ratios (plot ratios). The plot ratio (e) expresses the building density within a city area, and according to traditional Swedish city planning (Statens Planverk, 1985) plot ratio values are established for typical city categories, as shown in Table 25.1. The plot ratio was used as an intermediate parameter to estimate both the construction cost levels and the effective widths.

Table 25.1. Plot ratio definitions of characteristic areas, associated construction cost levels, and the distributions of the studied city districts.

Area characteristics	Plot Ratio (e)	C_1 [€/m]	C_2 [€/m]	Number of city districts in study
Inner city areas	e ≥ 0.5	286	2,022	317
Outer city areas	0.3 ≤ e < 0.5	214	1,725	296
Park areas	0 ≤ e < 0.3	151	1,378	1,090

Validity and reliability of the distribution capital cost model

With regard to the independent input parameter data (population density, specific building space, and specific heat demand) gathered from aggregated databases, the reliability of the model is naturally dependent upon the accuracy of the statistical records. Furthermore, the model data used for effective width estimations were based on less than 100 observations, and would benefit from extended research. Model output projections are the combinations of marginal distribution capital costs and the corresponding heat market shares, consecutively sorted from the lowest to the highest marginal distribution capital cost, as exemplified in Figure 25.2.

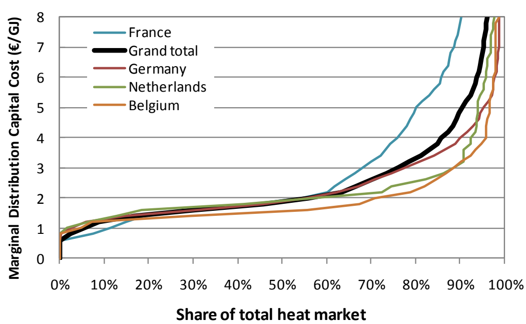

Figure 25.2. Current marginal distribution capital cost levels and the corresponding district heat market shares in the four studied countries.

Uncertainties in the model-produced outputs could come from possible deviations in other estimated input values and assumptions. These major deviations might include:

- DH companies having planned rates of returns higher than the levels represented by the assumed annuity (3% for 30 years in the study)
- The construction cost levels used in the study come from a mature DH country (Sweden), while the cost levels could be higher in novel DH countries
- Lower construction cost levels from future alternative pipe materials and network technologies (fourth generation of DH networks)
- Future city shapes other than those represented in the 2001 Urban Audit database (Eurostat, 2009).

Application of the distribution capital cost model

Given that all the input data parameters in Figure 25.1 are available, there is no limit to the applicability of the distribution capital cost model. The core feature of the model is the possibility to produce specific DH investment cost levels for areas and locations that do not currently have DH. This feature of the model emerged from the initial reformulation of the traditional expression for linear heat density into four attainable independent variables that allow estimations of future DH system heat demands. See also Chapter 33 in the *European Energy Pathways* book.

For more information:
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Further reading:

Persson, U. and Werner, S., 2011. Heat Distribution and the Future Competitiveness of District Heating. Appl. Energy 88:568-76.

Persson, U. and Werner, S., 2010. Effective Width – The Relative Demand for District Heating Pipe Lengths in City Areas. Paper presented at the 12th International Symposium on District Heating and Cooling, Tallinn, Estonia. September 5th to 7th.

Assessment of district heating development in EU27

26

Research question

District heating (DH) facilitates the efficient use of energy resources, as well as the conversion to renewable energy resources for building heating. For instance, DH plants can utilise renewable fuels that are unsuitable for small-scale use (e.g., tops and branches as well as, waste fractions). In addition, the excess heat from industrial operations, electricity production, and waste incineration can be utilised for building heating if a DH system is in place. DH systems are also flexible, in that they can use the above-mentioned and other energy sources for heat production. Small-scale heat production normally does not show the same level of flexibility. Therefore, DH has a competitive advantage over many other heating options in an energy system that strives for resource efficiency and a high proportion of renewable sources. Considering these issues, and the fact that there is strong potential for DH in many European countries (Werner, 2006a), one can conclude that DH can play an important role in a sustainable energy system and may be considered as an important energy infra-structure in such a system. Thus, the development of the DH sector is crucial for the construction of pathways towards sustainability. The question to be answered is "What would the development of the district heating look like in the Policy and Market scenarios, respectively?"

Country wise bottom-up analysis

To assess the development of the DH sector within the EU27, a country-based bottom-up approach was applied. This means that the scope was broken down to assess initially the development of the DH sectors in the individual countries. Subsequently, the development of DH in the included countries was collated, to produce an overall picture for Europe. To assess the development of DH in all 27 countries of the EU was beyond the scope of this subproject. Instead, the eight most important countries (Finland, France, Germany, Italy, Poland, Spain, Sweden, and the UK) were treated individually, and the remaining countries were treated as one unit ('eight plus one regions'). These eight countries include the largest European countries, account for 65% of the current DH production in the EU27, and are the countries with the greatest potential for increased application of DH, according to Werner (2006a). The selection of countries was in line with that performed in the Pathways ”Buildings group”, which facilitates co-operation which this neighbouring group.

Current situation

First, the current DH situations in the eight plus one regions were investigated by consulting a variety of sources, such as Euroheat and Power (2010), SNCU (2009), AGFW (2007), AIRU (2006), Svensk Fjärrvärme (2007), and Egeskog et al. (2009).

Growth potential

Second, the economic potentials for DH in the nine regions were assessed. An optimistic value of the potential of DH was achieved by assuming that 80% of urbanized areas could be served by DH (see high potential for DH in Figure 26.1). DH coverage of 80% or more exists in cities with fully developed DH systems, such as Gothenburg and Uppsala in Sweden. A steady rate of urbanisation (based on extrapolation of the reported historical values; World Bank, 2010) implies that the economic potential of DH, as defined here, increases with time.

To establish a more conservative value for the economic potential of DH, the work of Persson and Werner was consulted. Persson and Werner assessed the potential market share for DH in urban areas, and showed that it decreased with energy savings in buildings and increased in line with willingness to invest in DH distribution networks, i.e., the allowed distribution cost (see Chapter 33 in the *European Energy Pathways* book). The results of Persson and Werner were used to formulate a mathematical relationship in which the allowed distribution cost and development of energy use in buildings were used as inputs to calculate the development of DH market share in urbanised areas with central heating (since central heating is essential for a successful conversion to DH). The country-wise results of Persson and Werner were used to develop a country-wise adoption of the market share, which depended upon the size and density of the cities in the eight plus one regions. The resulting development of the market share in urban areas for a particular country had to be multiplied by the degree of urbanisation and the share of central heating in that country, to establish the development of the lower economic potential for that country. The share of central heating was based on figures from Werner (2006b) and the Odyssee database (2010).

Development of DH demand

With the high and low levels of development of DH potential in the eight plus one regions in hand, the third step was to establish the development of DH demand for the Policy and Market Pathway. For this, assumptions regarding the expansion rate for DH had to be made (Figure 26.1). In Sweden, the annual expansion rate since 1970 has been approximately 1% (Swedish Energy Agency, 2009a). Based on this, the growth rate up to the lower economic potential was set at a maximum of 0.6% per year for the Policy Pathway and 0.8% per year for the Market Pathway, so as not to overestimate the growth rate. When the lower economic potential is reached, a much lower expansion rate is expected. Thus, the growth rate up to the higher potential was set to approximately 10% of the growth rate to the lower potential. Country specific adjustments of the growth rate were made and were based on country wise heat market analyses. In this way, the development of DH demand was established in the ”eight plus one regions”, as illustrated at the bottom of Figure 26.1.

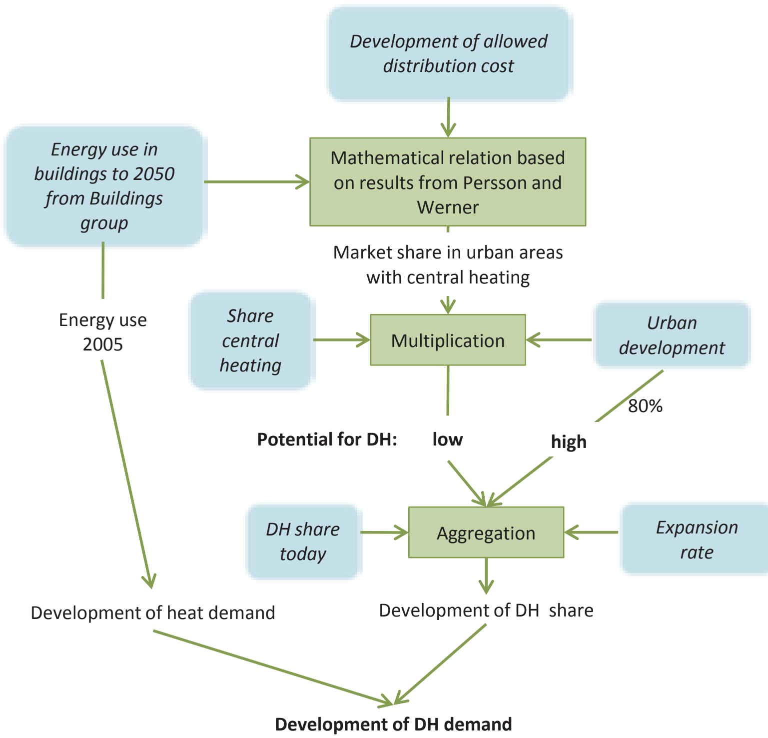


Figure 26.1. Illustration of the used method for assessing the development of DH in a specific country. The text in blue boxes represents input data, and the green boxes represent calculation steps. Arrows illustrates information flow.

Development of DH production

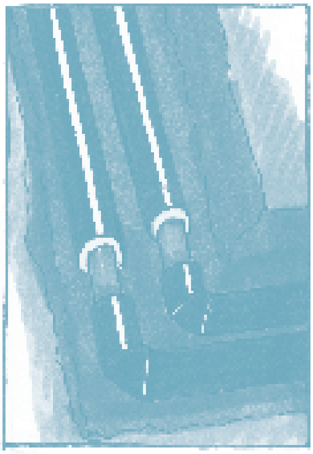
Increased demand for DH and the decommissioning of old units has to be met by new production units. If new units are cleaner, cost-effective development towards sustainability can be achieved. For establishing the development of production technology in the two pathways, country specific analyses of the heat market were performed. In this analysis official reports were also included, e.g. reports from Euroheat and Power (2010), SNCU (2009), AGFW (2007), AIRU (2006), and the Swedish Energy Agency (2009b). Also, information from branch agencies were consulted, and personal communications were established with branch agencies and other experts. There was also close co-operation with other groups in the Pathway project, e.g., the ”Electricity group”, the ”Buildings group”, and the ”Waste Management” group. From all these sources, plans, and intentions, the potentials and possibilities could be derived, which gave a broad base for establishing the development of DH production in the eight plus one countries in the two pathways (see also Chapter III).

Validity and reliability of the method

The approach described above was used to establish the possible developments of the DH sector that would reflect development towards a sustainable energy system. As is the case with other models of future development, the present model cannot easily be validated in its entirety. However, some parts of the results can be validated. For instance, the calculated high and low potentials for DH in each country can be compared to current status reports (Euroheat and Power, 2010; Werner, 2006a). The fit is good, and the countries in which DH is reported to be fully developed (Finland, Poland and Sweden) have exceeded the lower potential derived from the described approach. There is also agreement between our results and the reported potential regarding which countries have good expansion opportunities (i.e., Germany, France, and the UK).

Concerning the development of DH production, we have not used a common strict algorithm (for instance, one based on cost minimisation in different investment options). Instead, the development is based on the experience of development to date and, as already mentioned, on country specific heat market analyses, including plans and possibilities, as well as the results from the other groups within the project.

Regarding reliability, some crucial input values can be discussed. For instance, the calculated market share is quite sensitive to the development of the allowed distribution cost, which has been assumed to follow the price of natural gas (reduced by 25%). If instead one assumes no increase in the allowed distribution cost, the resulting market share decreases significantly (due to energy savings in buildings). The development of energy use in buildings was assessed by



the ”Buildings group” (see Chapter 44 - 46 in the *European Energy Pathways* book), and is reasonable for a sustainable pathway in which energy savings are crucial. In addition, the used ”Urban development” is reasonable. The ”Share of central heating” was assumed to remain constant throughout the whole period (to 2050). It is possible that the share of central heating will increase as the building stock is renewed, especially if sustainable development and DH is in focus. This implies that the lower potential for DH will increase. However, since no basis for such a development was found, a constant value was assumed. The last input to be considered is the ”Expansion rate”. As already stated, this value was assumed to be lower in both pathways than the actual value for DH in Sweden, so as not to exaggerate the development.

Application of the method

The above described method has been used to establish the development of the Market and Policy Pathway; see Chapter 32 in the *European Energy Pathways* book.

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This book describes the methods and models used to achieve the results presented in the **European Energy Pathways** book.

Scenario analysis of the European waste management system

27

Aim

The first aim was to quantify the possible future energy recovery from renewable waste fractions, which may contribute to EU targets regarding renewable energy and decreased emissions of climate-altering gases. The following question was posed: ”To what extent can energy from renewable waste fractions contribute to the EU targets for renewable energy and decreased emissions of climate-altering gases?”

The second aim was to identify possible pathways for the needed shift in waste management, from landfilling to alternative waste treatment methods, so as to reduce the environmental impact of waste. The question was: ”How can the waste managment system develop under given scenarios?”

Method description

The method used in both studies (see below) is based on scenario analysis. Scenario analysis is a methodology to explore and/or to illustrate possible developments in the future, taking into account alternative possible upcoming developments. The Global scenario group (2010) states that “scenarios help us to explore where we might be headed”. This methodology can be a way to analyse in a structured way an uncertain future.

Application of the method

The methodology has been applied in the studies presented in Chapters 29 and 30 in the *European Energy Pathways* book.

Chapter 29: Energy from waste - potential contribution to EU targets

The future potential of energy recovery from waste is evaluated in two scenarios:

1. The *Total potential scenario* estimates the full potential of recovering energy from the renewable waste quantities in year 2020. The considered energy technologies are combined heat and power plants (CHP), heat-only plants, and condensing plants for electricity production only. The changes in waste

management systems pre-suppose large investments in both incineration plants and district heating systems.

2. The *Reasonable growth scenario* refers to the reasonable growth of waste-to-energy capacity in Europe, based on the historical growth rate. Between 1995 and 2005, the waste-to-energy capacity increased to a total of 13 Mtonnes, corresponding to a growth rate of 1.3 Mtonnes/year. This annual growth rate is assumed to continue from 2006 to 2020.

The starting point for both scenarios is the current estimated energy recovery from the renewable waste stream of 52 TWh in Europe (year 2006). From this, future waste quantities and potential energy recovery are estimated.

Chapter 30: Pathways for European waste management

Three pathways for the European waste management system are explored:

1. A policy-driven scenario, in which strong policy measures are introduced in order to decrease landfilling and to increase alternative waste handling methods with less environmental impact. Such measures include producer responsibility, a ban on landfilling of specific waste streams, and measures to stimulate waste minimisation or waste prevention.

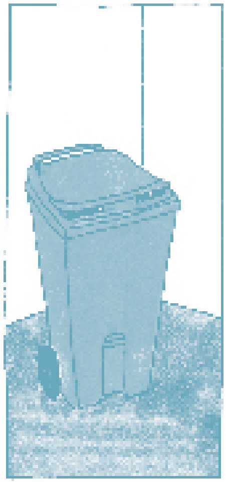
2. A scenario driven by market mechanisms to stimulate energy recovery from waste and decrease landfilling. This could include support schemes, such as investment aid, electricity certificates or feed-in tariffs, and might be achieved through the introduction of recycling certificates, as proposed in Sweden (Bisaillon et al., 2009).

3. A third scenario assuming a limited decrease in landfilling represents a more moderate change of the European waste management system. This is based on fewer policy measures in place, as well as weak market conditions for the alternatives to landfilling.

Validity and reliability of the method

Scenario analysis, which is a methodology that is typically used when uncertainties are large, can, in a structured way, contribute information regarding an uncertain future. As large uncertainty is in the nature of such studies, validity is low because it is difficult to tell if the results are correct. Instead, the validity can be explored by comparing the results with the results of similar studies.

Compared to the study reported by the EEA (2006), the results presented in Chapter 29 of the *European Energy Pathways* book are similar, although they differ regarding the extent to which agricultural waste fractions are included. The potential for energy from waste and its contribution to reduction of



greenhouse gases has been explored previous, i.e., by CEWEP and Ffact (2008), with similar results. Our scenario of "Reasonable growth" gives similar results to those presented by Manders (2008).

The results presented in Chapter 30 of the *European Energy Pathways* book present several possible pathways for the European waste management system. Such scenario analysis does not aim to predict the future, rather to increase knowledge, and it contributes information even though we do not yet know how the European waste management system will develop.

The reliability of the method is considered to be high, as the calculation is based on straightforward and transperent modelling, which is easy to control and replicate. In addition, the starting point and input data used are taken from the official database Eurostat (2009), which is the best available common data source on European waste steams.

However, the modelling results are dependent upon numerous assumptions regarding the parameters that are included in the systems studied. If a second study was undertaken, other assumptions would probabably be made, based on newer facts that were not available or that have changed since the time of the study. Altered or other assumptions would alter the results to some extent. An example of this is the assumption regarding the future growth of waste quantities, which is of great importance for the outcomes. Given the current, significant uncertainties in relation to future economic growth, updated information would probably lead to an altered analysis, other assumptions, and consequently, new results regarding waste quantities.

For more information:
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Further reading:

Profu, 2007. Waste as a renewable energy source in Europe, a scenario analysis part 1 of 2.

Profu, 2009. Energy from waste- An international perspective, Avfall Sverige Report U2009:05.

Systems analysis of increased energy recovery from renewable waste fractions

28

Aim and research question

The aim was to quantify the possible, future energy recovery from renewable waste fractions that might contribute to EU targets for renewable energy and decreased emissions of climate-altering gases. The question posed was: "To what extent can energy from renewable waste fractions contribute to the EU targets for renewable energy and decreased emissions of climate-altering gases?"

Method description

For analysing energy recovery from the European waste management system the concept of systems analysis is used. With its origin in the systems approach or systems thinking (e.g., Churchman, 1968; Jackson; 1991, Checkland, 1999), systems analysis is based on the understanding that analysing a system, i.e., a group of inter-related objects, is a more complex task than analysing the objects individually. Systems analysis is used to avoid sub-optimisation (Churchman, 1968). Everything that is outside the system but still exerting an influence on it is called the surroundings or the system's environment. Analysis of the interaction between the system and its surroundings is an essential part of systems analysis (Ingelstam, 2002).

In this application, the studied objects within the European waste management system are mainly the waste sources and waste treatment facilities, which are connected via waste flows. Through the energy recovered, the waste mangement system is connected to the energy system, and the waste-to-energy plants are located in both the waste management and energy systems. Through other material flows, the waste management system is connected to other systems in the surroundings, such as the markets for material recycling (Figure 28.1).

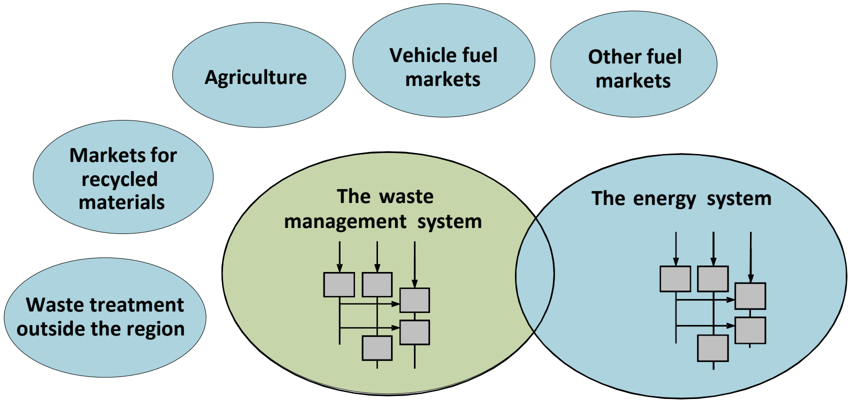

Figure 28.1. The waste management and energy systems and the system's surroundings.

Application of the method

When analysing the energy recovery from renewable waste fractions, as in Chapter 29 of the *European Energy Pathways* book, the interaction between waste management and the energy systems is in focus (Figure 28.1). When the energy recovery from waste is increased there are two main consequences in the waste management and energy systems:

1. The amount of waste sent to landfilling is decreased; and
2. The usage of alternative fuels for heat and electricity production is decreased.

Together, these effects have a greater environmental impact than if the waste mangement and energy system were studied separately. In Chapter 29 of the *European Energy Pathways* book, the concept of systems analysis is used in combination with a scenario analysis of the European waste management system, as described in Chapter 27 in this book.

Validity and reliability of the method

It is difficult to evaluate the validity of the results compared to an actual outcome, as we are analysing a development that will occur in the future. Instead, we can compare our conclusions to those of similar studies. Thus, several studies conclude that renewable waste fractions have potential as future renewable energy sources in Europe (e.g., EEA, 2006; CEWEP and Ffact, 2008; Manders, 2008).

The reliability of the method is considered to be high, as the calculation is based on straightforward and transparent modelling, which are easy to control and replicate. In addition, the starting point and input data used are taken from the official database of Eurostat (2009), which is the best available common data source on European waste steams.

However, the modelling results are dependent upon numerous assumptions regarding the parameters that are included in the systems studied. If a second study was to be conducted, other assumptions would probabably be made, based on newer facts that were not available or that have changed since the time of the study. Changed or other assumptions would alter the results to some extent. An example is the assumption made for the future growth of waste quantities, which is of great importance for the results. Given the current, large uncertanties regarding future economic growth, newer facts would probably lead to an altered analysis, other assumptions, and consequently, new results regarding waste quantities.

For more information:
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Further reading:

Profu, 2009. Energy from waste - an international perspective, Avfall Sverige Report U2009:05.

Profu, 2009. Energy from waste - Potential contribution to EU renewable energy and CO_2 reduction targets. Avfall Sverige Report U2009:18.

Seven step methodology for regional and local energy planning

29

In order to meet global and/or EU goals for sustainable development, actions that are undertaken in the local community are crucial. Although methodologies for local energy planning exist, many of them are not suitable for considering the long-term (i.e., 30-50 years from now) transformation of local energy systems. This is an important topic, since local energy infrastructures are long-lived and are not amenable to rapid changes. Therefore, there is a need for a methodology that enables the definition of both short-term action plans and long-term strategies and visions, and that facilitates the linking of these two aspects. The work is based on the concept of "think global, act local".

Seven Steps for Energy planning

The basic hypothesis behind this work is that seven specific steps must be assessed in order to formulate a roadmap for transforming local energy systems to sustainable systems. This hypothesis has been tested in the six case studies in Göteborg (Sweden), Valencia (Spain), Dunkerque (France), Gdansk (Poland), and Arnhem and Lochem (The Netherlands).

With few adjustments, the basic hypothesis with the seven steps proved to be relevant, based on the six case studies and in relation to which the assessment has been iteratively developed. The seven steps in the assessment are as follows:

1. Project initiation (clarify purpose and create commitment among decision makers)
2. Establish a detailed description of the present system
3. Assess local, EU, and global goals for sustainable development
4. Identify and assess key technologies that can bridge to a future sustainable system
5. Identify key actors in the region
6. Formulate and analyse pathways towards a more sustainable energy system
7. Establish a roadmap (with respect to technologies, markets, and institutions)

The six regions/municipalities included in the present study show considerable variability in terms of population size, land area, and characteristics of the existing energy systems. Nevertheless, the results of the project indicate that the seven-step assessment tool is applicable to each of the six case studies, despite their considerable differences and unique features (Sköldberg, 2010). This confirms the usefulness of the methodology.

A summary of the most important features of the seven step checklist:

- The preparation of different pathways should be based on a detailed description of the present energy system.
- The methodology combines short and long term views and identifies bridging solutions.
- Key technologies are identified and evaluated in order to find pathways towards a more sustainable energy system.
- The importance of key-actors participation in the planning process is emphasised.
- The methodology is general in its approach. This facilitates adaption to different local conditions.
- Identification and analysis of goals at different levels (international, national, regional) is an important feature of the planning process.
- No specific computer programs or software tools are required.
- The use of a structured energy balance, the Reference Energy System (RES), highlights systems related issues.
- A short term action plan is an important part of the Roadmap. It specifies who is responsible for what, when actions should be taken and how the actions should be evaluated.

From pathways to roadmaps

The pathway descriptions facilitated assessments of the extent to which existing local policies and plans contribute to a sustainable development, and in the absence of relevant plans, the extent to which policies or consideration of global goals could be identified. Different time horizons have been described and analysed. The concept applied in the case studies is illustrated in Figure 29.1. For all the case studies, pathways for the short-term (2012-2015), mid-term (2020), and long-term time (2050) have been created. It was considered important in the methodology to incorporate all three perspectives, to create an effective planning process that is both action-oriented and guided by clear long-term visions. When different pathways are identified and analysed, it is time to establish a roadmap. The roadmap is the preferred pathway, together with the process of how to transform this into real actions, and visions that act as guidelines for these processes. More about the outcome can be found in Chapter 31 in the *European Energy Pathways* book.

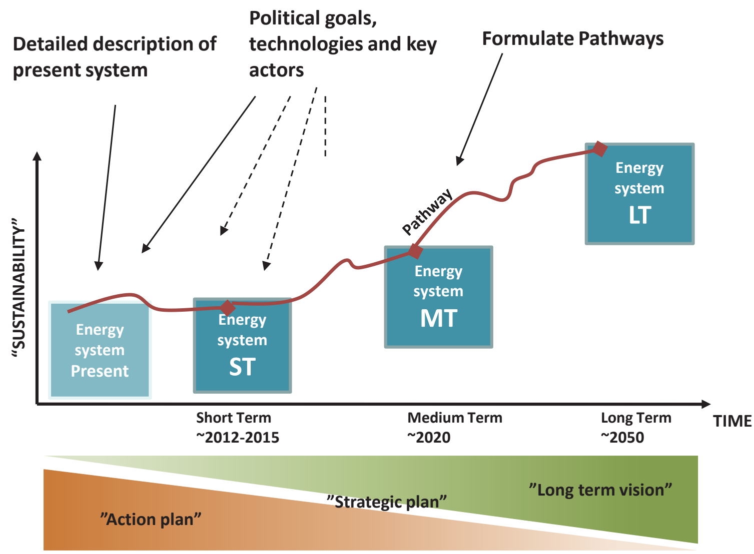

Figure 29.1. Basic description of a pathway and how it interacts with plans and strategies for different time horizons.

For more information:

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Further reading:

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