EUROPEAN ENERGY PATHWAYS

Pathways to Sustainable European Energy Systems

European

Energy Pathways

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Foreword

This book reports on the project "Pathways to Sustainable European Energy Systems", a 5-year project (2006-2010) that has evaluated 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 present energy system has been included in the analysis, since this will have a significant influence on the possibilities to transform the energy system over the coming decades. Therefore, a cornerstone of the project has been the establishment of detailed databases concerning the European energy infrastructure, and including the global fossil fuel infrastructure. Taking departure in the description of the energy system as provided by the databases, different bridging technologies and measures have been identified, which can transform the energy system so that the emissions targets for year 2050 can be met. The work has been interdisciplinary and has involved some 40 researchers in addressing various aspects of the challenge to transform the energy system. The following chapters summarise the results from the various activities – in all more than 30 topics are covered. The aim of this book is to give an added value to the scientific publications that have emerged from the project. Each chapter gives references to key publications for the material and topics covered in that chapter.

The work reported in this book was presented to, and discussed with, a broad group of stakeholders in industry and governmental organisations. The project has organised 15 workshops and numerous project meetings with the involved researchers, in which the results were discussed and the subsequent steps were defined. This interdisciplinary platform for discussion has been very valuable for ensuring progress and maintaining the focus of the project, and it is my impression that it has been a very stimulating experience for the participants in the project. The project has also made it possible to establish fruitful collaborations between researchers from different disciplines. I am convinced that these co-operative activities will continue and be expanded upon in the future.

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 made it possible to create the basis for the project presented in this book, and the Alliance for Global Sustainability (AGS) formed a perfect framework for initiating the project.

I would like to thank all the researchers who have participated in the Pathways project and made this book and all the associated scientific papers possible. Special thanks are due to Professor Lars Strömberg, Vice-President of R&D at Vattenfall AB, with whom the initial ideas that formed the basis for the project were discussed. I would also like to thank Mr. Bo Rydén at Profu AB. Without his enthusiasm, skills in organising work, and ensuring that the deadlines were kept, I have a feeling that I would have failed as a project leader.

The main sources of funding for the work presented in this book were Vattenfall AB (through AGS), the Swedish Energy Agency, and the European Commission through the projects ELOBIO, REFUEL, PLANETS, PATH-TO-RES. Additional funding was provided by E.ON Sverige AB (the Chalmers – E.ON initiative), Preem AB and Södra's Foundation for Research, Development and Education.

I hope that this book highlights the possibilities for transforming the European energy system and that it encourages politicians and other stakeholders to impose strong and clear policy measures for transforming the energy system. At the time of writing, the COP16 meeting in Mexico has just concluded, and the outcome gives reason for some optimism. Hopefully, this optimism will prompt Europe to take the lead in showing that following a pathway similar to the ones presented in this book is not only possible, but will also create new opportunities!

Filip Johnsson
Project leader

Göteborg, December, 2010

Summary

To reduce the increasingly serious threat of climate change, the global community must urgently address the challenge of substantially reducing emissions of greenhouse gases (GHGs). Reductions in GHGs, especially of carbon dioxide (CO_2), must be carried out in a way that maintains the security of supply, as well as social and economic sustainability. Meeting this challenge will require a thorough understanding of the associated technical, social, political, and economic issues.

This book shows that it is possible for Europe to meet the climate goals represented by the 2^{o}C target but that this will require that all technologies and measures are used, especially with respect to preserving the security of supply and economic competitiveness. A major impediment to the achievement of the goals is the abundant resources of fossil fuels, which means that it is of the utmost importance that carbon capture and storage succeeds. Equally important is the introduction on a large scale of renewable technologies, especially wind power and biomass and their corresponding support systems. As far as the stationary energy system is concerned (heat, power, and industries), the existing system will last for a long time so it is of importance to find technical solutions that can exploit this system without resulting in lock-in effects. It is shown that there are great opportunities for integrated solutions, such as the co-production of heat, electricity, and transportation fuels, as well as electrification of the transport sector. It can also be concluded that there are significant possibilities for introducing efficiency measures into industry and buildings.

In this book, two different Pathways are used to illustrate where the responsibility for implementing the necessary transformation of the energy system is placed. In the market-oriented Pathway, although there are few if any technology preferences, these preferences are left to the market to decide upon. In the other Pathway, which is policy-oriented, specific policy measures are directed towards renewable and energy efficiency measures; this requires that a greater share of the responsibility is given to politics. Both pathways can fulfil the same emission targets, albeit with differences in terms of the technologies and measures used and the complexity of the required policy measures. If society manages to make the necessary transformation of the energy system, it is likely that the transformation of the energy system will follow a mix of the two pathways. Therefore the pathways should be seen as examples on how the energy system can be transformed and, more importantly, that it is possible to transform the energy system to meet the 2ºC target without prohibitive cost for European society. It is hoped that this book can show that there are possibilities for developed economies, such as Europe, to take the lead in transforming the energy system.

Conditions and Methodology

The project reported in this book has two guiding principles for evaluation of pathways towards transforming the energy system: (i) the need to include the existing energy and institutional infrastructures in the analysis; and (ii) the importance of understanding the fossil fuel markets. These two principles are not emphasised in much of the literature dealing with transforming the energy system to meet climate change. With respect to methodology, the reported work applies a wide range of tools and methods to answer specific questions. The work has had an interdisciplinary nature, with researchers involved from various disciplines, with the focus on techno-economic analysis and technology assessments. Many specific and interesting results have emerged from this work, as described in the following chapters, including the two Pathways, which illustrate how the European energy system can be transformed to fulfill climate targets.

The book applies techno-economic analysis of the energy system, mapping of the European energy infrastructure, and assessments of technologies and methods for transforming the energy system. In addition, the work involves the application of non-technical methods to analyse the energy system from various perspectives, such as the function of law and siting issues with respect to renewable energy, path dependency from the social science perspective, and business management aspects for corporate sustainable development.

Key results

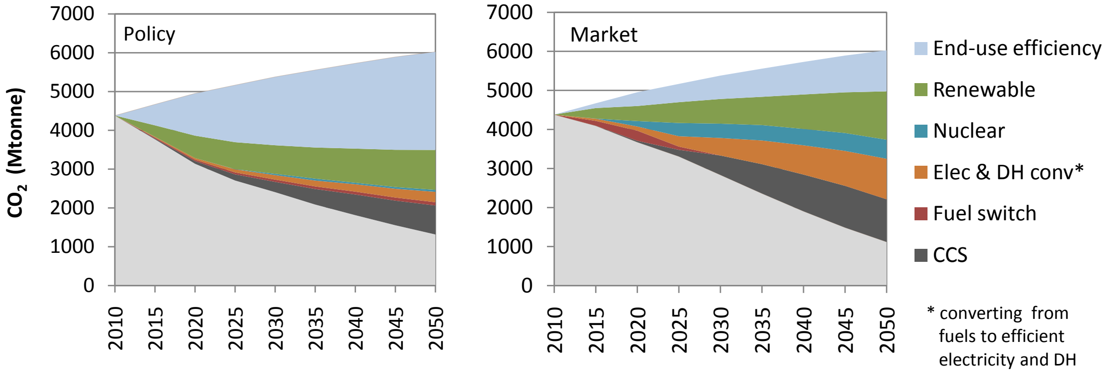
The work described in this book covers a broad range of topics related to how the European energy system can be transformed from now up to year 2050, to meet targets for emission reductions while maintaining security of supply and preserving social and economic sustainability. The following overall conclusions can be drawn from these efforts:

There are several possible pathways towards a sustainable energy system

There are several possible pathways towards a more sustainable European energy system. Although extensive changes in the energy system are required to follow the pathways, in general, the technologies and measures are already available. Thus, the major challenge for transformation of the energy system is a political one, even though significant technological developments are certainly needed.

Two pathways are proposed

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. The Market Pathway leaves more of the responsibility for transforming the energy system to market forces. In the latter pathway, the cost of emitting CO_2 (and other GHGs) is the principal policy measure. The pathways represent examples of different strategies for Europe to meet the challenges of climate change and other sustainability goals, rather than predictions of the future.



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.

All technologies and measures are required to follow the pathways
It is possible to make deep cuts in emissions until 2050, while at the same time maintaining the security of supply. However, this will require that all available technologies and measures are used. If we choose to reject certain technologies and mitigation measures, there is a high risk that the necessary transition will either not take place or will progress too slowly.

Bridging technologies can facilitate early reductions in emissions at lower cost
Several of the key options for transforming the energy system constitute what in this book are termed 'bridging technologies'. Bridging technologies take advantage of the existing energy infrastructure and facilitate the development of new energy technologies. Important bridging technologies are: co-firing of biomass in existing power plants, using incineration and industrial waste heat in district heating systems, applying process integration in industries, the retrofitting of the existing building stock, and the application of carbon capture and storage (CCS). Although entirely new and more "sustainable" technologies (e.g., hydrogen-based technologies, solar cell technologies, and nuclear fusion) will undoubtedly be developed, these technologies are unlikely to play major roles in the four decades leading up to the year 2050, which is the time-frame for the two pathways presented in this book.

There has to be a cost associated with emitting greenhouse gases
A prerequisite for achieving a market that drives the energy system towards following one of the two pathways presented in this book (or for that matter, any other pathway that results in the same level of emissions reduction) is that there must be a cost associated with emitting GHGs, most importantly, CO_2. This cost could be in the form of a tax or a charge in an emission trading scheme.

Electricity and district heating will be increasingly important as energy carriers
Reaching the ambitious climate targets in the two pathways of this work requires efficient use of the available resources. The electricity generation and district heating systems have the potential to facilitate efficient use of primary energy while reducing CO_2 emissions.

The existing energy infrastructure will strongly influence the pathways
An important condition for transforming the energy system is that there is already a system in place, i.e., the present energy infrastructure with associated actors and institutional framework. This comprises a large capital stock with a long turnover time. Furthermore, there are legal and social structures, as well as valuable know-how attached to the technologies that currently predominate, all of which offer possibilities for rapid implementation of the bridging technologies. However, they also limit the possibilities for large-scale

introduction of entirely new systems. The key is to use the existing infrastructure to initiate the transformation on a large scale and to create the optimal conditions for new technologies.

Existing and new energy infrastructures must be developed

Although the bridging technologies take advantage of the existing energy infrastructure, this infrastructure also needs to be developed, as a new support infrastructure must be established together with the corresponding institutional framework. The implementation of CCS and increased use of bioenergy will require an extensive transport infrastructure, e.g., CO_2 transportation and storage networks, and biomass handling facilities. The production of second-generation biofuels requires substantial changes in the agricultural and forestry sectors. Large investments will have to be made to strengthen, expand, and upgrade the electricity networks so as to accommodate increased levels of wind power and other forms of intermittent electricity generation. Expansion of district heating networks will be a challenge in terms of new investments, public support, and planning. Synergies can be created if the transition of the energy systems is co-ordinated with the transformation of other sectors, such as industry, transport, waste, and agriculture.

Pathways for the juridical framework must be in place

A sustainable energy and climate policy needs not only technical advances, but also a legal system that clearly supports the implementation of policies. This situation does not currently exist in the EU. In many cases, there are clashes between EU or national energy policies and other interests, e.g., with respect to impact on the local environment, and these interests are often supported by legal restrictions. In other instances, the technologies are so new that they are not covered by existing legislation. Even if the cost barrier for a technology is removed, barriers to its implementation may emerge in the design of the legal and administrative systems required for that technology. Thus, it is of great importance to develop legal systems that support the implementation of the policies required to transform the energy system.

Although following the pathways requires structural changes across sectors, synergies will be created

Reversal of the current situation and moving towards sustainability are complex processes that require fundamental changes across society. This book gives several examples of what needs to be accomplished and how this can be broken down by sector (e.g., the electricity, industry, transport, and waste management sectors).

Although the required structural changes imply great challenges for society, these changes also represent opportunities for synergies. Seizing these opportunities will be cost-efficient and will contribute to maintaining, and perhaps even strengthening, Europe’s competitiveness on the global market.

Companies are preparing to respond to the requirements of the energy pathways

Companies that are active in the stationary energy sector are already preparing to respond to requirements for sustainable development and are intensifying their efforts to integrate sustainable practices into their business models. By applying a strategic perspective to the environment, companies can develop new business opportunities and contribute to sustainable development within their sphere of activities.

Global fossil fuels resources are too large – this is the challenge!

From a climate change perspective, there is far too much fossil fuel. Although the world may be running out of conventional oil, from a climate perspective, this is not happening fast enough. Moreover, the availability of oil is not the major issue. Instead, there exist large resources of coal, natural gas, and other reservoirs of hydrocarbons, such as tar sands and oil shale. These large resources are constantly being developed, which means that it is of great importance that a price is attached to CO_2 emissions and other GHGs, so as to stimulate the development of renewable technologies, energy efficiency measures, and technologies that allow the use of fossil fuels without CO_2 emissions.

Carbon Capture and Storage is a key technology to meet the fossil fuel challenge

The threat from the abundant resources of fossil fuels makes it crucial to develop CCS technologies. If CCS is not applied, it will probably be very difficult to get fossil-fuelled regions and countries to comply with stringent GHG reduction targets, i.e., to reach a global agreement on emission reductions. In addition, for the EU, it will be difficult to reach its climate goals for 2050 without successful implementation of CCS.

Both pathways strengthen the security of supply

Security of supply (SoS) is one of the cornerstones of European energy and climate policy towards a sustainable energy system. Dependence on imports of natural gas and oil has serious implications for the EU and strongly influences the union's energy politics. In both pathways the SoS is strengthened through reduced import dependency and increased diversification of technologies and fuel mixes.

Energy efficiency must be implemented on both the supply and demand sides

Cost-effective implementation of energy efficiency improvements should include all parts of the energy system, from supply to end-use. The estimations made in the work upon which this book is based show that cost-effectiveness (in the long run) in the European energy system will be attained with approximately 30-50% energy conversion efficiency measures and 50-70% end-use measures. Most of these energy efficiency improvement measures will, in addition to increasing energy efficiency, reduce GHG emissions and lead to the increased use of renewable energy sources in the EU countries. These synergies will make the measures more cost-effective.

Biomass holds promises as a source of fuels for near-term bridging technologies

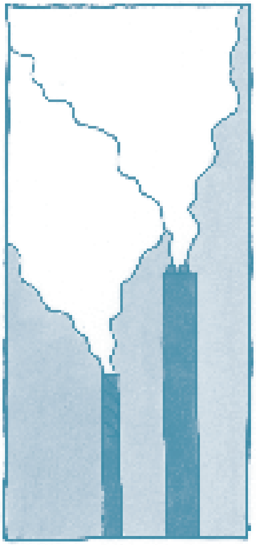
Biomass is the only renewable primary energy source that inherently generates carbon-based fuels, which is the basis for much of present-day energy technology. This makes biomass very suitable for use in both heat and power production and in the transport sector. Promotion of bioenergy use that exploits existing energy infrastructures in order to reduce risk and reach lower costs is proposed as an attractive near term strategy.

Industry has to consider all options to follow the pathways

European industry has the potential to contribute significantly to reducing CO_2 emissions and to development towards sustainability, directly through large reductions in emissions and indirectly through changes in the energy that is used and delivered. Adaptation strategies may include structural changes, energy efficiency improvements, fuel substitution, and the implementation of CCS.

Implementing pathways requires responsibility at all levels, from global to local

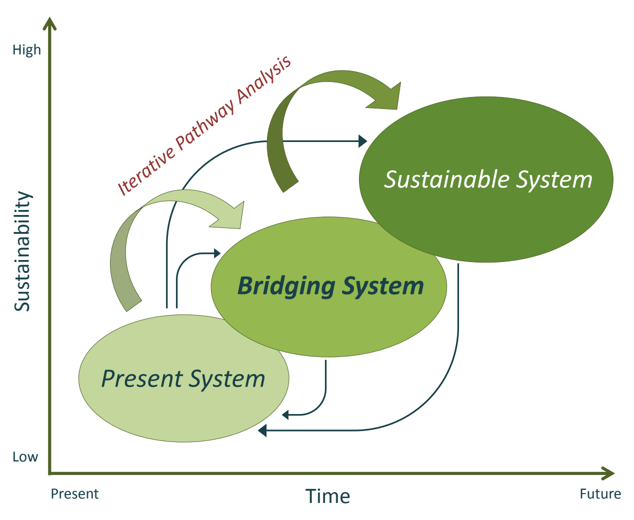
Although the two pathways discussed in this book differ with respect to who in society assumes the major share of the responsibility for transforming the energy system to follow the pathways, they also require governance at the international, national, and local levels.



An integrated methodology for pathway analysis has been developed

The results presented in this book are the outcomes of applying in a co-ordinated way a variety of energy-related methods and models, which originated from different scientific disciplines and traditions. Most of these elements are described in the Pathways *Methods and Models* book. Some of the analytical tools used are well-known, well-documented, and widely used in academic research. The others have been developed (or refined) during the Pathways project and are therefore unique. It is the aim that this book to add value to the many scientific publications that have emerged from the project, which although they are on a more detailed level, are limited to specific scientific disciplines or address a specific sector of the energy system.

The figure below summarises the development path from the existing system to a more sustainable system via bridging technologies. An important point to note is that the analysis to investigate possible pathways to a more sustainable system must be carried out in an iterative way, both within the timeframe of this project and of future projects. The graph should be seen as dynamic, in that new possibilities and barriers will appear/disappear over time. For example, when the work presented in this book was originally formulated some 5 years ago, the concept of electrification of the transportation sector was not yet an issue that was as widely discussed as it is now.



Conceptual presentation of the move from a non-sustainable energy system to a sustainable energy system. The project studies options and pathways that proceed through the bridging system.

Content

Introduction

To reduce the increasingly serious threat of climate change, the world must urgently address the formidable challenge of substantially reducing emissions of greenhouse gases (GHGs). Reducing the levels of GHGs, especially carbon dioxide (CO_2), must be carried out in a way that maintains the security of supply, while maintaining social and economic sustainability. Meeting this challenge requires a thorough understanding of the associated technical, social, political, and economic issues. Although it is thought possible to meet the set climate goals, all commercially available and close to commercially available technologies and measures must be used, with special consideration given to maintaining the security of supply and competitiveness.

There is an urgent need to start climate change mitigation and to achieve global emission reductions of 50-85% for CO_2, relative to emission levels in year 2000, so as to limit the global temperature increase to around 2ºC. It is reasonable to assume that this means that the developed parts of the world must reduce emissions by more than the global average reduction.

Historically, economic growth (increased wealth) has resulted in increased use of energy, and it has proven difficult to decouple fully growth from increased energy use and thereby, from increased emissions of CO_2 (and other GHGs) since, there has been a strong dependency on fossil fuels for energy. In addition, society cannot be expected to use less energy than is considered necessary for economic vitality, given the available information and prevailing market conditions. There is also the challenge from increases in the global population, although affluence and increased wealth are greater threats to climate change mitigation than population increases. This is double-edged sword for poor regions of the world, for which an increase in wealth is a prerequisite for reducing population growth (especially with respect to the fact that increased wealth for the poor results in access to education and birth control). Another option to reduce the use of energy is to use alternative technologies, such as replacing an old inefficient power plant with a new one with higher efficiency. However, this may result in increased competitiveness and to what is often referred to as the 'rebound effect', i.e., more units of energy sold. Lifestyle changes have also proven difficult to achieve with respect to "downsizing" energy use. With increased wealth, people tend to spend the additional income on carbon-intensive activities, such as (at least in the rich part of the world) low-fare airline travel or long-distance charter trips, rather than on low-carbon alternatives.

Fuel shifting has been applied widely, especially in the stationary energy sector. As an example, Europe and North America have seen significant shifts from coal-fired to natural gas-fired electricity generation. This has lowered the carbon intensity of electricity generation (increased thermal efficiency and employed a less-carbon-intensive fuel). However, as indicated above, this has also made electricity production more competitive in the energy market, indicating a rebound effect, and, at least for Europe, increased dependency on foreign natural gas production (with a consequent reduction in the security of supply), as opposed to using domestic coal (especially lignite) resources. Deployment of wind power and shift to biomass have indeed reduced emissions, although the overall effect is still limited, and for some biomass use, the climate benefit is not always obvious. In the 1970s and 1980s, there was an increased use of nuclear power, which resulted in lower CO_2 emissions compared to a situation in which the corresponding electricity (base load) would have been produced from fossil fuels (such as coal). Since that time period, nuclear power has lost public acceptability in many regions and, in addition, the high upfront costs make it a risky investment in a deregulated market (as opposed to the nuclear programs in the 1970s, for which the risks were more or less taken by governments). Nonetheless, in Europe, there is currently a movement in favour of increasing nuclear power, and there are ongoing proposals and decisions as to lifetime extensions and upgrades for the existing nuclear plants.

The capture and storage of carbon can be achieved using Land Use Change and Forestation (LUCF) and through the capture of CO_2 from large point sources with subsequent storage in deep underground formations. LUCF is not straightforward and although the world has seen significant deforestation, especially in developing regions (e.g., Asia and South America), there are increasing attempts to develop sustainable forest industries. Carbon Capture and Storage (CCS) is a new technology that shows promise, although it will take at least 10 years before it is commercially viable, and then only provided that a sufficiently high cost is associated with emitting CO_2. The eventual successful application of CCS will make it more likely that fossil fuel (especially coal) dependent regions will accept a global climate change agreement.

This book presents a techno-economic analysis of the European energy system, mapping of the energy infrastructure, and assessments of technologies and methods for transforming the energy system. In addition, non-technical methods are applied to analyse the energy system in terms of: (i) the function of law and plant siting issues in relation to renewable energy; (ii) path dependencies from a social science perspective; and (iii) business management considerations for corporate sustainable development.

THERE ARE SEVERAL POSSIBLE PATHWAYS TO A SUSTAINABLE ENERGY SYSTEM

The work presented in this book indicates various pathways for a more sustainable European energy system. Presented and discussed are two such pathways up to the year 2050, as well as the important technologies and measures that are vital for these pathways. Although extensive changes in the energy system are required, in a general sense, the technologies and measures are already available. Therefore, although significant technological developments are certainly needed, the major challenge is the political one.

The COP15 meeting held in Copenhagen did not secure a global post-Kyoto climate treaty. The outcome of the COP16 meeting in Cancún, Mexico gives cause for optimism, and it seems as if tackling climate change is regarded by politicians and industry as being as important now as it was before the Copenhagen meeting. In Europe, the research and development of new technologies is continuing at the same or faster pace as before, and there is significant interest across the regions in transforming local energy systems, as evidenced by the high levels of interest in various network initiatives, such as the Covenant of Mayors (EC, 2010). This may be due in part to an increasing awareness that not only climate change imposes a threat, but that mitigating climate change goes hand in hand with improved security of supply and sustainable development in general. In terms of the latter, there seems to be a growing consensus regarding its increased importance. In the EU, there is growing concern over security of supply, and it is clear that in a "business as usual" scenario, the EU will be increasingly dependent upon imported energy.

> *"The UN ship that began to list so precariously in Copenhagen has got back on an even keel in Cancún. The measures to save the Earth's climate are still insufficient, but the UN has taken a step towards rebuilding confidence. We managed to prevent multilateral climate cooperation from capsizing."*
>
> Swedish Minister for the Environment, Andreas Carlgren
> (www.sweden.gov.se/ December, 2010)

Meeting the 2ºC target for climate change represents a serious challenge from the technical and political points of view, especially in light of the current trends in developing economies, abundant fossil fuel resources, and the rather long turnover times in the capital stock of energy infrastructures and the long lead times for the development and scale-up of low-carbon technologies. The two pathways described in the next section, as well as the chapters on the underlying technologies and measures describe the challenges associated with transforming the European energy system and demonstrate that these pathways are examples of changes that can lead to a more sustainable energy system.

As indicated above, it is important to exploit all the technologies and measures that are currently commercially available or that are approaching commercial status. Given that the cost to transform the system can be regarded as non-prohibitive for European society, the political challenge may also be overcome. For the stationary energy system (electricity and heat), the cost for following the proposed pathways is estimated to be up to 50 €/tCO_2 by the end of the period, as shown in this book. For the energy system as a whole, the cost of achieving the required reductions by 2050 is likely to be in the order of 100 €/tCO_2. The political challenge is to overcome various obstacles related to public acceptance, lack of knowledge, possible shortage of materials and manpower, and the establishment of new markets and market regimes.

In summary, the major challenge that lies ahead is to transform the energy system to meet the emission reduction targets that are required to stabilise the climate at acceptable levels. Yet, once the factors and policies are in place that promote the required transformation of the system, there will be new business opportunities and, most likely, a more sustainable society in general. Although this book deals exclusively with Europe, many of the conclusions drawn should be applicable to other regions. Hopefully, this book will facilitate Europeans and European institutions in taking the lead in transforming the energy system. It is reasonable and desirable that Europe (and other developed economies of the world) should, by developing new technologies, show the way forward in transforming the energy system in a more sustainable direction. These technologies will hopefully be applied successfully in developing economies to enable these regions to advance rapidly in terms of responsible, climate-protective development.

The next section lists key results from the pathway analysis presented in this book, together with details and references to the underlying work presented in Chapters 1 to 46.

This book is accompanied by the **Methods and Models book**, which describes the methodologies used in the Pathways project.

European Energy Pathways
- Key results

TWO PATHWAYS HAVE BEEN DEVELOPED

This book presents two pathways to sustainable European energy systems, the “Policy Pathway” and the “Market Pathway”. 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). The Market Pathway leaves more of the responsibility for transforming the energy system to the market. In this scenario, the cost to emit CO_2 (and other GHGs) is the dominating policy measure. This book does not intend to present predictions, or to propose which of the two pathways should be followed. The two pathways should be regarded as two examples of different possibilities for Europe to meet the challenges of climate change and other sustainability goals, rather than as predictions of the future.

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-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 (the energy infrastructure) and thereafter, evaluate how technologies and measures can be implemented in a step-wise manner over the next decades.

The two pathways involve significant reductions in CO_2 emissions in the European energy system from now up to 2050 (and beyond). Climate modelling, such as that reported by the IPCC, suggests that global emission reductions of 50-85% for CO_2 and relative to emission levels in the year 2000, are required for stabilisation of GHG atmospheric levels at 440-490 ppm (~350-400 ppm CO_2), which corresponds to a global temperature increase in equilibrium of around 2.0ºC to 2.4ºC (IPCC, 2007). After the Copenhagen meeting, the importance of emission targets has been underlined, as state-of-the-art climate research indicates that: 1) a reduction of 50-70% in GHG emissions is required to limit the temperature increase to 2ºC; 2) further reductions will be needed after 2050; and 3) the emission levels should peak not later than 2015 if reaching the target is to be feasible (>66% probability) (Fee et al., 2010).

The policy of the European Union (EU) in recent years has been in line with these guidelines, with the European Commission (EC) acknowledging that global emission reductions in GHG of about 50% (relative to 1990 levels) are required by 2050 (EC, 2007).

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.
- Focuses on the end-use with respect to technologies and measures.
- Gives a well-balanced mix of technologies, involves strong reduction in primary energy use and is therefore favourable with respect to security of supply.
- Requires large investments in the electricity transmission network to accommodate the large fraction of intermittent (wind) power generation.
- Represents a significante decrease in energy use per capita over time, i.e. a substantial cange from the historical trend. This trend alteration would typically require life-style changes.
- Represents a future in which a large number of actors and decision makers at all levels down to private consumers will have to take responsibility for the transformation of the energy system.

The Market Pathway

- Relies more on the market to transform the energy system, and presents a future in which the cost associated with emitting CO_2 (and other GHGs) is the dominating policy measure.
- Requires large-scale dissemination of all technologies and measures, including extensive CCS with coal as a fuel.
- Is supply-oriented with respect to choices regarding technologies and measures, and will exert less pressure for life-style changes.
- Benefits from existing infrastructure through increased use of electricity generation and district heating, as well as through shifting fuels to produce these energy carriers.
- Represents a significante decrease in energy use per capita over time, i.e. a substantial cange from the historical trend, although not as significant as in the Policy Pathway.
- Represents a future in which most of the responsibility for the transformation of the energy system is in the hands of large energy companies and professional market actors.

The current European standpoint for negotiating an international treaty on limiting GHG emissions is that the EU should reduce emissions by 30% by 2020, and that all developed countries should reduce emissions by 60-80% by 2050 (relative to the levels in 1990). Irrespective of the outcome of such negotiations, the EU is committed to reducing GHG emissions by 20% by 2020 compared to the emission levels in 1990 (EC, 2007).

The current EU targets for 2020 are considered to be the initial steps in curbing climate change, and the EC proposes that the European energy policy be renewed in 2010, setting targets for 2030 and a vision for 2050 (EC, 2008a). Recent discussions in the European Parliament on targets for 2050 have cited 60% RES and 35% energy efficiency improvements by 2050 (European Parliament, 2009).

The responsibility for transforming the energy system

Both pathways involve a complex transition of the energy system, which is required to attain a sustainable energy system. Thus, following the pathways will require structural changes throughout society. Both pathways require strong policies that are based on the consensus that the energy system and society in general have to be transformed towards a sustainable system. The reduction of GHG emissions to the assigned target levels is the main driving force behind both pathways. Both pathways assume that market forces and politics will ensure that security of supply and competitiveness are maintained or improved along the pathways. The two pathways diverge with respect to where the main responsibility lies for transforming the energy system.

The Policy Pathway can be seen as creating a future in which politics takes a large share of the responsibility for the execution of the required transformation through targeted policies on renewable and energy efficiency measures, as well as detailed policies on specific technologies (e.g., building codes, transport regulations, energy certification of various appliances). Thus, the required policy is in line with the EU Energy and Climate Package (EC, 2008b), which in addition to imposing emission reductions (until 2020) defines targets for renewable energy and energy efficiency measures. The EC has emphasised that in addition to reducing GHG emissions by 20% by 2020, or by 30% if an international agreement is reached, the share of RES should reach 20% of energy end use by 2020, and efficiency measures should be implemented to ensure that primary energy consumption is 20% lower than it would be in a baseline scenario without efficiency measures.

In the Market Pathway, more of the decisions on how to transform the energy system are left to the market. This pathway can be seen as creating a future in which the cost of emitting CO_2 is the main policy measure, although this cost can arise in different ways, e.g., through carbon taxes or carbon cap-and-trade systems. Thus, this pathway assumes fewer targeted policies with respect to renewable and energy efficiency measures or other targeted policy measures. Yet, also in this pathway there may be a need for specific incentives – including support for R&D to stimulate development of prospective technologies.

The overall aim has been to derive two clear-cut pathways, so as to illustrate the consequences of the two different strategies with respect to where the responsibility lies in transforming the energy system. In reality, the most promising pathway for the future is the one that achieves climate targets while maintaining security of supply and competitiveness, and this is most likely a mix of the Market and Policy Pathways.

Energy and emission trends in the two pathways

The targets for reductions in CO_2 emissions are the same in both pathways, i.e., around 70% reduction by 2050 (see Figure I). 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% 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

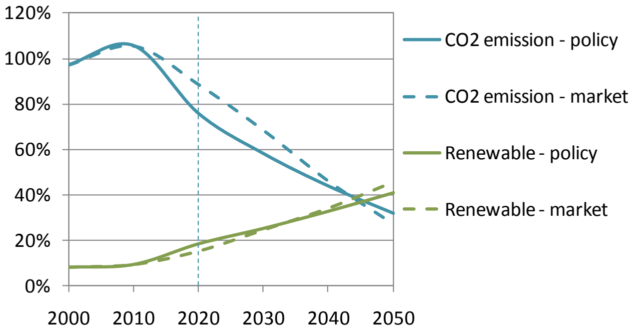


Figure I. CO_2 emissions in the EU27 and the share of renewable energy in final energy demand, for the Policy and Market Pathways.

will surpass 5000 TWh in both pathways, which represents a four-fold increase compared to the situation in year 2000.

Figure II shows the CO_2 mitigation measures (displayed as “wedges”) for the two pathways for the entire energy system, as obtained using the methodology described in Chapter 22 in the *Methods and Models* book. This figure compares the two pathways to a Baseline scenario (which is based on the historical development trend, without any imposed sustainability targets). Compared to the Policy Pathway, the Market Pathway has a more even distribution of mitigation measures. The Policy Pathway is to a large extent dependent upon end-use energy efficiency measures, whereas the key measures in the Market Pathway are more supply-side-oriented.

In terms of its significant reliance on the success of energy efficiency measures, the Policy Pathway is similar to the so-called Blue Map scenario reported by the IEA (IEA-ETP 2008) and to the “Energy and Climate Package Scenarios” in the Primes model of the EC, as described by Capros et. al. (2008). In addition, the “Pathways to a Low-Carbon Economy” reported by McKinsey (2009) also has a strong focus on energy efficiency measures. Thus, the analyses given in the literature place strong emphasis on energy efficiency measures. Although this is desirable, decision makers should be aware that historically, it has been difficult to implement energy efficiency measures despite the fact that many of those measures were cost-efficient. Thus, there has been a large energy efficiency gap, which is the difference between the energy efficiency that would have been achieved if all cost-efficient options were implemented and the actual efficiency improvements that were carried out. Rather than reflecting outcome of careful analysis, energy efficiency measures in scenarios may represent the difference

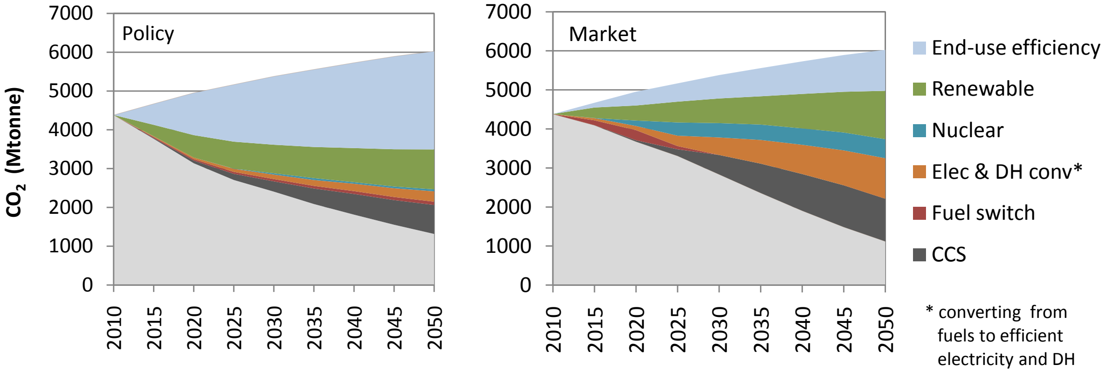


Figure II. CO_2-emission mitigation measures, as “wedges”, for the Policy Pathway (left) and Market Pathway (right).

between what is required to meet targets and what is estimated to be possible to achieve through technologies on the supply side. Therefore, it is vital to conduct a thorough analysis of how this energy efficiency gap can be closed. This is discussed in Chapter 44 and is an area that obviously needs to be studied further.

Figure III shows the same results as in Figure II but with the reduction wedges divided by sector. In the Policy Pathway, the distribution of emission reduction between sectors is similar for all sectors.

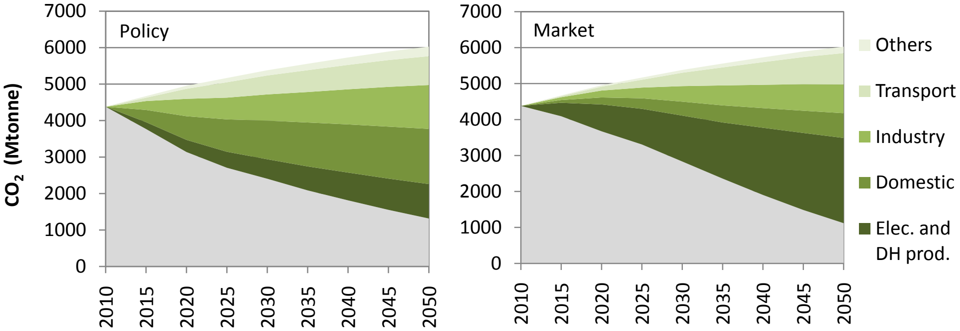


Figure III. CO_2-emission "wedges" by sector in the Policy Pathway (left) and the Market Pathway (right). Elec = Electricity, DH = District Heating.

In the Market Pathway, there is a greater reduction on the supply side, including a larger share of the reduction in the electricity and district heating production. The sizes of the wedges can be taken as indicators of where the responsibility for reduction lies. Thus, the Market Pathway assigns less responsibility to the end-use and industry sectors with a larger share of reductions in the electricity and heat generation sectors. The latter are also sectors in which it is generally less costly to reduce emissions, whereas other industry sectors may be more costly (although actual costs differ considerably between different types of industry) and industry is also more vulnerable to competition (electricity and heat plants cannot move outside the EU, wheareas industry can relocate). Since end-use efficiency measures typically are cost-efficient, it is of the utmost importance that ways are found to secure their implementation. However, as indicated above, this has proven in the past to be difficult owing to what is often referred to as 'high transaction costs'. Although both pathways require that a sufficiently high cost is associated with emitting CO_2, as discussed above, implementation of the Policy Pathway will require more targeted and sector-specific policies.

The primary energy use in the EU will decrease in both pathways, as compared to the current level (Figure IV). The Policy Pathway entails a more rapid decrease, with lower levels of primary energy use reached by 2020 and 2050, as compared to the Market Pathway. However, both pathways present a 'trend shift' towards much lower primary energy use than the development in a Baseline scenario, which is based on the historical development trend. In the Policy Pathway, this trend shift is significant.

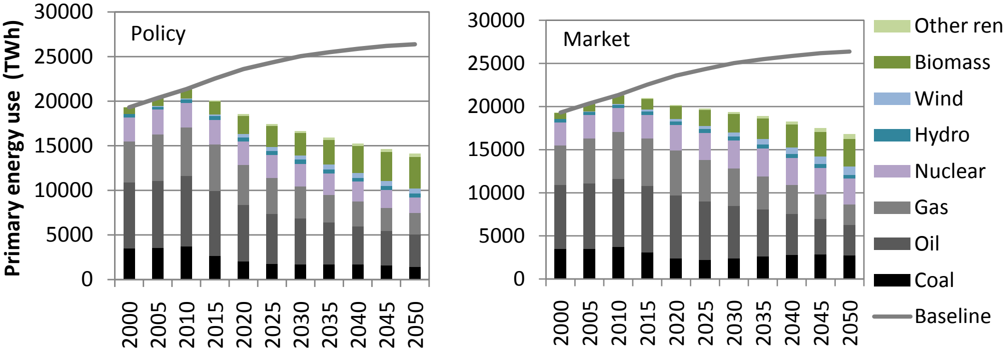


Figure IV. Total primary energy consumption in the Policy Pathway (left) and Market Pathway (right). Other ren = other renewables.

As mentioned above, in the Market Pathway, there are no separate targets for energy efficiency, as is the case in the Policy Pathway. End-use efficiency improvements will still occur when considered profitable, but in the absence of an explicit policy, the rate of end-use efficiency is expected to be lower in the Market Pathway than in the Policy Pathway. However, increased efficiency in the energy conversion on the supply side is significant in the Market Pathway, contributing to the large reduction in primary energy use.

Compared to the present-day situation, the use of fossil fuels will be reduced by 50% by 2050 in both pathways. After peaking around 2015, there will also be a decrease in the EU's dependency on imported energy, compared to the current situation. This will lead to a significant improvement in the security of supply. In 2050, imported oil, coal, and natural gas will constitute less than 35-40% of the EU's primary energy use in both pathways, as compared to levels of over 50% today and the even higher level expected in 2015.

ALL TECHNOLOGIES AND MEASURES ARE REQUIRED TO FOLLOW THE PATHWAYS

This book shows that it is possible to make deep cuts in emissions until 2050 while maintaining security of supply and competitiveness. However, this will require that all available technologies and measures are used.

As indicated previously, a transition towards a sustainable energy system (and a sustainable society in general) requires reductions in climate and environmental impact and the maintenance of competitiveness and security of supply. The transition should preferably take place over only a few decades, with almost complete elimination of European CO_2 emissions by 2050. The results reported in this book show that these three goals can be met but will require that all available technologies and measures are used. If we choose to reject certain technologies and mitigation measures, there is a high risk that the necessary transition will either not take place or progress too slowly. This is of great importance and, as discussed below, the most important factor will be to assign a cost to emitting CO_2 and other GHGs. Therefore, the focus needs to be on political actions rather than on decisions as to technological options. Yet, there may also be a need for specific incentives – including support for R&D to stimulate development of prospective technologies which otherwise may not develop in response to policies that mainly stimulate expansion of the most economic near term alternatives.

Applying all available technologies and measures for transforming the energy system will help to maintain the security of supply and should also lower the risk of jeopardising competitiveness. The latter is important, since certain fuels and technologies are highly sensitive to changes in the surrounding world, such as price fluctuations on the international energy markets, and over-reliance on a single fuel will increase the risks with respect to security of supply and competitiveness. It is important to stress that mitigation of climate change is not associated with technical limitations for transforming the energy system. Figure V shows the electricity generation system in the two pathways (note that Figure V shows the generation mix for the two pathways, not emission reduction wedges) and at least until the year 2020, the transformation of the system is based on commercially available technologies. After 2020, CCS will play an increasingly prominent role, assuming that CCS will be commercially available by then. CCS is to a large extent based on existing technologies and its success is more likely to depend on factors other than technical issues (e.g., public acceptance, the ability of society to impose a cost on the emission of CO_2, and agreement on regulations for storage and monitoring). An additional uncertainty is related to supporting systems, such as investments in transmission networks and storage devices for the accommodation of large-scale wind power. This book reveals possibilities for various so-called ‘moderators’, which will be used to accommodate large-scale wind power in a thermal power generation system (see Chapter 6).

From Figure V it can also be concluded that if energy efficiency measures are successfully implemented (Policy Pathway), it will obviously be favourable for the security of supply, resulting in a more balanced system with respect to the actual mix of technologies.

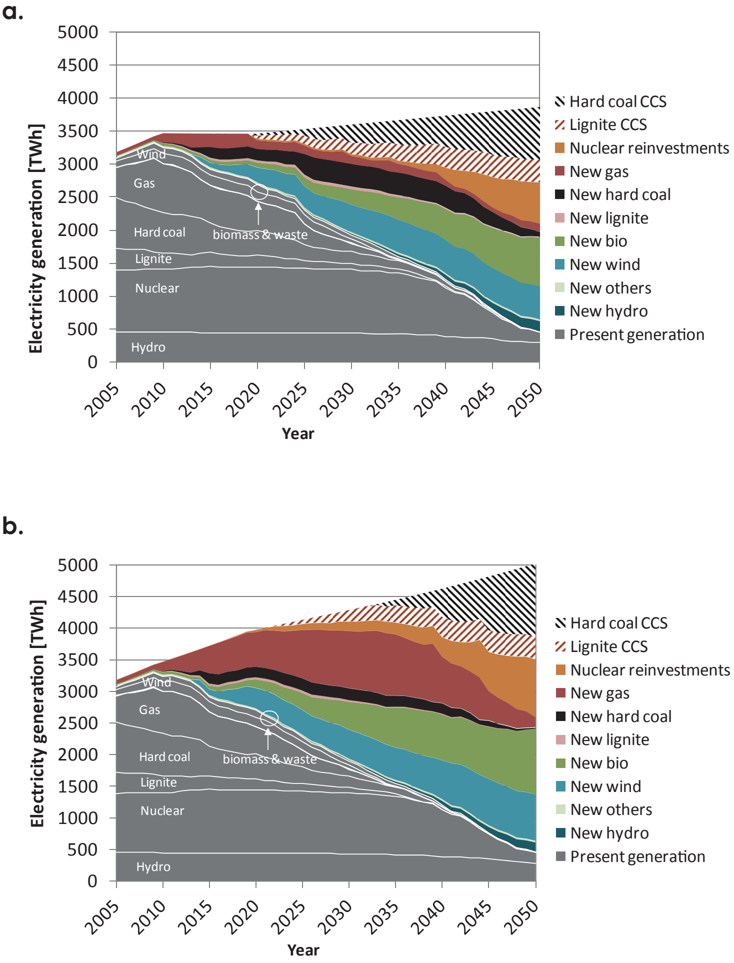


Figure V. Electricity generation in the EU27 countries and Norway, as obtained from the modelling work presented in this book (previously presented by Odenberger and Johnsson, 2010). "Others" include PV, wave, small-scale hydro, and tidal power. a. Policy Pathway; b. Market Pathway. The coloured fields in the graphs represent electricity generation in new plants and the grey fields how the present system is being used.

Considering the large investments that will be needed over the next decades until 2050, there may be a shortage of labour and scarcity of materials, such a steel, especially if there is continued growth of the global economy. In Chapter 1 it is shown that under conditions similar to those of the Market Pathway, large annual investments are required for power plants with CCS from year 2020 onwards. Similar scale of investments in European thermal power plants were seen in the 1970s, implying that such investment levels should be possible. Yet, the future investments will take place in a different context where there will be global competition for labour, steel and other resources. In addition, large investments are required not only for thermal plants (CCS and nuclear upgrades), but also for renewable technologies, such as wind power and biomass CHP plants. Obviously, the Policy Pathway places less emphasis on the supply of materials than the Market Pathway. As for thermal power plants, including CCS plants, this project presented in this book shows that existing sites can partially or completely accommodate the new plants (replacing decommissioned plants), which will facilitate the transformation of the system. Large-scale application of wind power on the other hand obviously requires new sites, which in many instances will result in siting issues. This illustrates that all technologies confer possibilities and impose challenges and problems, highlighting the need for all options, since local conditions and the existing energy infrastructures differ between regions and EU Member States, which means that the preferences for technologies will also be different. In fact, the results shown in Figure V were

“Good news”

The two Pathways to 2050 presented in this book both represent extensive changes in the energy system and implementing these will impose a great challenge for Europe. Yet, the “good news” are:

It is possible to follow the pathways using commercially available technology, while maintaining security of supply and, in spite of that a cost to emit CO_2 is imposed, most likely also maintaining competitiveness of Europe.

There are **great possibilities for synergies** by integrating different sectors (electricity, industry, transportation, agriculture, waste).

Companies are already preparing to respond to requirements from conditions similar to that required by the pathways given in this book.

EU can reach the 2020 20% emission reduction target. Both the Policy Pathway and the Market Pathway provide great opportunities for reaching the targets set for 2020 within the EU. The Policy Pathway even shows a possible GHG emission reduction greater than 20%.

Energy efficiency on the supply side is as important as energy efficiency in end-use, and should be easier to achieve since it demands less incentives and offers synergy opportunities for other targets.

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obtained from a model that is regionalised down to EU Member States, and the results show considerable differences between the Member States (although not shown in this book).

Key technologies and measures

To follow the two pathways discussed in this book, the following key technologies and measures must be applied on a *large scale* over the next decades:

Wind power together with associated investments in the electricity grid, including energy storage devices (Chapters 6 and 8). For the efficient large-scale introduction of wind power, the transmission networks in several regions need to be improved significantly. Once this is accomplished, there will be improvements in the import and export of electricity between regions and Member States, which will make non-predictable generation systems, such as wind power, more efficient.

Efficient biomass supply systems. The agricultural and forestry sectors have the potential to produce large quantities of primary biomass for energy in a sustainable way, without the risk of competition with food production or high emissions from land use change (Chapters 25-28).

Co-firing of biomass in coal-fired power plants (Chapter 12). Biomass co-firing holds the advantage of making use of the infrastructure associated with the coal power plants and represents a bioenergy expansion that is not constrained by the rate at which new bioenergy conversion facilities can be put in place. Biomass co-firing also offers a near-term market for lignocellulosic biomass, which can stimulate development of supply systems for biomass also suitable as feedstock for 2nd generation biofuels. Another valuable key option is biomass repowering in natural gas-fired power plants. Chapter 13 illustrates such an introduction of biomass in natural gas systems.

Energy efficiency improvements in both the supply side and end-use. With respect to the European building stock, the most important end-use energy efficiency goal is to improve existing buildings (Chapters 44-46). New buildings will constitute a rather small fraction of energy efficiency savings in most regions, although they are important for demonstrating new technologies.

CCS and its related infrastructures for transport and storage. In the near term, it is crucial to get demonstration projects up and running, such as those supported by the EU (cf. Chapters 16-17). This is important to ensure that CCS becomes available by 2020 (as assumed in the work described in this book). At the time of writing (late-2010), this seems rather optimistic.

Fuel shifting and structural changes in industry. All options must be used to adapt successfully to the two pathways through fuel shifting, polygeneration, process integration, and the repositioning of their product mixes. This work shows that transforming European industry towards increased sustainability is possible, but requires technological development, economic incentives and large investments. It also shows that the industry - as well as the energy companies - are preparing for transforming in this direction (Chapters 34-35). In this regard, Chapters 18-19 and 37-43 describe the opportunities for industry, including the prospects for CCS.

District heating, at existing and new sites, to harvest the potential benefits of combined heat and power, industrial waste heat, and municipal solid waste incineration (Chapters 29-30 and 32-33). The integration of gasification-based biofuel plants in district heating systems is one option for increasing the energy efficiency and improving the economic competitiveness of such biofuels (Chapter 36).

Electrification of the transportation sector through the development of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs). This offers significant possibilities for lowering CO_2 emissions and other pollutants from the transport sector, as well as for decreasing oil dependency, although battery costs remain high. The value of the existing electricity infrastructure can be used (cf. the concept of path dependency discussed in Chapter 5), and the fossil fuel share in transportation is centralised with CCS as a possibility.

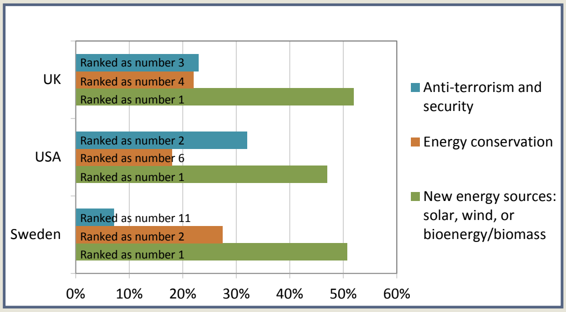
Increased support for the electricity network and transmission network within and between EU Member States (cf Chapters 3 and 4), as recently advocated by the EC (TEN-E, 2010). Smart grids for controlling the charging and discharging of EVs and PHEVs (see Chapter 14), as well as smart control of other electricity-consuming devices. The latter has not been explicitly investigated in the work of this book but the results indicate that smart grids will provide valuable opportunities for efficient use of the technologies and measures investigated.

Use of biofuels in the transport sector. In this case, the development of second-generation biofuels and the use of biofuels for synthetic natural gas (SNG) production are the main alternatives. (Chapter 26).

In addition, there will have to be **changes in legislation** to facilitate efficient and rapid approval of renewable power plants at Greenfield sites (most importantly, wind power, see Chapter 7), and to facilitate the establishment of CCS infrastructure, especially with respect to international networks. Moreover for electrification of the transportation sector the diffusion of the vehicles will of course take time considering the turnover times of the vehicle fleet and competition with other technologies such as development of the conventional car and cars run on 2^{nd} generation biofuels.

Areas that the public want to see their government fund

To investigate public attitudes, opinions, and understanding of issues regarding energy, the environment, climate change, and climate change mitigation options, several joint studies based on polling surveys of the general public have been performed during the period 2003-2010 in the UK, Sweden, the US, and Japan, as part of the work behind this book (see Chapter 20). Both the European and the American surveys asked the respondents to rank the priorities for their national energy agency, and found remarkable similarities in terms of the areas that the public wanted to see their government fund. Out of a list of 13 alternatives, new renewable energy technologies, such as wind and solar energy, were the clear leader, with a majority (around 50%), of the respondents in both the US, UK, and Sweden listing it as one of their top two national research priorities. Energy conservation was also ranked rather high in all surveyed countries, with the highest ranking in Sweden compared to the US and the UK (ranked as number 2, number 6 and number 4, respectively). The anti-terrorism option (related to energy system) had a much higher priority in both the US (ranked 2nd in 2003 and 4th in 2009) and the UK (ranked 3rd in 2003) than Sweden (ranked 11th in 2005 and 12th in 2010). In the US, new oil and gas reserves were also ranked highly (compared to UK, where this alternative was also presented to the respondents but only 6% of the respondents considered it a priority; the Swedish survey did not include this alternative), and it moved to 2nd place in the ranking in 2009, after new energy sources. In Sweden, the most significant changes in priority choices over time (2010 compared to 2005) concern public transport and energy-efficient buildings, which are now ranked 4th and 6th, respectively (ranked as number 5 and number 12, respectively, in 2005).



Comparisons between the surveyed countries (2003-2005) concerning the ranking of priorities in three areas of the national energy agency.

Lifestyle changes or new technologies

Respondents were also asked for their opinions regarding how they believed their country would handle the climate change issue and whether lifestyle changes or new technologies would solve the problem. In comparison to the respondents in the US, UK, and Japan, the Swedish respondents (in 2005) seemed to have the strongest confidence in new technologies, with 34% of the respondents believing new technologies would be developed to mitigate global warming. In contrast, in Japan (2003), 66% of the respondents believed that changes in lifestyle were required to reduce energy consumption, as compared to 33% of the US respondents (2003), 25% of the British respondents (2003), and only 20% of the Swedish respondents (2005). Since then, the percentage of US respondents who believe lifestyle changes will be necessary has increased. However, the most significant shift in opinion (2010, compared to the situation in 2005) has been noted for Swedish respondents, who now seem to follow the US respondents' position, with a clear majority (53%) of the respondents believing lifestyle changes will be necessary, while fewer respondents believe new technologies will be developed to solve the problem.

BRIDGING TECHNOLOGIES CAN FACILITATE EARLY REDUCTIONS IN EMISSIONS AT LOWER COST

Several of the options listed above constitute what is here termed bridging technologies. Bridging technologies take advantage of the existing energy infrastructure and facilitate the development of new energy technologies. The most important bridging technologies are co-firing of biomass in existing power plants, using incineration and industrial waste heat in district heating systems, the retrofitting of the existing building stock, and the application of CCS. Although entirely new and more "sustainable" technologies (e.g., hydrogen-based technologies, solar cell technologies, and nuclear fusion) will undoubtedly be developed, these technologies are unlikely to play major roles in the four decades up to these year 2050, which is the time-frame of this book.

The concept of bridging technology is of course nothing new. In fact, almost all technologies and measures that can be employed at scale over the coming decades can be seen as bridging technologies. The term is used herein merely to stress that all technologies and measures that are presently available, or that are expected to be available for application in the next few decades, must fit into the existing energy system or are heavily dependent upon the present system for good performance. The challenge is to facilitate large-scale application of all the above bridging technologies in the period up to 2050, so as to meet the CO_2 emission reduction goals by 2050, while at the same time developing renewable technologies, such as large scale wind power, new efficient technologies, new efficiency measures, and smart energy systems.

Several of the technologies share the same supporting energy infrastructure, which also has to be improved to meet the new requirements. For example, the electricity transmission network must be improved to accommodate efficient use of intermittent power generation. At the same time, the application of smart electricity networks and improved transmission networks will give rise to new possibilities for developing an efficient energy system, with respect to bridging technologies, energy efficiency measures, and new technologies.

Overall, the interaction between base-load plants and load-following plants must be optimised in a different way than it is today. For example, it will be important to ensure that CCS plants are operated in base-load mode so that the CO_2 flow is held constant and the advantage of maintaining a high load factor is greater than it is in current fossil-fuelled base-load plants. Thus, a difference from the present system will be that there will be more base-load plants and more unpredictable generation from wind power. This entails higher requirements for smart grids and demand-side measures, such as controlled charging and discharging of electric vehicles and the use of energy storage devices. The responses to variations in load could then ideally be devoted to demand-side measures and variations in the production mixes in polygeneration plants for heat, electricity, and transportation fuels.

When implementing bridging technologies it is of importance to be aware of possible options for further development over time. For example, under certain conditions, it may be valid to build new coal-fired power plants before the year 2020, assuming that there is a clear plan for how CCS will be phased in over time. Biomass co-firing may be implemented in such a plant, so as to build up a sustainable market on the biomass supply side. Furthermore, the new non-CCS coal plant can be built to develop the processes and materials with high steam data (to maximise thermal efficiency) which is important for the efficient application of CCS. After 2020, such a plant could be retrofitted to CCS, and new CCS plants could be built that incorporate the experiences and knowledge gained from the non-CCS plant. The development of these large industrial processes and new components and technologies will take at least 10 years. Considering that we need to reduce CO_2 emissions to almost zero within 40 years, it is clear that the development of both bridging and new technologies must be intensified and that policies need to be instigated that send out clear signals to industry that efforts spent on such development will be rewarded in the long run.

The identification of a bridging technology is based on proposing how prospective energy technologies may eventually benefit from development that was initially induced by the bridging technology. Yet, promotion of flexibility and caution of path dependency is motivated, given that it is not possible to say with high level of confidence how the energy system will evolve the coming decades. For example, from the perspective of biomass co-firing paving the way for 2nd generation biofuels, a steady growing biomass demand for co-firing may be considered a lock-in risk. But if biomass co-firing grows steadily in the context of a carbon cap complying with an ambitious climate target (and the transport sector contributes substantially), co-firing may represent a cost-effective long term use of biomass resources. The transport systems may then have evolved to a state where climate compatible technologies other than those based on biofuels are dominant. The essence of the strategy is that it starts up biomass supply chains, and leaves their long-term application open to future investment decisions, either preferring new advanced multi-fuel power plants, 2nd generation biofuel plants, or perhaps new types of plants that co-generate fuels, power and heat from biomass, coal and gas.

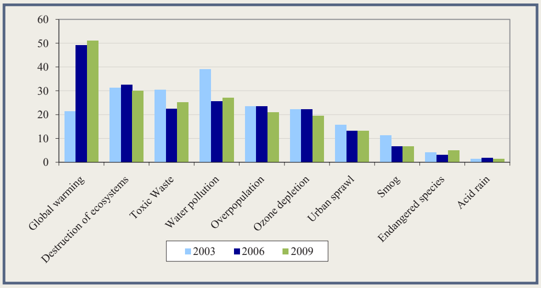
THERE HAS TO BE A COST ASSOCIATED WITH EMITTING GREENHOUSE GASES

The two pathways presented in this work have a clear focus on reducing GHG emissions (around 70% reduction by 2050). Both pathways maintain or improve the security of supply in the EU, primarily by decreasing the dependence on fossil fuel imports, but also because they result in a better balance of fuels on the supply side and make the energy system more flexible. There is increased energy efficiency and decreased use of oil as the primary energy source. Both pathways are based on assumed strong continued economic growth in the EU. A prerequisite for achieving a market that drives the energy system towards following one of the two pathways (or any other pathway that results in the same level of emission reduction) is that there must be a cost associated with emitting GHGs, most importantly, CO_2. This cost could be in the form of a tax or a result from an emission trading scheme. Although there are arguments in favour of both strategies, in the EU, the political consensus favours a trading scheme, the European Emission Trading Scheme (EU- ETS). The EU ETS is the main tool in the climate policy of the EU (cf. Chapter 15).

The EU-ETS will undergo change in 2012, when aviation will join the scheme, and in 2013, when the third trading period starts, it will be further expanded to incorporate petrochemicals, ammonia and aluminium industries, as well as to include additional GHGs. To date, the EU-ETS has had a limited effect, since the emission allowances for much of the time have exceeded demand. In phase 1 (2005-2007), this was because of a generous cap, while in phase 2 (2008-2012), it was due to lower-than-expected demand due to the global economic crisis (cf. Chapter 15). Thus, it is of great importance that the cap (i.e., the amount of emission allowances) is reduced to match the targeted reductions in emissions. Unfortunately, the banking of allowances in combination with the economic recession have resulted in an excess of allowances, and it is likely that the price of an emission allowance will not exceed 20€/tonne CO_2 until the year 2020. This price level is likely to be too low to apply sufficient pressure for the energy system to be transformed along the two pathways discussed in this book. Yet, providing the cost for emitting CO_2 soon after 2020 increases to comply with required reductions, at least for the electricity generation system, it should be possible to follow the pathways as shown in Figure V (for which the required allowance price starts at 10 €/tonne and increases to 25 €/tonne CO_2 by 2030 followed by a steady increase to about 50 €/tonne CO_2 by 2050 in Policy Pathway, somewhat higher in the Market Pathway).

Public attitudes to climate change and other environmental issues

A survey was carried out to investigate attitudes towards climate change (see Chapter 20). Respondents were asked to rank the importance of different environmental issues. In the first survey (carried out between 2003 and 2005), global warming was considered to be the most important issue in both the UK and Sweden, while the US respondents ranked it only as number 6 after water pollution, ecosystem destruction, overpopulation, and toxic waste. This result was comparable to the outcomes of Gallup surveys conducted in the US over the same time period, in which various forms of water pollution were ranked as the leading environmental concern in the US. However, since 2003, there has been a significant change in US public opinion regarding the importance of global warming. In the 2006 survey, global warming was ranked as number one, followed by the destruction of ecosystems and water pollution.



US respondents' ranking of the most important environmental issues in 2003, 2006, and 2009. There has been a dramatic change since 2003 regarding the extent to which people in the US view global warming as a problem of importance. Source: O'Keefe and Herzog, 2009.

ELECTRICITY AND DISTRICT HEATING WILL BE INCREASINGLY IMPORTANT AS ENERGY CARRIERS

Reaching the ambitious climate targets set as political goals requires the efficient use of available resources. The electricity generation and district heating systems have the potential to facilitate the efficient use of primary energy while reducing CO_2 emissions.

Electricity generation system

This book shows that European electricity generation can reduce its CO_2 emissions to almost zero by 2050 (see example in Figure V) at a cost that should not exceed 50€/tCO_2. This is promising, as the electricity and heat sectors dominate the EU ETS, being responsible for 72% of the total emissions (Chapter 15) in this scheme. This implies that the specific CO_2 emissions from electricity generation could be significantly reduced in almost all European countries (Figure VI). In only a few countries where specific emissions are already very low, e.g., in the Nordic countries, specific emissions may increase to some extent. By 2020, the average specific emissions in all Member States will be less than 600 kgCO_2/MWh in both pathways. In 2005, the corresponding level was 900 kgCO_2/MWh (Chapter 10).

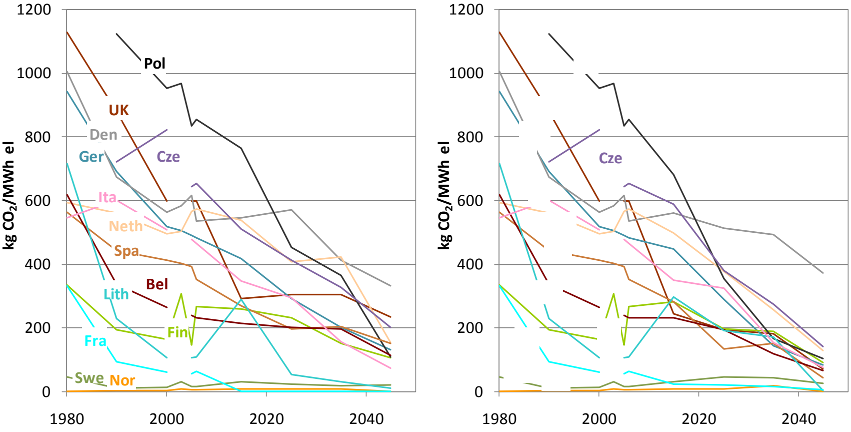


Figure VI. Average specific CO_2 emissions from electricity production in selected European countries in the Policy Pathway (left) and the Market Pathway (right) (see Chapter 10 for details).

Regarding electricity, there is already an established infrastructure. Although this has to be improved to accommodate higher capacities of wind power and possibly other renewable forms of electricity generation, the existing system constitutes a solid base from which improvements can be made. As indicated above, electrification of the transportation sector will reduce oil dependency at the same time as the share of electricity generated from fossil fuels will be produced in CCS plants. Thus, a shift to electric vehicles does not necessarily confer immediate reductions in carbon emissions, rather it must be viewed as a transition to a system in which electricity becomes a low emission energy carrier. As shown in Figure VII, an electric car powered by "EU-average marginal electricity" gives higher CO_2 emissions than an average car today (see Chapter 10). However, already from 2020, it has the potential to give lower emissions due to reduced CO_2 emissions from electricity generation, as shown in Figure VI.

Therefore, there has to be an overall integrated strategy for the stationary and transport sectors. From an efficiency point of view, biomass use in large centralised plants is preferable, since these can achieve high conversion efficiencies (albeit through co-firing with coal). The use of waste heat in district heating (DH) systems is another way to improve energy efficiency. In the longer term, biomass use in polygeneration plants that produce a range of energy (and other) products is an attractive option. As for electricity use in the transport sector, the systems have to be developed over time, with co-firing of biomass in existing power plants with high steam data (i.e., high efficiency) as an early "stepping stone" technology that will pave the way for more advanced polygeneration plants.

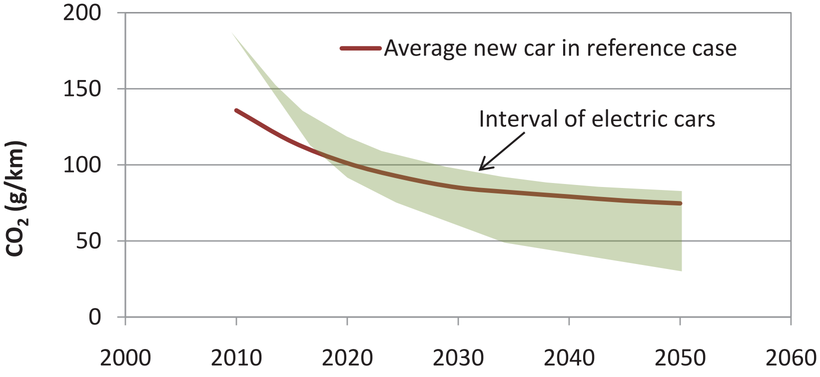


Figure VII. Development patterns of specific CO_2 emissions from new "average cars" and new electric cars, respectively (see Chapter 10).

District heating systems

As indicated above, DH provides possibilities for efficient use of fuels (combined heat and power) and for the recovery of waste resources, such as industrial waste heat and heat from waste incinerators. Thus, by using such waste heat resources, DH can serve as a bridging technology. In particular, where a DH network is available, it is possible to shift the fuel used from fossil fuels to biomass over time without changing the end-use sector. In addition, when there is an available DH network, the building of waste incineration plants bridges the cost gap to less expensive landfilling. Since landfilling is normally associated with emissions of toxic compounds and the climate-affecting gas methane, incineration with heat used in DH has twofold climate benefits, not only reducing the CO_2 emissions from the fuels that would otherwise be used for heating, but also reducing methane emissions from landfills (Chapter 29-30).

This book shows that there is considerable potential for the expansion of DH in many European countries (Chapter 32). France and Germany have the greatest expansion potentials, while Italy and the UK also have significant possibilities in this respect. In the work of this book, a detailed study of 83 cities in France, Germany, Belgium, and The Netherlands verifies this outlook (Chapter 33). The present market share of DH in these areas is 21%. In the EU, the average market share of DH is around 13%.

The DH share of the heating market by 2050 is predicted to increase by 100% in the Policy Pathway and by 150% in the Market Pathway (Figure VIII).

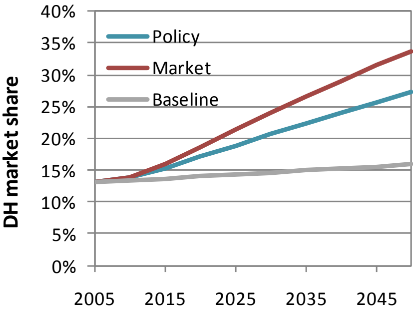


Figure VIII: The development of DH in the two Pathways, as compared to Baseline, given as the DH share of the heating market.

District heating in Europe

In the EU25 countries, there are more than 5000 district heating (DH) systems.

DH supplies about 13% of the total annual heating demand.

The penetration of DH varies among member states, reaching at 30-50% in the Baltic States, Denmark, Finland, and Sweden.

About 80% of the DH in the EU25 is generated using fossil fuels, in either combined heat and power plants (about 75%) or heat-only boilers (about 25%).

In the district heating sector in Sweden over the last 20 years, there has been an almost complete shift from fossil fuels to biomass, illustrating the possibilities for DH systems.

Obviously, DH competes with other heating technologies, such as heat pumps and domestic heating. Furthermore, energy efficiency measures will result in reduced heat demand. Nevertheless, it has been shown that when energy efficiency measures are carried out in buildings, the corresponding reduced demand for heating in most cases is not an obstacle to DH in high-heat-density areas, since the increase in cost for distribution is low compared to the typical prices of supplying district heat and competing heat (Chapter 33). Given the slow turnover of the building stock, DH also has the potential to generate emissions reductions more rapidly than measures such as passive housing.

As indicated above, DH also opens the way for the application of polygeneration plants to the production of electricity, heat, and transportation fuels in different combinations. Matching the heat production of such technology with the heat demand of DH systems has been achieved for each Member State of the EU25 (Chapter 36). The results show that all countries, with the exception of Italy, theoretically already have sufficient DH capacity to absorb the excess heat of the polygeneration capacity needed to reach the biofuels target. In reality, this potential will depend inter alia on the size of the polygeneration facilities.

THE EXISTING ENERGY INFRASTRUCTURE WILL STRONGLY INFLUENCE THE PATHWAYS

An important condition when transforming the energy system is that there is already a system in place – the present energy infrastructure with associated actors and institutional framework. This comprises a large capital stock with long turnover time. Furthermore, there are legal and social structures, as well as valuable know-how attached to the technologies that presently predominate, all of which offer possibilities for rapid implementation of bridging technologies, while also limiting the possibilities for the large-scale introduction of entirely new systems. The key is to use the existing infrastructure to initiate the transformation on a large scale and develop conditions for new technologies, such as second-generation biofuels, CCS, and the expansion of wind power.

The energy infrastructure

An important facet for the work reported in this book is the inclusion of the energy infrastructure in the analyses of the two pathways. This was achieved using the Chalmers Energy Infrastructure database (CEI db), which include major power plants in the EU27 and the fuel infrastructure, as described in the *Methods and Models* book. Special care has been taken to record the age of the power plants, which determines when they can be expected to be phased out. The energy infrastructure consists of components that typically have long lifetimes. This means that once investments have been made in a power plant, transmission network or natural gas pipeline, it will be costly to shorten the expected lifetime (or rather, new investments will have difficulties competing with the existing plants). Typically, such systems have a technical lifetime of at least 25 years, although it can be up to 40 years.

The CEI db comprises several sub-databases that describe different parts and areas, both on the demand side and supply side, of the European energy system (Figure IX). 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 CEI db is continuously being updated and the scope widened. More extensive descriptions of some of the sub-databases and their applications are given in Chapters I in the *Methods and Models* book.

This book is accompanied by the **Methods and Models book**, which describes the methodologies used in the Pathways project.

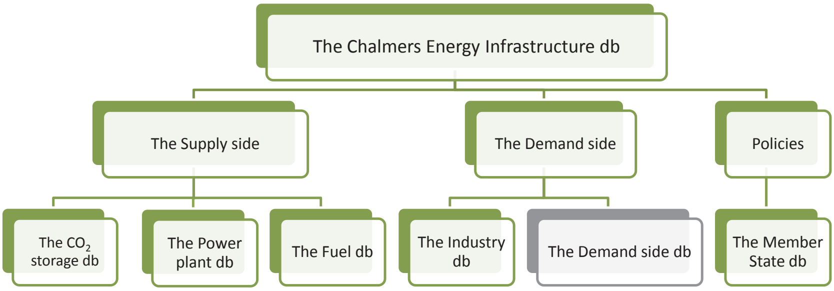


Figure IX. The structure of the Chalmers Energy Infrastructure database. The sub-databases marked in green are ready to use, while that in grey is under construction.

As an example of the data stored in the databases, the power plant infrastructure of the EU27 is shown in Figure X. The EU has a significant power plant stock aged 20-40 years, constituting almost 300 GWe, and mainly coal-fired, hydro power, and nuclear power plants. Coal and nuclear plants represent the fundamental energy infrastructure of the EU, and although plants will be phased out over time, they will continue to be important for several decades, as shown in Figure V. However, in terms of what has been built in the past 10 years and what is currently being built or planned, natural gas-fired power plants (NGCC) and wind power plants predominate. From Figure X and the modelling incorporating this data (shown in Figure V above), it can be concluded that the existing energy infrastructure will strongly influence the pathways up to the year 2050. In addition, there is an additional momentum in terms of the development of the global infrastructures for oil, coal, and gas used to support the existing energy system. It is obvious that the system described in Figure X not only represents the technical components (e.g., power plants), but also the institutional framework with its associated norms, expectations, traditions, and conventions.

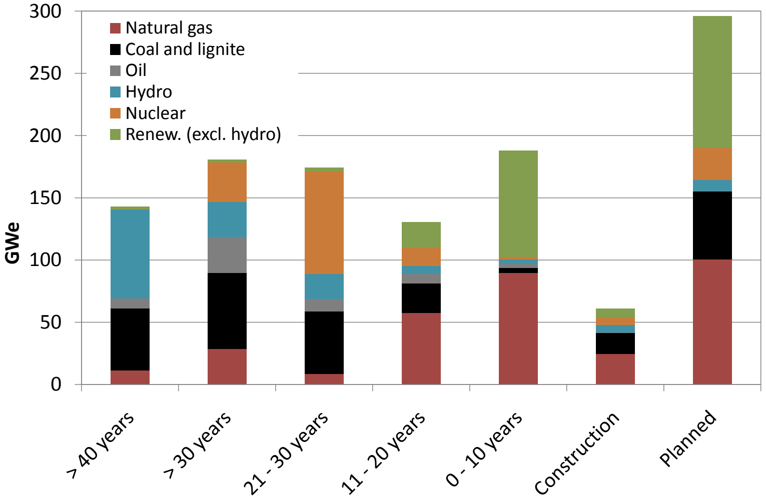


Figure X. Power capacities distributed by type/fuel and age for the year 2010, and for planned power plants in the EU27, as obtained from the Chalmers Power Plant database. (Renevable generation is associated with some uncertainties.)

The social embedding of energy technology and systems

Technologies, the economy, politics, and the law are embedded in social relationships and structures that build on norms, expectations, traditions and conventions that serve to stabilise and order human interactions. 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 people's actions, intentions, understandings and reactions 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. All this implies that there are path dependencies upon technology, policy, and the institutional and legal frameworks.

Path dependence

Path dependence focuses on the constraints on choice imposed by earlier decisions, through returns or incentives, and contributes to an understanding of "bounded rationality" in organisational decision making (see Chapter 5). A core idea is that the temporal sequencing of events potentially has crucial consequences for consequent decision steps. An important distinction is made between two types of path dependence:

- A *self-reinforcing sequencing* of events tends to reproduce an institutional pattern by "increasing returns", by means of some form of utility or benefit.

Since early events are being re-enforced by the reproduction of a mechanism of increasing returns, self-reinforcing path dependence tends to be highly resistant to change.

- A *reactive sequence* has a different logic, since late events are driven by reactions to earlier events through ‘backlash’ processes that change or negotiate the early events.

Policy and its implementation hardly constitute a linear road from goal to goal fulfilment. Implementation research has shown that this road is often winding and crowded with serious obstacles. It is crucial to have a sense of common direction and path dependence among the implementing actors, who tend to be driven by diverse goals, using diverging strategies and organisational action logic. The policy itself is often complex and lacks precision, and as a consequence, the implementing actors (public administrators, business representatives, legal or scientific experts) make discretionary decisions based on their interpretations of the policy goals.

All this constitutes both limitations for change and possibilities for speeding up transformation of the energy system by taking advantage of the current institutional framework with its norms, knowledge, and conventions. Focusing on the possibilities, it is possible to exploit the existing infrastructure to initiate the transformation on a large scale and to develop conditions for new technologies, such as second-generation biofuels, CCS, and large-scale introduction of wind power.

EXISTING AND NEW ENERGY INFRASTRUCTURES MUST BE DEVELOPED

Although the bridging technologies take advantage of the existing energy infrastructure, this infrastructure also needs to be developed, as new supporting infrastructure has to be established together with the corresponding institutional framework.

The implementation of CCS and the increased use of bioenergy require an extensive transport infrastructure, including CO2 transportation and storage networks and biomass handling facilities. The production of second-generation biofuels requires substantial changes in the agricultural and forestry sectors. Large investments will have to be made to strengthen, expand, and upgrade the electricity networks, in order to accommodate high levels of wind power and other forms of intermittent electricity generation. Expansion of DH networks will be a challenge in terms of investment, public support, and planning. Synergies can be achieved if the transition of the energy systems is co-ordinated with transformations of other sectors, such as industry, transport, waste, and agriculture.

CCS infrastructure

Two key prerequisites for the commercialisation of CCS are that an integrated transportation and storage infrastructure is established in a timely manner (planning must be commenced within a few years) and that market regimes are established (e.g., public-private partnerships). Co-ordinated planning is needed for a large-scale CCS infrastructure that takes into account the existence of emission clusters, consisting of both power plants and industries. It is important to instigate CCS support schemes and concerted actions for building up a CCS infrastructure, so as to minimise the time before the expected roll-out costs are reached, i.e., the costs normally assumed in modelling, such as those in the pathways shown in Figure V.

Wind power and grid issues

A power system with a large share of intermittent renewable sources, such as wind power, should be fitted with moderators that allow the shifting of power production in time, so as to meet demand. In the work that forms the basis of this book, the efficiencies of different moderators were investigated, using western Denmark as a test case (applying restrictions related to balancing with neighbouring regions). Wind power penetration rates corresponding to 20% and 40% of the grid capacity were investigated (Chapter 6). Moderators assimilate power when there is over-production and deliver power when the demand increases. This is beneficial for the thermal power plants, as these would otherwise have to undergo frequent stops and start-ups, which decrease efficiency and increase costs and emissions. The application of existing moderator technology was found to decrease system emissions by 7.5%-10.3%.

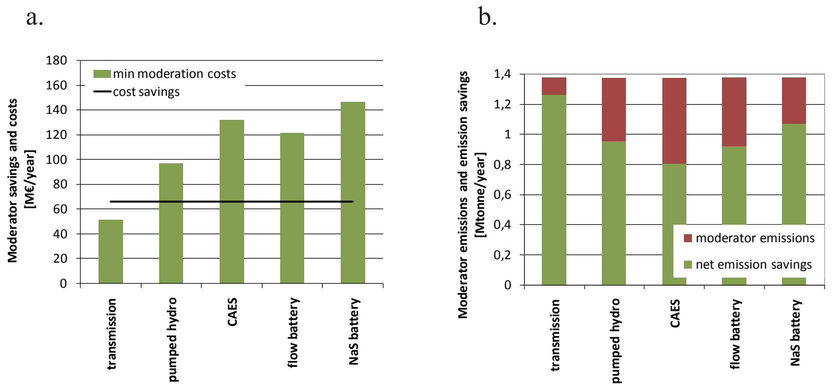


Figure XI. Costs associated with different moderators and their emissions (weekly balanced moderator used as an example). a) Cost savings (solid line) compared with costs for moderation (bars). b) Emission savings reduced by emissions associated with moderation (see Chapter 6).

Smart grids and demand-side management

As a way to decrease the need for new investments in strengthened transmission capacity and/or storage, the demand side can be adapted to the variations in electricity generation. The concept of smart grids and demand-side management (DSM) are strongly connected, in that smart grids typically involve information exchange (for instance, sending price signals to users) over the grid to support DSM. This will facilitate the efficient introduction of intermittent electricity production, such as wind power, by moving part of the demand to the time when production levels are high. As discussed above, the two pathways will involve an increase in low-CO_2-emitting base-load generation, which together with increased levels of wind power will make DSM and smart grids increasingly attractive. Electric cars and plug-in hybrid electric cars can be used for DSM.

The results from the simulation of the western Denmark system indicate that the use of DSM to manage the variations in load throughout the day is sufficient to accommodate in an efficient manner wind power generation corresponding to 20% of the total demand for electricity. With wind power generation in the range of 40% of the total demand, the variations in wind power exceed the variations in load and need to be balanced on a weekly basis, typically with moderators, such as pumped hydro or transmission systems.

Biomass supply infrastructure

Bioenergy expansion requires the establishment of a functioning biomass supply infrastructure. For example, in most European countries, the wood supply infrastructure has still to develop in response to changing demand patterns, as bioenergy becomes an increasingly important end use. This development not only concerns technology and the economics of logistical systems, but also institutional development. Therefore, regulations need to reflect the new situation and ensure that the increased forest biomass output respects sustainability considerations, which in many instances also need to be elucidated. One example is the increased utilisation of the residues from forests, including stumps, which requires regulation and compensatory measures to maintain nutrient balances. Furthermore, the increased demand for forest wood in general can be expected to stimulate measures to intensify forest management, e.g., forest fertilisation may become more common. This intensification needs to be managed in a responsible way. Similarly, very limited cultivation of lignocellulosic plants for energy exists in Europe. To date, production has mainly consisted of fibre crops for non-energy purposes and harvest residues, such as straw. Currently, harvest residues are collected mainly for animal feed and bedding, although in a few countries they are also used for energy purposes (heat and power).

PATHWAYS FOR THE JURIDICAL FRAMEWORK MUST BE IN PLACE

A sustainable energy and climate policy requires not only technical advances, but also a legal system that clearly supports the implementation of policies. This does not presently exist in the EU. There are conflicts between energy policies and other interests, e.g., in terms of impacts on the local environment, and these interests are often supported by legal restrictions. In other cases, the technologies are too new to be handled by existing legislation. Even if the cost barriers to a technology are removed, barriers to implementation may still be found in the design of the legal and administrative systems required for implementation of the technology.

The law has basically two functions: to solve conflicts between individuals and, most importantly here, to direct human behaviour so that politically important objectives are attained. Therefore, the law plays a crucial role in the design and application of the pathways to a sustainable energy system.

A balance must be found between the required new infrastructures that lead to a more sustainable energy system and the protection of sensitive natural areas, private land use, and recreational interests. The difficulties that can arise are exemplified by the diffusion of wind power. Typically, goals for increased renewable power generation from wind mills are diametrically opposed to goals for the preservation of sensitive areas and, perhaps more often, public perceptions of visual and noise disturbances. A study of the UK, Norway, Sweden, and Denmark shows that the separate national governments handle these issues in rather different ways (see Chapter 7). Given that the level of installed capacity varies greatly between these countries, it is clear that differences in legislation have had a significant impact on technology implementation. Recommendations for successfully reaching the goals for installed national wind capacity include removal of the general permit requirement, which would leave the entire process to the planning system, and breaking up of the municipal planning monopoly. A successful system would have to include national planning instruments that both set targets and direct the lower-level planning. Moreover, it is necessary to establish control functions for the contents, adoption, and implementation of overview plans, since these will serve as the link between the national level and the legally binding detailed plans. Substantial rules for the planning and location of wind power plants, including the environmental impact assessment, should be implemented at this stage in the planning process. The final stage of the process would be the "detail plan"; this plan is probably the best suited instrument to control local development.

Many of the issues associated with the transition and large-scale implementation of bridging technologies are new to society and therefore not covered by current legislation. One important example is CCS, which involves the large-scale transport and storage of CO_2. These activities are not fully covered by present day rules and regulations. CCS should be handled by EU directive 2009/31/EG, which is due to be in place by June 25th, 2011, although there will still be much work to be done in implementing and adapting CCS legislation on the national levels. Some aspects of the technology, such as damage and land issues, could fall outside current legislation, in which case it will be important to create a working legal framework.

FOLLOWING THE PATHWAYS REQUIRES STRUCTURAL CHANGES ACROSS SECTORS

Reversal of the current trend and moves towards sustainability represent a complex process that requires fundamental changes in the society as a whole. This book gives several examples of what has to be accomplished and on which sectors other than energy, such as the industry, transportation, agricultural, forestry, and waste management sectors, attention needs to be focused. The book also exemplifies the changes needed in the institutional framework of society, including the legal framework and the business models and strategies of companies, and shows how sustainability can be part of the business of these companies.

The results presented in this book show that there are few, if any, simple or fast solutions. The transition to a more sustainable energy system will take time. In many cases, the transition must be allowed to progress in a step-wise fashion, so that new measures and technologies can be developed and established efficiently. It is also of important that these technologies are accepted by the vast majority of the public and that they are regarded as part of everyday life.

Realising biomass supply potentials requires structural changes in the agricultural and forestry sectors

Realising future biomass supply potentials requires far-reaching changes in present land use, including the planting of many million hectares of land with bioenergy plants (Chapter 26). It is expected that lignocellulosic biomass will be used as the main raw material in the longer term. The importance of lignocellulosic crops has also been recognized by the European Commission (EC), which in its communication on an EU strategy for biofuels includes as one of the three main aims: *"…to prepare for the large-scale use of biofuels by improving their cost-competitiveness through the optimized cultivation of dedicated feedstocks, research into "second generation" biofuels, and support for market penetration by scaling up demonstration projects and removing non-technical barriers"* (COM, 2006).

As described above, institutional development will be required as biomass production for energy increases. The ways in which agriculture and forest bioenergy develop will determine whether and to what extent bioenergy expansion leads to positive or negative outcomes for the climate and the overall environment.

Ongoing structural changes in the waste management system

European waste management will be forced to undergo extensive changes to reduce its environmental impact in accordance with current EU directives. The outcomes are likely to include decreased quantities of waste sent to landfilling and increased re-use, recycling, and recovery of waste. The current European waste management system is largely dependent upon the landfilling of waste (Figure XII). Landfilling is the waste handling alternative that has the lowest cost, both in terms of investment and operating costs. However, the environmental impact of landfilling waste is significant; as large amounts of methane are emitted when the organic waste fractions decompose in the landfill.

Recovery measures in waste management include energy recovery, and the potential for energy recovery from renewable waste fractions is significant. Renewable waste streams have the potential to contribute up to 20% of the total EU reduction target for greenhouse gases up to 2020, owing to a double climate benefit in reducing both methane and CO_2 emission levels (see Chapters 29 and 30). The corresponding contribution to the target of increased share of energy from renewable sources is 10%.

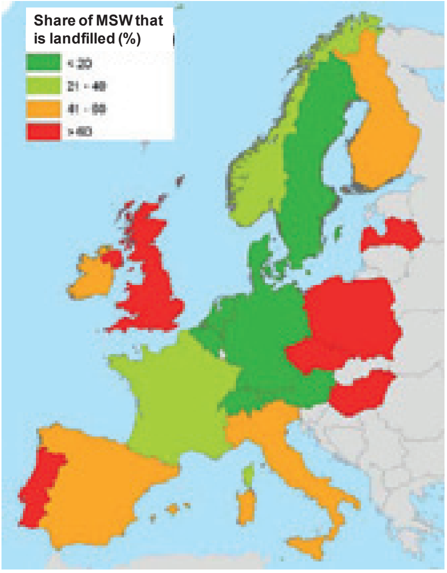


Figure XII. Share of treated municipal solid waste that was landfilled in 2008.

Structural changes within industry – the example of the steel industry

Structural changes within energy-intensive industries will be important for achieving low emission levels (Chapter 37). A specific example is the EU iron and steel industry, which is both material- and energy-intensive. This industry has played, and will continue to play, a vital role as a mainstay of European industry. The European share (EU15) of global steel production was 9.5% in 2009 (WSA, 2010). The iron and steel industry now faces structural changes within steel production (see Chapter 41). Primary ore-based steel production (the Blast Furnace/Basic Oxygen Furnace route) would, according to the assumptions made in the project, lose its role as the main mode of steel production. Instead, secondary scrap-based production (the Electric Arc Furnace route) will grow to constitute 55%-60% of the total EU15 steel production by 2030.

THE TWO PATHWAYS OFFER SYNERGIES BETWEEN SECTORS

Although the structural changes that are needed for the transition to a sustainable energy system involve great challenges for society, they also entail opportunities for synergies. Seizing these opportunities is cost efficient and contributes to maintaining, and perhaps even strengthening, the competitiveness of European industry on the global market.

Timing is of the utmost importance when it comes to realising the full potential of the synergies that appear during the transformation of the energy system. Enablement of parallel structural changes in the various sectors is crucial. Assuring that the timing is correct is in many respects a task for politicians and decision makers.

Historically, the market has been efficient when it comes to taking advantage of opportunities for synergy. To give the market and the actors in the market enough freedom with regard to responsibility for the transition towards a sustainable energy system increases the probability that this transition will be cost-efficient and include the synergies.

District heating – an energy infrastructure with significant potential for synergies

The development of the European DH sector is of crucial importance to exploring synergies in the heating sector. DH allows for several possibilities or strategic advantages for integration between sectors (Chapter 32):

1. Industrial waste heat typically is at low temperature and therefore, lacks useful applications. However, DH makes it possible to utilise this otherwise wasted resource for heating purposes.
2. Waste incineration becomes a competitive measure from a waste management perspective if efforts are made to minimise landfilling. Energy recovery is, in addition to its value in terms of volume reduction, an important part of waste incineration.
3. Combined heat and power (CHP) production is a powerful measure for improving the efficiency of energy conversion.

4. The byproducts of agricultural and forestry production, i.e., “unprocessed” bioenergy sources, are fuels that require large inputs for handling, combustion, flue gas cleaning, etc., which DH can facilitate.

Combining two or more of these strategic advantages is an attractive option. For example, a combined plant that uses biomass for the production of transportation biofuels, and in which waste process heat is recovered and electricity is produced through CHP, combines three of the strategic advantages.

Significant possibilities for synergies for the refinery industry – an example

There are significant possibilities and measures for energy-intensive process industries to reduce CO_2 emissions and to create synergy effects for CO_2 abatement. However, several of the abatement options will rely on appropriate infrastructures and integration between sectors. One important example is the refining industry, for which the distances and connections to DH networks, natural gas grids, neighbouring industries, and CO_2 storage sites have been evaluated (Chapter 42). Figure XIII shows the geographical distribution of refineries in Europe. The red bars indicate refineries with the possibility to connect to a natural gas grid. The yellow bars indicate refineries within chemical clusters. The black bars indicate refineries with the possibility to connect to a DH network. Possible CO_2 storage sites are represented by grey lines. Since Kraft pulp and paper mills are possible producers of renewable feedstock for refineries, their locations are indicated in the map as green triangles. Potential carbon capture clusters are highlighted in grey. To date, few appropriate infrastructures for these options have been established, and co-ordination across different sectors remains a challenge that must be overcome before the full potential of these options can be exploited.

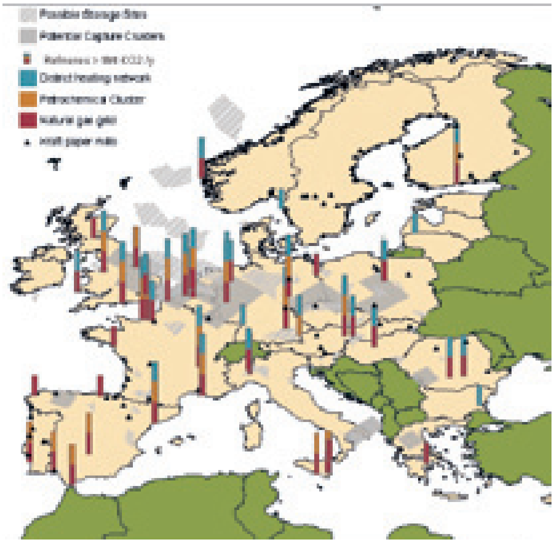


Figure XIII.
Geographical distribution of refineries, kraft pulp mills, CO_2 storage sites, and carbon capture clusters.

Linking mobile and stationary energy systems

Energy systems for modes of transport, which are heavily dependent upon fossil oil, have during the 20th century developed in a manner that is decoupled from stationary energy systems. Although major changes have yet to take place, the prospect of dwindling oil reserves and the necessity to decrease CO_2 emissions and to enhance efficiency suggest that increased integration of mobile and stationary energy systems will occur as indicated above. This integration will create new synergies. The increased reliance on large-scale utilisation of intermittent (or variable) resources, such as wind and solar energy, will necessitate the derivation of efficient methods for adjusting electricity supply and demand, which may be feasible through the development of hydrogen and electricity storage systems, including the use of the transportation sector as a storage device (Chapters 8 and 14). The production of some types of alternative transport fuels, e.g., liquid fuels via biomass gasification, will generate waste heat that can be used in DH or in connection with biofuel production from fermentation, a process that is likely to consume large quantities of low-temperature heat.

Multifunctional bioenergy systems

Biomass production for energy purposes is a good example of a situation in which a holistic perspective must be adopted. The primary aims of greater use of renewable energy sources, such as biomass, are to improve energy security and to reduce society's influence on the climate by displacing fossil fuels.However, the production of biomass for energy may also yield significant additional environmental benefits related to changing how land is used for forestry and agriculture.

Multifunctional bioenergy systems with well-chosen localisation, design, management, and system integration can offer numerous environmental services, which in turn create added value for the bioenergy system and synergies (see Chapter 26). Some multifunctional bioenergy systems are exploited for directed environmental services, an example being the cultivation of Salix as a vegetation filter for water purification and the handling of sludge or as a protective zone against nitrogen leakage. Other systems provide environmental services of a more general nature, for instance, increased carbon fixation and land fertility, cadmium unloading, and improved hunting potential.

COMPANIES ARE PREPARING TO RESPOND TO THE REQUIREMENTS OF THE ENERGY PATHWAYS

Companies in the stationary energy sector are already preparing to respond to the requirements for sustainable development and are intensifying their efforts to integrate sustainable practices into their business plans. By applying a strategic perspective to the environment, companies can develop new business opportunities and contribute to sustainable development within their sphere of activity.

In Chapter 34, it is concluded that companies with a proactive strategy for environmental sustainability follow a sustainable vision for their business that includes reducing their carbon emissions, improving the environmental qualities of their products, and investing in clean technologies. In addition to mapping these proactive strategies for environmental sustainability through case studies of energy companies with a strong environmental focus, the key mechanisms that facilitate such strategies have been investigated to reveal pathways for sustainable development for companies in the stationary energy system. The results (Chapter 34) illustrate that by applying a strategic perspective to the environment energy companies can develop new business opportunities and contribute greatly to sustainable development within their sphere of activity.

Carbon strategies of ten of Europe's largest energy companies

A focus on the actual emitters of greenhouse gases is essential for assessing the real prospects of achieving a transition to a more sustainable energy system (see Chapter 35). A brief account of the 'carbon strategies' of ten of Europe's largest energy companies, based on their responses to the 2009 Carbon Disclosure Project inquiry, reveals that these companies are in the process of implementing strategies that reflect the need for less-carbon-intensive and more sustainable production of energy carriers. Renewable capacity investments represent the largest chunk of the investments, although investments in conventional thermal capacity are also significant. This underlines the importance of new mitigating technologies, such as CCS, for making real progress towards CO_2 abatement. Overall, the portfolio of measures that constitute the companies' carbon strategies seems be geared more towards internal efforts than towards customers and stakeholders. In the next step, product stewardship and the corporate vision also have to be geared towards sustainability, if these large energy companies are to make a broader contribution to sustainable development.

THE GLOBAL FOSSIL FUELS RESOURCES ARE TOO LARGE – THIS IS THE CHALLENGE!

From a climate change perspective the reserves of fossil fuels are too large. Although conventional oil reserves are declining, from a climate perspective, not happening fast enough, and in any case, oil is not the main issue. Instead, the vast resources of coal, natural gas, and other hydrocarbons, such as tar sands and oil shale, represent a major obstacle to efforts to restrict emissions.

The fossil fuel reserves hold significantly larger amounts of carbon than can be allowed into the atmosphere in the 21st century if we are to limit the increase in global warming to 2°C. Therefore, climate preservation cannot be driven solely by the prospect of fossil fuel scarcity. Strong policies are needed to prevent the release of hazardous amounts of CO_2 into the atmosphere. Preventive policies, i.e., broadening the supply base and promoting energy efficiency, will also be beneficial for ensuring the security of supply, thereby avoiding the possible price shocks related to gaps in the supply of oil or gas.

An important part of the work reported in this book was to understand the global markets for coal, oil, and gas (Chapters 21-23). These markets have been mapped and assessed with respect to resources and their associated infrastructures on a global scale (even though the project has a European focus, these markets are truly global). The mapping was considered necessary because of the different views as to how fast we are running out of fossil fuels. This has strong implications, since the availability of fossil fuels has been a key factor in the development of the global economy for the past century, and will remain so throughout the coming century. In addition, in the four decades remaining until 2050, the existing and planned fossil fuel infrastructures will greatly influence possibilities to transform the energy system.

Coal – abundant resources and reserves

Coal is arguably an abundant resource. The global conventional reserves are 710 Gtons hard coal and 280 Gt lignite, which represent reserves of more than 160 years at current consumption levels (6.1 Gt in 2006). The potential reserves could be several-fold higher, as the total global resource of coal is estimated to be about 20-times larger than the proven reserves (~20000 Gt).

Oil – plentiful, although supply could be tight

Oil can be considered as the most important fossil resource because of its versatility. The extraction rate of this resource will decline as proven reserves approach exhaustion. It is estimated that half of the world's conventional oil will have been used sometime between 2022 and 2028, and that production will have peaked or reached a plateau some years earlier (Chapter 21). In the IEA World Energy Outlook for 2010 (IEA, 2010), it is stated that conventional crude oil production probably reached an all-time high peak of 70 million barrels/day in 2006 and will plateau at slightly below that until 2035 – provided that new fields are found and developed at the same pace as the existing fields are depleted. This does not mean that the world will run out of oil over the coming decades. Large resources potentially exist in unproven reserves of oil and unconventional oil, and there are possibilities to synthesise liquid fuels from coal or natural gas. However, it does mean that the supply situation is likely to become tight.

Although a shift towards unconventional oil and the production of synthetic fuels is expected, the phase-in may not be fast enough to feed the growing demand as conventional oil production levels off or dwindles. The share that unconventional oil has of global oil production is not likely to exceed the projections made by the IEA (2006), i.e., less than 5% in 2015 and 8% in 2030. The twenty super-giant fields that account for 25% of global production are ageing and in unknown condition; a rapid decline in a few of these would more than offset all the new unconventional oil. Countering this is the potential to increase production from existing fields using new technologies. There are examples of oil fields producing significantly more than what originally expected, for instance in a couple of the Norwegian oil fields. This all leads to a situation of great uncertainty in the oil market and the risk of shocks, at least in the short-term, when demand exceeds production.

Natural gas – increased import dependency for Europe

European dependency on natural gas imports will increase, which will affect the security of supply, not only for the gas sector but also for the electricity sector. Future gas demand will partially depend on the level of continued CO_2 emission restrictions, a possible nuclear phase-out in the UK, Germany, and Belgium, and the extent to which the option to store CO_2 in subsurface reservoirs will be applied. Problems related to gas production capacity, together with abundant supply to the EU markets and increased competition, indicate that Russia will lose market share in the short term, particularly since piped Russian gas is not competitive on the main growth markets, i.e., the UK, Italy, and Spain. Nevertheless, in the long run, it can be expected that EU dependency on gas from Russia and the Middle East will increase. A critical factor is the large and timely investments required along the entire fuel chain to meet rapidly increasing demand, often in regions with uncertain investment conditions.

Coal, oil and gas – threats to the climate!

As shown in Figure XIV, the total resource base of fossil fuels can allow much higher carbon emissions than can be allowed without significant risk for the climate. The coal *reserves* alone hold so much carbon that if it was emitted as CO_2 would probably increase world temperatures by at least 2-3^{o}C.

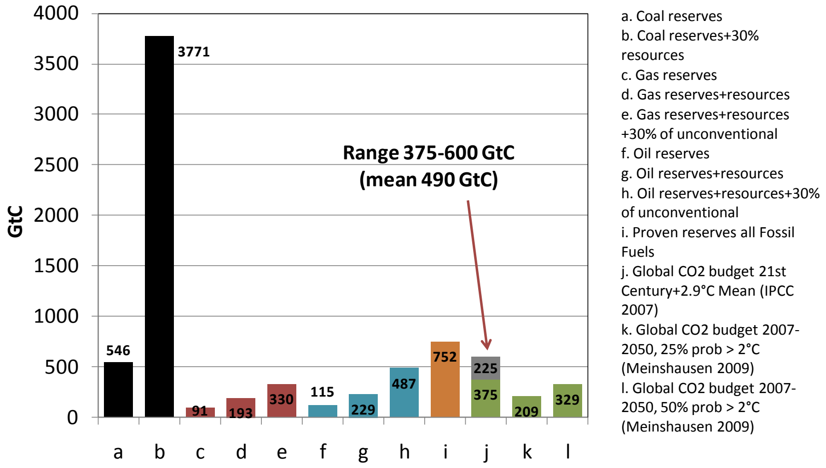


Figure XIV. CO_2 emission potential (in GtC) for various reserves/resources of coal (black), gas (red), and oil (blue), as well as for proven reserves of all three fossil fuels (orange), as compared with estimates of global C-budgets specified by the IPCC (2007, grey/green) and Meinshausen (2009, green). (See Chapters 21-23 for details.)

CARBON CAPTURE AND STORAGE (CCS) IS A KEY TECHNOLOGY TO MEET THE FOSSIL FUEL CHALLENGE

The threat represented by the abundant resources of fossil fuels makes it crucial to develop CCS technologies. If CCS is not applied, it will be very difficult to get fossil-fuelled regions and countries to comply with stringent GHG reduction targets, i.e., to reach a global agreement on emission reductions. It will also be difficult for the EU to reach its climate goals for 2050 without the successful implementation of CCS.

Both the Policy and Market Pathways include CCS as an important bridging technology to 2050 and beyond (Figure V). The rationale for developing CCS should be that there are too large fossil fuel reserves (and resources) in a climate change context. However, CCS will only be implemented if society is willing to attach a sufficiently high price to CO_2 emissions, which is a prerequisite of both the Market and Policy Pathways. Although different arguments have been put forward in favour and against CCS, the most important outcome of successful commercialisation of CCS is likely be that it will most likely facilitate for fossil fuel-dependent economies to agree with stringent GHG reduction targets. In this respect, the EU can take the lead by following pathways similar to the two discussed in this book and by introducing technologies for the capture, transport and storage of CO_2.

Failure to implement CCS will mean that the global community will have to agree on immediately starting to phase out the use of fossil fuels. Achieving such agreement seems more unlikely than reaching a global agreement on stringent GHG reductions. Thus, in the near term, it is crucial to get demonstration projects up and running, such as those supported by the EU. If not, there is a risk that CCS will be significantly delayed. Within the CCS community (research and development in industry and academia), the year 2020 has typically been considered the year in which CCS will become commercially available, and this is applied in the two pathways. Commercialisation of CCS by 2020 seems rather optimistic, considering the long lead times for CCS development and the slow pace of implementation of climate policies.

Of the 5000 MtCO_2-eq of GHG emissions in the EU in 2008, roughly 75% was from fossil fuel combustion. Despite the general consciousness regarding the problem of climate change, substantial new fossil fuel infrastructure is under construction or at the planning stage. This works against near-term climate targets and it seems that knowledge and awareness of this development are low. CCS technology offers possibilities to achieve cuts in emissions by dealing with a relatively low number of point sources, in that more than 80% of the emissions in the current EU Emissions Trading Scheme (ETS) originate from the ~800 largest power plants and industries (Chapter 15).

The main application of CCS is in the utility power sector. The two pathways predict 1000-2000 TWh of electricity generation with CCS by 2050, leading to 25-50 GtCO_2 being captured between 2020 and 2050. The majority of CCS will be performed in coal-fired power plants. When commercialised, coal CCS is expected to become competitive at carbon prices of about 20-25 €/tCO_2. Marginal prices for CO_2 will range between 30 €/tonne and 40 €/tonne for most of the 2000-2050 period, rising sharply in the last few years to reach the targets set for 2050 (Chapter 17).

There is also a significant potential for CCS in the industrial sector. The pulp and paper industry alone has a total capture potential of 60 MtCO_2/y from 171 mills. However, only 15 Mt/y of this is from fossil sources, the remaining part being biomass carbon (Chapter 18). Using the full potential of these industrial sectors would mean substantial “negative” emissions, if the biomass can be considered to be carbon-neutral. Another sector of interest is the refining industry, which is responsible for 3% of the GHG emissions in the EU. The total potential from the 58 refineries in the 19 countries studied in the Pathways project is 128 MtCO_2/y. Refineries located along the North Sea coastline generally have the most advantageous locations with respect to utilising the surrounding infrastructure (Chapter 42). To estimate the full realisable EU potential for industry CCS, the Pathways database for all industrial installations in the EU ETS has been linked to potential storage sites. Special attention has been paid to clusters of industrial sites where the capture volumes are sufficiently high for a CO_2 infrastructure to be installed in a cost-competitive manner. If the full potential of the CO_2 capture technologies considered in the study could be realised, about 60-75% of the emissions (270-330 $MtCO_2/y$) could be avoided. Prices are estimated to be in the range of 20-40 €/tCO_2 (Chapter 19).

Most of the EU Member States have structures that are suitable for CO_2 storage. To date, fourteen Member States have identified onshore reservoirs only. Several Member States have clusters of large power plants together with considerable national or regional concentrations of plant ownership, factors that may facilitate the ramping-up of a bulk CCS infrastructure. CCS plants will probably be located on existing sites, and coal plants that are currently under construction may choose to retrofit for CCS instead of building new plants. CO_2 pipeline trajectories are likely to follow existing trajectories for natural gas pipelines, thereby minimising interference with the surroundings and facilitating and speeding up the permission processes. Some 5.2 $GtCO_2$ could be transported and stored in Germany between 2020 and 2050, while the corresponding figure for the UK is 3.7 Gt. Total system costs up to 2050 are in the range of 18-23 G€ in Germany and 20-30 G€ in the UK, with specific CO_2 transport and injection costs of 3.4-4.4 €/tCO_2 in Germany and 5.4-8.1 €/tCO_2 in the UK. The suggested infrastructures for Germany and the UK are shown in Figure XV (Chapter 16).

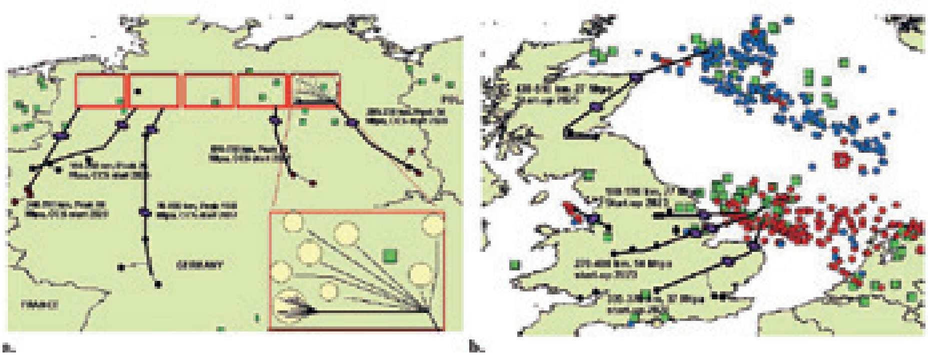
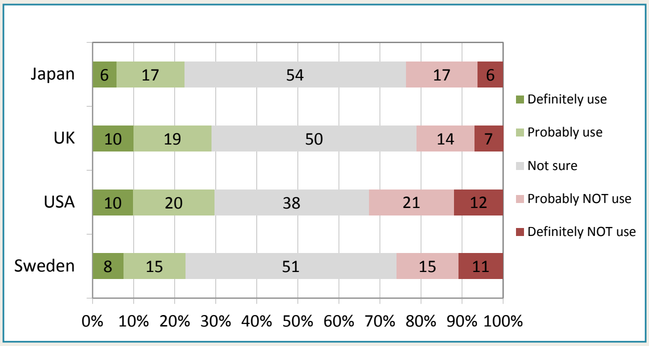


Figure XV. CCS infrastructures from large point sources to storage sites, as obtained from results generated in the work of this book (Chapter 16). a, Germany; b, the UK.

Public attitudes regarding climate change and CCS

A survey was carried out to investigate people's attitude towards climate change (Chapter 20). In one question, respondents were asked to give their opinions on whether or not specific mitigation options should be applied. The results show a strong preference for using energy efficient cars, wind energy, energy-efficient household appliances, and solar energy to address global warming. In contrast, there was little awareness of CCS, and the majority of the respondents in the surveys were unsure as to the use of CCS to address global warming, while the remaining respondents were roughly divided between supporting and not supporting CCS.



Comparison of the respondents' opinions in the surveyed countries regarding support for or opposition to CCS; the respondents were asked if they would use CCS if they were to design a climate change mitigation plan (results from 2003-2005).

BOTH PATHWAYS STRENGTHEN THE SECURITY OF SUPPLY – through reduced import dependency and diversification of technologies and fuel mixes

Security of supply is one of the cornerstones of European energy and climate policy towards a sustainable energy system. Dependence on imports of natural gas and oil has serious implications for the EU and strongly influences the union's energy politics.

In a "business as usual" scenario, the EU will be increasingly dependent upon imported energy. The production projections of the EC and the IEA suggest a growing supply gap, owing to increased demand coupled to declining indigenous production (Figures XVI and XVII). Currently, the EU produces around 40% of its gas requirements, which will drop to about 15% by 2030 in a baseline projection. Coal and oil show similar trends; baseline hard coal and lignite production is projected to decrease from the current 2000 TWh/y to about 1300 TWh/y in 2050, while demand will almost double to about 7000 TWh/y. The demand for oil in the EU27 already far exceeds production, and a significant drop in production seems inevitable. Therefore, the EU faces risks related to an increased supply gap and dependence on imports for the most important fossil fuels, both of which compromise the security of supply (Chapter 24).

In both the pathways, the import needs of the EU are reduced (Figures XVI and XVII). Reduced import dependence is a consequence of reductions in fossil fuel use, which in turn are the consequence of increased energy efficiency improvements and a shift towards renewable energy sources. Consequently, the strong dependence on fossil fuels is abandoned for a more diversified and balanced energy use and supply. The energy mixes in the pathways are more flexible and robust, being adapted for possible future global changes in fuel markets. This would strengthen the security of supply, as well as protecting consumers within the EU against exposure to high and volatile fossil fuel prices.

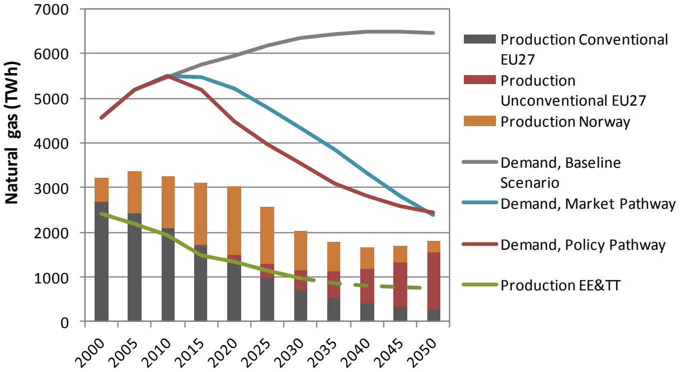


Figure XVI. Comparison of natural gas production levels in the EU27 and Norway with demand in the Baseline scenario, Market Pathway, and Policy Pathway. (See Chapter 24 for details. EE&TT is European Energy and Transport - Trends to 2030 (EC, 2008c).)

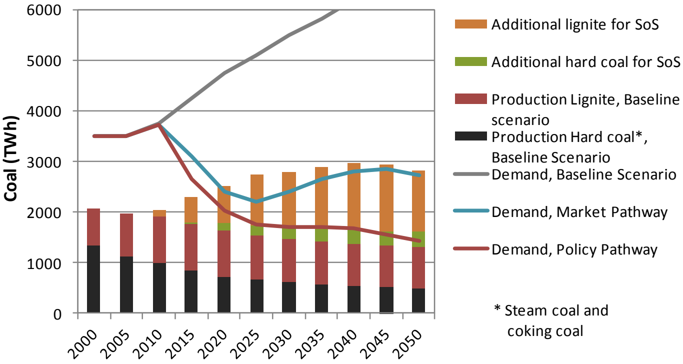


Figure XVII. Comparison of coal production levels in the EU27 with EU levels of demand in the Baseline scenario, Market Pathway, and Policy Pathway.

Potential for decreased dependence on imports

It should be possible to decrease further the dependence on imports through concerted efforts to increase fossil fuel production within the EU. There are possibilities for greater extraction, e.g., of unconventional gas and oil, and for the increased exploitation of indigenous coal resources. The EU could become self-sufficient for coal and close to self-sufficient for natural gas. However, in the case of oil, the potential for increases in unconventional production is limited. Strong policies for increased domestic extraction would be driven by the security of supply rather than by climate targets, although they could still give climatic benefits, such as a shift from oil products to CO_2-lean electricity for transportation through generation at coal power plants with CCS.

ENERGY EFFICIENCY MUST BE IMPLEMENTED ON BOTH THE SUPPLY AND DEMAND SIDES

Cost-effective implementation of energy efficiency improvement should include all parts of the energy system, from supply to end-use. Estimations made in the work on which this book is based (see the Methods and Models book) show that cost-effectiveness (in the long run) in the European energy system can be attained with approximately 30-50% energy conversion efficiency measures and 50-70% end-use measures. Most of these energy efficiency improvement measures will, in addition to increasing energy efficiency, reduce GHG emissions and lead to the increased use of renewable energy sources in the EU countries. These synergies will make the measures more cost-effective.

Policies should give equivalent incentives to improve efficiency across the entire energy system

In European energy policy, the reasoning for energy efficiency improvements has traditionally been put forward by the users of that energy. The consequence of this can be seen in the EC's documents on efficiency, in which end-use measures get the most attention. Cost-effective measures on the supply side are often overlooked. If EU countries are to achieve significant efficiency improvements, sub-optimisation cannot be allowed. It is therefore important to formulate energy efficiency targets that provide incentives for improving efficiency throughout the energy system.

Efficiency improvements in the building stock

Efficiency improvements in the building stock are (together with increased efficiency in industry and transport) a key issue in attempts to reach end-use efficiency targets (Chapters 44-46). Increasing standards and expansion of the building stock would increase end use by 40% in 2050, if energy efficiency was frozen at the current level (see Baseline in Figure XVIII). Continuing efforts at efficiency along the present lines could, on the other hand, stabilise energy end use at the current level (see the Market Pathway in Figure XVIII). A reduction consistent with the EU's 20% efficiency improvement target by 2020 and beyond is profitable in an overall analysis (the Policy Pathway in the figure), although a forceful policy is required for success (see Chapter 44).

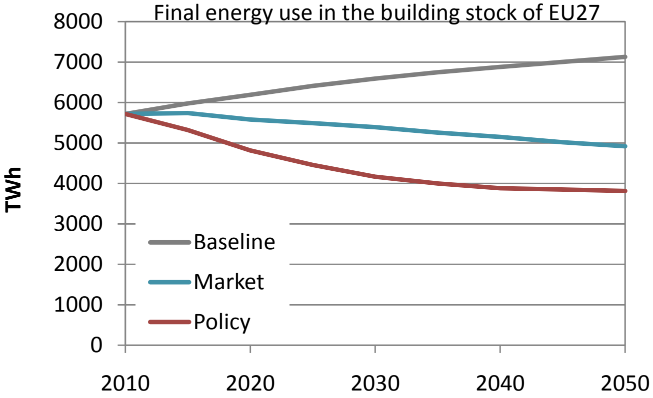


Figure XVIII. Final energy use in the building sector in the two pathways and in the Baseline scenario.

Demand-side action - the energy efficiency gap

Several studies have indicated possible energy demand reductions in the building sector of around 30% to the year 2020, assuming that all profitable measures are implemented. The same target is stated in the EC's studies since the Green Paper for efficiency goals was published (European Commission, 2006). However, it is difficult to accomplish energy efficiency measures on the demand side, as this involves millions of decision makers, often non-professionals, who have to make "billions of decisions". There are many uncertainties and options, which are difficult to evaluate for those who seldom work with energyquestions. This is in contrast to carrying out activities in the energy supply sector, in which the projects are generally much larger, a limited number of decisions are needed, and these decisions are often made by professionals. Thus, not all of the profitable measures on the demand side are likely to be implemented. This is the so-called 'Energy Efficiency Gap'.

Why is the energy efficiency gap so large?

In Sweden, only around 15% of the ideal efficiency potential has been achieved in recent years (Chapter 44). Why has the remaining 85% not been realised?

Analyses have revealed the following reasons and obstacles:

- Lack of knowledge and competence
- Uncertainty regarding the technical performances of some measures and expected savings gained
- Lack of time
- Other issues have higher priority
- Transaction costs, as it takes time to seek information about the measures, to procure the measures, and to follow-up the outcomes
- Too high demand for return on investment
- Financing problems
- "Split incentives", whereby one partner is responsible for the investment, while the other partner pays the energy bill
- Facility management organisations not encouraging efficiency improvements

Many of the above-listed obstacles can be overcome, some by government policy measures and some by initiatives taken by the facility management and similar. However, one cannot expect to bridge the entire energy efficiency gap.

Considering the typical features and problems of the demand side, it must be recognized that achieving larger reductions than those set out in the Market Pathway will most likely require a very strict and targeted policy. The EU has acted boldly and forcefully in mandating strict requirements for new construction and in setting energy performance limits for a number of appliances in the Eco Design Directive (EU, 2009). However, the remaining major challenge is in realising the potential of construction and installation measures in the existing stock. Thus, equally forceful restrictions and policy measures must be implemented in these areas (for example, to take advantage of the window of opportunity that opens when a major renovation of a building is planned). This is necessary if the reduction levels in the Policy Pathway are to be achieved.

BIOMASS HOLDS PROMISES AS A SOURCE OF FUELS FOR NEAR TERM BRIDGING TECHNOLOGIES

Biomass is the only renewable primary energy source that inherently generates carbon-based fuels, which are the basis for much of present-day energy technologies. This makes biomass very suitable for use in heat and power production and in the transport sector. Promotion of bioenergy use that induces a relevant development and that exploits existing energy infrastructures in order to reduce risk and costs is proposed as an attractive near-term strategy.

Considerable resources exist – but the supply system needs to be developed

Successful implementation of biomass technologies will depend on the biomass supply infrastructure. In the near term, residue flows in the agricultural and forestry sectors could support increased bioenergy use in Europe. In the longer term, dedicated biomass production in forests and short rotation plantations may become increasingly important (Chapters 25-27).

Scenario-based estimates indicate a technical bioenergy resource potential for Europe (including Ukraine) corresponding to about 20 EJ/yr by 2030. It needs to be noted that a considerable proportion (up to one-third) of Europe's present agricultural land area would need to be converted to bioenergy plantations to achieve such high supply levels. Global estimates indicate that it might be possible to produce several hundred EJ/year of biomass in the longer term, and the EU may base a substantial part of its bioenergy use on imports from other, mainly tropical, regions.

A comparison with biomass production in agriculture and forestry provides perspectives on the prospective bioenergy supply in relation to what is presently harvested from land use. Today's global industrial roundwood production corresponds to 15-20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots and tubers, and pulses) corresponds to about 60 EJ/yr (FAOstat, 2010). Thus, biomass extraction in agriculture and forestry will have to increase substantially in order to provide feedstock for a bioenergy sector that is large enough to make a significant contribution to the future energy supply.

The climate and wider environmental effects of bioenergy vary

Bioenergy projects can lead to both direct and indirect land use changes, which can affect the environment in different ways (Chapter 28). Land use change associated with bioenergy expansion can lead to both beneficial and adverse outcomes in terms of the contribution of bioenergy to climate change mitigation and the environment in general. When land use change results in GHG emissions, the negative impact is usually greatest in the near-term, and the cumulative net GHG savings improve over time as the savings from fossil fuel replacement accumulate. Thus, the overall net savings in emissions may be subject to a time lag, and this needs to be taken into account in considering the role of bioenergy.

The production and extraction of biomass for energy may entail direct competition for land, water etc. with food and fibre production, and this may also negatively affect nature conservation and the protection of biodiversity. Policies that induce increased demand for so-called first-generation biofuels increase the demand for conventional food commodity crops and can worsen the environmental impacts of present land use practices. Shifting from first-generation to second-generation biofuels reduces the demand for conventional crops and can also mitigate the pressure on prime cropland. However, increased demand for (mainly) lignocellulosic feedstock, combined with demand for biomass from the stationary energy sector, can still push land prices upwards and increase the pressure on forest resources. On the other hand, increased cultivation of perennial lignocellulosic plants could be valuable for mitigating some of the environmental impacts associated with intensive agriculture, such as nutrient leaching and erosion that results in water and soil degradation.

Biomass can be used for many purposes - optimal use depends on objectives

There are several possibilities to convert biomass to different energy products, e.g., solid, liquid and gaseous fuels, heat, electricity, and combinations thereof. There are considerable variations in raw material costs, as well as in investment costs, which vary between the different principal technologies and also for the same technology. Different technologies have different requirements of scale to maintain efficiency, so the challenge is to find options that maintain high conversion efficiency using a reasonable size of conversion plant (important when conversion plants cannot benefit from seaborne supplies).

The existing energy infrastructure could be advantageous for bioenergy in that it could facilitate a relatively cheap and lower-risk option for establishing a market for biomass. As mentioned in a previous section, cost-effective and near-term options for biomass-based climate change mitigation exist in the stationary energy sector and can also have energy security benefits. Analyses presented in this book (Chapter 12) point to a considerable technical potential for biomass co-firing with coal in the EU27, corresponding to 50-90 TWh/y and requiring a biomass supply of approximately 500-900 PJ/year. A 5% level of integration of biomass into natural gas-fired CCGT plants corresponds to a capacity of 8 GWe (40-50 TWh/y) (Chapter 13).

Biofuel use in transport is associated with a higher mitigation cost, although it is presently the major renewable alternative to gasoline and diesel. As described elsewhere in this book, options such as hydrogen and electric vehicles, which rely on hydro, wind, and solar PV, will require decades to become established on a substantial scale. The integration of gasification-based biofuel plants into DH systems is one option for increasing energy efficiency and reducing GHG emissions, and for improving the economic competitiveness of such biofuels.

The development of lignocellulosic resources is recommended

Regardless of the long-term priorities for biomass use for energy, the stimulation of lignocellulosic biomass production through the development of near-term and cost-effective markets seems to be a no-regrets strategy for Europe. As discussed in Chapters 12-13, biomass co-firing in coal plants is a near-term bridging technology that can act as a "stepping stone" technology for establishing a supply infrastructure for lignocellulosic resources. In addition to the development of near-term markets, several steps can be taken on the supply side (see Chapters 25-27) to promote bioenergy expansion while mitigating the possible negative effects:

The residues and processing of by-products from the agricultural and forestry sectors represent a resource that should be mobilised further; this can be done at relatively low cost:

- Land use competition can be mitigated by producing lignocellulosic crops on lands that are less suitable for conventional agriculture.
- Forest extraction in new forest areas and adjusted management of existing areas can increase forest biomass production
- Paper recycling and recovery should be enhanced.
- Forest industries could benefit from biomass energy markets by being transformed into "biorefineries" that produce fuel and generate energy in addition to their traditional products.

The possibility of future stronger links between the energy, agricultural, and forestry sectors can also be seen as a motivation for promoting uniform global instruments for meeting the energy and climate challenges. If strong biomass competition emerges in Europe but not in other regions, European companies will lose their competitive edge, which may lead to slower growth and even reductions of capacity and production.

INDUSTRY HAS TO CONSIDER ALL OPTIONS TO FOLLOW THE PATHWAYS

European industry has the potential to contribute substantially to reducing CO_2 emissions and progressing towards sustainability, both through large reductions in direct emissions and indirectly, through changes in the energy that is used and delivered. Adaptation strategies may include structural changes, energy efficiency improvements, fuel substitution, and the implementation of CCS.

All types of strategies are necessary to reach low emission levels

Direct emissions of CO_2 from industry account for slightly more than 20% of total European emissions. In 2050, these emission levels are assumed to be reduced by about 50% in the two pathways. Reaching this target requires the implementation of all types of adaptation strategies, incorporating structural changes, energy efficiency improvements, fuel substitution, and CCS. Furthermore, the rationale for emission reduction includes assumptions as to declining production volumes in mineral oil refineries. In the Policy Pathway, energy efficiency improvements and larger-scale use of solid biofuels for process heating are important components. In the Market Pathway, direct emissions reach slightly lower levels, depending primarily on assumptions related to increased implementation of CCS and conversion to electricity use, both through more fundamental changes in production processes and by conversion to heat pumps for process heating (see Chapter 37).

Based on the analyses of industry presented in this book, a continuation of past development trends towards decreasing specific energy use in industry through energy efficiency improvements and structural changes seems to be feasible for most industrial sub-sectors. However, such development would require technological advances, incentives (in terms of policies or increasing emission or energy costs) for industry to implement reduction measures, and large investments. Furthermore, it would require considerable structural changes towards less-energy-intensive (per value added) products and production processes (e.g., increasing share of recycled raw materials), which are included in the estimate given above. The future directions of structural changes in industry and their impacts on energy use and emissions are of course uncertain, and need to be studied further.

Energy-intensive industry plays a key role

Energy-intensive industry, including the sub-sectors of primary metals, chemicals, pulp and paper, cement, and refineries, account for about 80% of total CO_2 emissions from European industry. These sectors have a substantial potential for large, step-wise, capital-intensive reduction measures. The implementation of key measures in energy-intensive industries is especially dependent upon energy market conditions and infrastructure, and thus relies on interactions with other parts of the energy system.

The dependency on energy market development is clear in the case of kraft pulp production, in which implementation of energy efficiency measures is likely to result in a net surplus of energy. The most profitable choice among the available options for using this surplus energy depends on the development of the energy market. The largest reduction in CO_2 emissions would be achieved if new options, such as CCS or lignin extraction and export, were implemented, while more conventional usages, such as electricity production, DH, and bark export, have higher economical robustness (see Chapter 39).

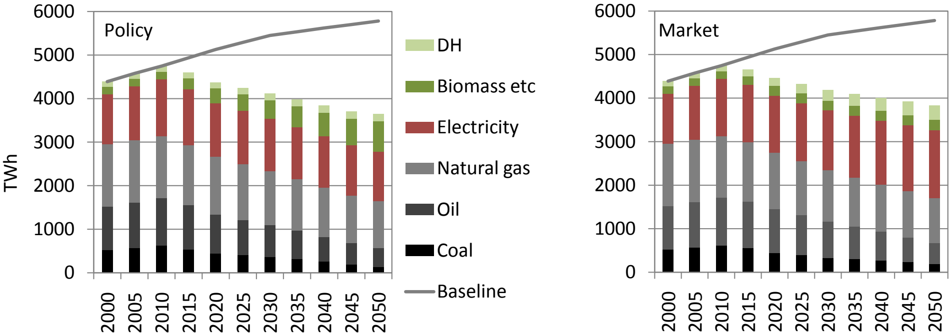


Figure XIX. Development of total final energy use in European industry, in the Policy and Market Pathways, respectively.

The potential for CCS in industry is substantial, although it is dependent upon the infrastructure

The potential for CCS in European industry is substantial and favoured by the availability of surplus heat in many industrial installations. The total economic potential in the most relevant industrial sub-sectors, including mineral oil refineries, integrated steel plants, cement plants, kraft pulp production, and bulk chemical production, has been estimated as 300-420 $MtCO_2$/y. In the presented pathways, an implementation rate of 30-50% of the potential has been assumed (see Chapters 18-19 and 37).

The associated infrastructure is vital for the potential for industry measures, such as total-site industrial integration, delivery and use of DH in industry, production of bio-methane, and implementation of CCS. As an example, when taking geographical conditions and infrastructure into account, it is clear that the majority of the potential sites for industrial CCS are located within possible capture clusters, which consist of large stationary point sources for fossil- and biomass-based CO_2 emissions, including both power plants and industrial sites. Therefore, realisation of the entire potential requires that the locations of both industrial clusters and biomass-based emissions are taken into account when planning the future CCS infrastructure.

Policy options are needed to restrain carbon leakage

European industry cannot be regarded in isolation, and this is especially the case for energy- and carbon-intensive industries, which are operating in a highly competitive global market place. Increased costs for carbon mitigation and other environmental policies cannot easily be passed on to consumers without affecting competitiveness. Nevertheless, several different policy options may be employed to protect energy-intensive industries and to restrain carbon leakage: (i) the free allocation of carbon emission allowances based on past emissions (grandfathering); (ii) the introduction of so-called border tax adjustments (BTA), i.e., import taxes and export subsidies, so as to level the playing field with countries outside the region; (iii) the differentiation of mitigation efforts between sectors; and (iv) direct subsidisation of industries that lose competitiveness. In many national- and regional-level studies, it is implicitly assumed that industrial competitiveness remains unaltered, i.e., owing to the existence of uniform multilateral regulations or BTA regimes (see Chapter 41).

IMPLEMENTING PATHWAYS REQUIRES RESPONSIBILITY AT ALL LEVELS, FROM GLOBAL TO LOCAL

Although the two pathways discussed in this book differ with respect to who in society assumes the main responsibility for transforming the energy system to follow the pathways, they also require governance at all levels of society, including the international, national, and local levels.

Obviously, there must be a global consensus regarding the importance of tackling climate change if the required reductions in GHG emissions to the end of the period concerned in this work are to be achieved. This does not necessarily mean that there must a global agreement on the system used to implement policy measures, such as that within the Kyoto protocol. Different policy measures may be adopted in different regions and these may be in the hands of different stakeholders (e.g., governmental organisations, industry) and at different levels in society, such as international treaties, national policies, and initiatives at local levels. It is most likely that responsibility will have to be taken at all these levels, if the transformation of the energy system is to follow any pathway similar to those presented in this book. In addition, market regimes must be international in order to offer efficient trade between countries, whether in the form of market-based policy measures or possibilities to export and import energy technologies and energy carriers. In addition, several technologies require harmonised jurisprudence. For example, widespread implementation of CCS will require an international juridical system for the transport and storage of CO_2, as well as for the monitoring of the stored CO_2.

The work reported in this book assumes international governance acts as the main driving force for transforming the energy system, such as that represented by EU-ETS. The prerequisite for a strong international commitment for tackling climate change is obviously a corresponding national commitment among a large group of countries, such as those forming the European Union. Nonetheless, this book also points to the importance of commitment at the local level (Chapter 31), i.e., at the municipal or community level. This level is of importance, since many decisions are taken at the local level and the decisions made are close to the daily life of the general public, which is important for winning confidence, especially with respect to decisions with direct consequences for the end-use system. Failures at the local level will most likely result in failures also at the international level. Presently, there is increasing interest and increased activities at the local level, whereby communities around the world set up their own targets, often linked to corresponding international targets. In Europe, there has been overwhelming interest in the Covenant of Mayors (EC, 2010), with more than 2000 local authorities signing an agreement in which they commit themselves to go beyond the 20% targets set in the EU Energy and Climate Package. There are also corresponding national initiatives, such as the "Sustainable Community" ("Uthållig Kommun") in Sweden.

AN INTEGRATED METHODOLOGY FOR PATHWAY ANALYSIS HAS BEEN DEVELOPED

The results presented in this book represent the outcomes of applying, in a co-ordinated way, a variety of energy-related methods and models that originate from different scientific disciplines and traditions. Most of these are described in the *Methods and Models* book. Some of the analytical tools used 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.

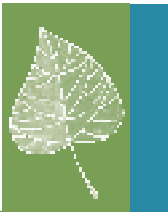
To a certain extent, the Pathways project has also served as a "testing ground" for exploring the possibilities and challenges of co-ordinated multi-model analyses of complex problems. The *Methods and Models* book gives three such examples: 1) the linking of three electricity supply models in order to reflect investments in increased capacity, dispatch, and transmission of electricity in Europe; 2) methodological development for estimating the aggregate potential of energy efficiency measures in European industry based on detailed process simulations and infrastructural conditions; and 3) the integration of sector-specific results (e.g., concerning buildings, electricity, and industry) to assess the development of the DH sector in Europe.

The work has included workshop activities with all the researchers in the Pathways project, especially with respect to establishing, discussing, and assessing the two pathways discussed in this book. These integrative activities between researchers have been iterative, with sector-specific results assessed and integrated to form the pathways for the entire energy system. Thus, this book represents an added value to the many scientific publications from the project, which although they are on a more detailed level, are limited to a specific scientific discipline or address a specific sector of the energy system.

Chapters 1- 46

1

Pathways towards a CO_2-lean European electricity system



Assuming that there will be significant reductions in CO_2 emissions by the European electricity system - around 85% by 2050 – there will have to be dramatic changes in the European electricity supply system. The share of renewable electricity generation is expected to increase by about 30% percent by 2020 as a result of meeting the EU renewables target. Depending on scenario assumptions, carbon capture and storage (CCS), nuclear power and conventional gas power will secure different market shares beyond 2020. Furthermore, depending on regional resources, policies, and already decided investments, significant differences will remain between European regions, even in the long-term.

MODELLING ELECTRICITY GENERATION

The analysis presented in this chapter, was carried out using the ELOD model. The model covers the entire electricity supply system in the EU27 (on a country-by-country basis) plus Norway. The time horizon spans 2003 (starting year) to 2050. The important scenario assumptions of the analysis are summarised in Table 1.1. The model includes the majority of existing power plants (data taken from the Chalmers Power Plant Database, see Chapter 2 in the *Methods and Models* book) and a comprehensive menu of new technologies for investments. Existing power plants are phased out according to assumptions regarding remaining lifetimes (the age distribution of existing power plants is a key feature of the Chalmers Power Plant Database). Assumptions as to technical life-times vary according to the technology: 85 years for hydro; 60 years for nuclear; 40 years for coal and lignite; 30 years for gas; and 25 years for wind. In particular in Eastern Europe, a large part of the existing capacity consists of power plants of advanced age. Assumptions as to fossil fuel prices are taken from ”*European energy and transport trends to 2030”*(European Commission, 2008), while estimates of biomass costs and potentials

This book is accompanied by the **Methods and Models book**, which describes the methodologies used in the Pathways project.

are based on the work of de Wit and Faij (2010). Electricity demand projections are the result of research conducted within the Pathways project (see e.g. Chapter 44).

Defining the pathways from sector specific scenarios

Two different European Energy Pathways are defined in this project: the Policy Pathway and the Market Pathway. The Policy Pathway relies more on targeted policies that promote energy efficiency and renewable energy; the measures in this pathway are primarily demand-side-oriented. In contrast, in the Market Pathway, the measures are more supply-side-oriented and the cost to emit CO_2 is the predominant policy measure. These two Pathways are based on the results from the sector-specific scenarios and analyses described in Chapters 1-46 of this book.

Table 1.1. Selected scenario assumptions for the electricity-supply sector

Scenario	Electricity demand	CO_2 emissions	Renewables	Nuclear power	CCS
Policy	Including EU efficiency target	40% cut by 2020 and 85% cut by 2050 (compared to 1990)	30% by 2020 and 45% by 2050 (of electricity generation)	Reinvestments and single (planned) new investments. Phase out in Germany and Belgium	Default ENCAP costs
Market	EU baseline	30% cut by 2020 and 85% cut by 2050 (compared to 1990)	30% by 2020 (of electricity generation), no target thereafter	General new (optional) investments in nuclear states and no phase out	50% cost increase compared to the Policy scenario

The two scenarios that have been analysed make the same assumptions for renewables in terms of costs and potentials. Furthermore, both scenarios share the same long-term CO_2 mitigation target, i.e. 85% reduction by 2050 (by 2020, however, the targets are slightly different). However, nuclear power and CCS are estimated to be around 50% and 30% more expensive, respectively, in the Market scenario due to larger anticipated international demand and less policy-induced technological development (more on assumed technology costs and performances may be found in Chapter 11 in the *Methods and Models* book).

EUROPEAN OUTLOOK

The development of European electricity generation in the Policy and Market scenarios is presented in Figure 1.1 (Market scenario) and Figure 1.2 (Policy scenario). Almost half of the existing capacity will be phased out by 2030 due to the assumed technical life-times, as well as climate and renewable policies (more on the relevance of the assumed technical lifetimes may be found in Chapter 2). In combination with the assumption of increasing electricity demand (occurring slowly in the Policy scenario and more rapidly in the Market scenario), this suggests a significant need for new investments. The assumed renewable target in the Policy scenario implies that renewable electricity will undergo a substantial capacity increase during the coming decades. However, also in the Market scenario, the penetration of renewables will be substantial, especially towards the end of the period when marginal costs for CO_2 reduction will be high. The distribution between wind power and biomass power is relatively equal in terms of produced electricity. Depending on scenario assumptions, investments in non-renewable electricity generation are divided among conventional gas and coal power, CCS schemes, and nuclear power. The Market scenario shows a substantial increase in gas power in the short- to medium-term. The absence of a strict renewable policy beyond 2020, relatively expensive nuclear power, and CCS will enable this increase. In the longer perspective, gas power loses much of its competitiveness due to increasing gas prices and increasing marginal costs for CO_2 abatement.

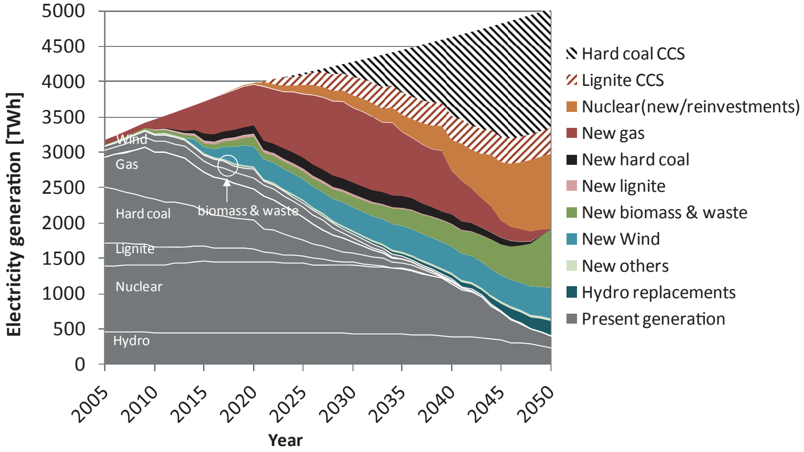


Figure 1.1. European (EU27 plus Norway) electricity generation in the Market scenario.

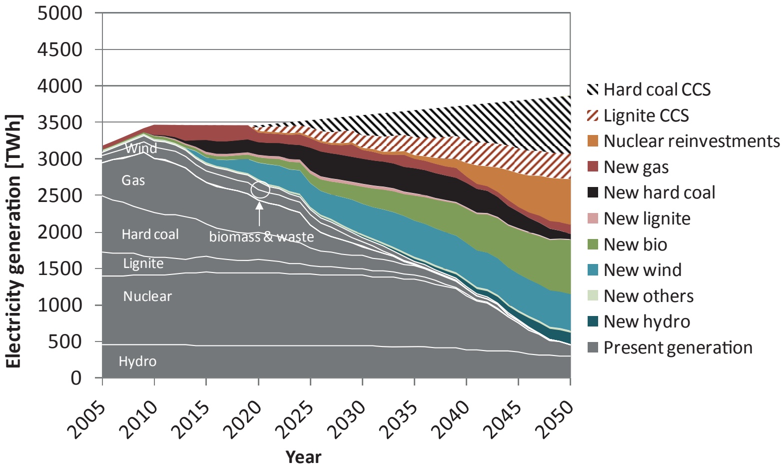


Figure 1.2. European (EU27 plus Norway) electricity generation in the Policy scenario.

The marginal costs for CO_2 reduction are higher in the Market scenario due to higher electricity demand, more costly CCS and nuclear power, while the reduction target (expressed as Gt of CO_2) is the same as for the Policy scenario (see Figure 1.3, left panel).

Typically, the marginal costs for electricity generation are 50-60 €/MWh in the Policy scenario and 60-70 €/MWh in the Market scenario (see Figure 1.3, right panel). However, in this respect, there may be significant differences between Member States (see more in Chapter 4 concerning the role of new

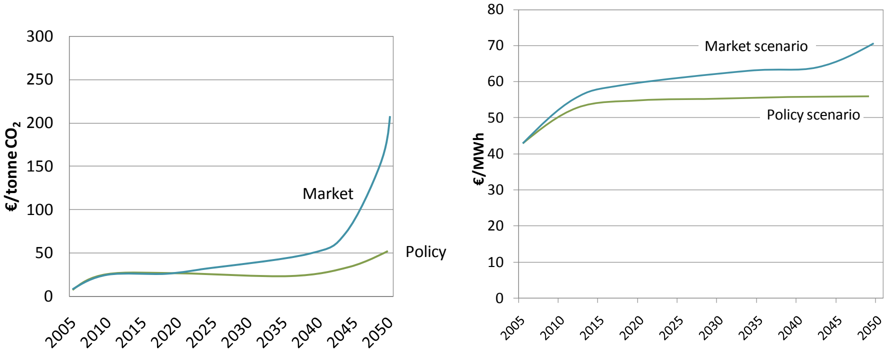


Figure 1.3. Schematic of the model-calculated marginal costs of CO_2 reduction (left panel) and electricity generation (averaged for all Member States, right panel) in the Market and Policy scenarios.

interconnectors). Furthermore, the income for renewable electricity generators from the renewable target defined in both scenarios is typically 20-25 €/MWh. This means that renewable electricity generation gains a total "income" of approximately 70-85 €/MWh in the Policy scenario and approximately 80-95 €/MWh in the Market scenario (until 2020).

Figure 1.4. The four main regions of the EU (plus Norway) used in the present analysis.

REGIONAL OUTLOOK

As mentioned earlier, the ELOD model covers all 27 EU Member States and Norway. As a complement to the European perspective given in the previous section, a regional outlook is given in this section. For reasons of simplicity, the countries included in the model have been divided into four main European regions (Figure 1.4). The long-term development of electricity generation in these four regions is summarised in Figure 1.5, which presents the relative distributions of renewable-, nuclear-, and fossil fuel-powered electricity generation today and in 2030 for the Policy and Market scenarios.

The distribution of the different means of producing electricity varies substantially across the four regions (and across countries within a given region). Northern Europe, as defined here, will have the largest share of renewable energy sources in the future, while fossil fuels are expected to continue to play a vital role in the other regions, especially in Southern and Eastern Europe. Furthermore, the higher demand for electricity in the Market scenario leads to a larger share of fossil fuels than in the Policy scenario.

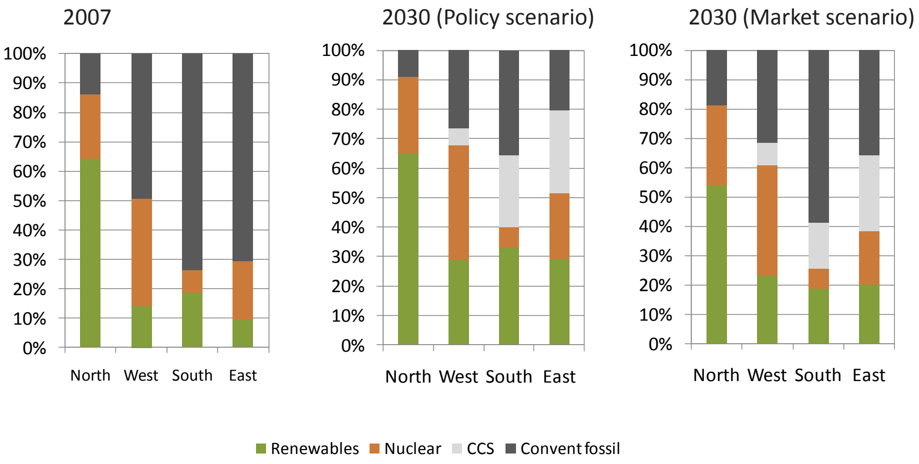


Figure 1.5. The distributions of renewable-, nuclear-, and fossil fuel-based electricity generation in the four chosen European regions in 2007 and 2030 (for the Policy and Market scenarios).

A closer look at the development over the past 15 years (statistics taken from EUROSTAT, 2010) and in the coming 40 years (based on the ELOD model results) in the four main regions of Europe is presented in Figures 1.6-9. The country-specific (and region-specific) features for new investments that distinguish countries (and regions) from each other in the model are: the costs and potentials for CO_2 disposal (capture is considered equal in cost for all the countries); and potentials and costs for renewables and nuclear power. The latter is optional only in those countries in which it exists today. This also applies to lignite-fired power.

THE NORDIC COUNTRIES

In Northern Europe (cf. Figure 1.6), renewable electricity generation, is the main option for significantly reducing CO_2 emissions. Since it is assumed that the contribution from new hydro power schemes will be marginal, most new investments in renewables will be in wind power and biomass power. In addition, nuclear power plays an important role, and a sixth nuclear unit in Finland, to be brought online in 2020, is included in the calculations. At the same time, the Swedish capacity for nuclear power is slowly being phased out. CCS is not cost-efficient in the Policy scenario, but yields a relatively small share in the Market scenario.

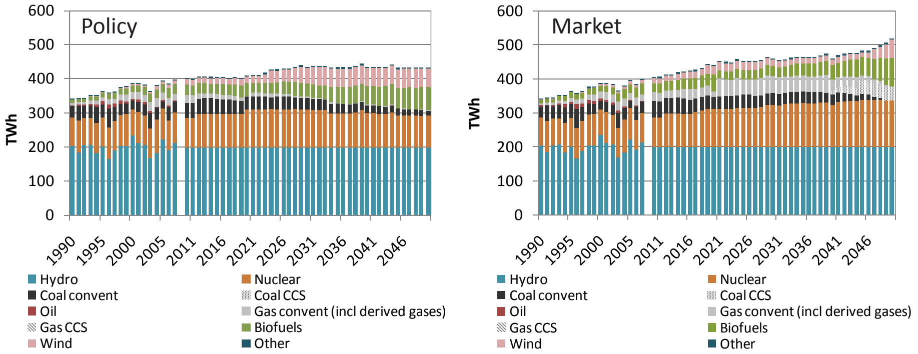


Figure 1.6. Long-term development of the electricity generation systems in Northern Europe (Sweden, Denmark, Finland, and Norway) under the Policy scenario (left) and Market scenario (right) assumptions.

WESTERN EUROPE

In Western Europe (cf. Figure 1.7), CCS plays an important role beyond 2025, in both the Policy and Market scenarios. The share of renewables is around 30% by 2030. Conventional coal power declines steadily but persists, even towards the end of the period. In the Policy scenario, only 1.8 GW of new nuclear power is invested in France (only planned investments are taken into account in the Policy scenario). In Germany and Belgium, nuclear power is assumed to be phased out after a life-time of 60 years. However, in the Market scenario, nuclear power may grow beyond planned investments also in Germany and Belgium (which is reflected in the model results).

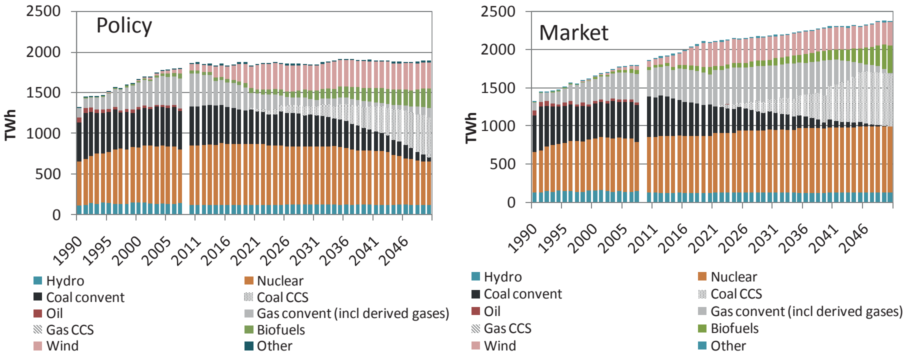


Figure 1.7. Long-term development of the electricity generation system in Western Europe (Germany, Austria, UK, Ireland, Luxembourg, France, Belgium, and The Netherlands) under the Policy scenario (left) and Market scenario (right) assumptions.

SOUTHERN EUROPE

In Southern Europe (cf. Figure 1.8), the model results indicate that gas power is the most important player in the short-to-mid term. A considerable share of the facilities is already decided upon or planned. At the end of the period, CCS gains momentum and becomes the dominant contributor towards the end of the period. The relatively low penetration of nuclear power is mainly explained by its low share today. Even though, for example, Italy currently considers nuclear power as an option, it has not been included in the model (even in the Market scenario, the option of investing in new nuclear capacity is restricted to countries that are currently using nuclear power).

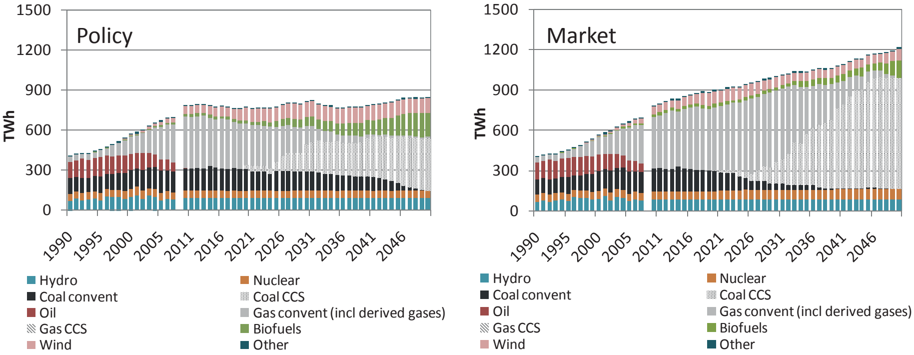


Figure 1.8. Long-term development of the electricity generation system in Southern Europe (Italy, Spain, Portugal, and Greece) under the Policy scenario (left) and Market scenario (right) assumptions.

EASTERN EUROPE

In many Eastern European countries (cf. Figure 1.9), the short- and mid-term needs for new investments are substantial, since many power plants are aged. Therefore, significant changes in power supply are imminent in this region. In the ELOD modelling, many of the power plants within this region are so old that the assumed technical life-time is exceeded already at the beginning of the modelling period. Therefore, a significant share of existing power capacity is replaced by new schemes within a relatively short period of time. This is indicated in Figure 1.9 by a rather pronounced initial decrease in coal power, accompanied by a corresponding ramping-up of the use of gas power (the model does not generally reflect limitations in the possible pace of construction of new power plants).

Contrary to the other regions, it is assumed that the growth in electricity demand in Eastern European countries is significant in both the Policy and Market scenarios. Finally, the amount of biomass-based power (CHP, co-firing, and some condensing power plants) forms a substantial share towards the end of the period, and this is significantly larger in relative terms than in any other region. This is explained by the assumptions made regarding abundant (and relatively cheap) biomass resources.

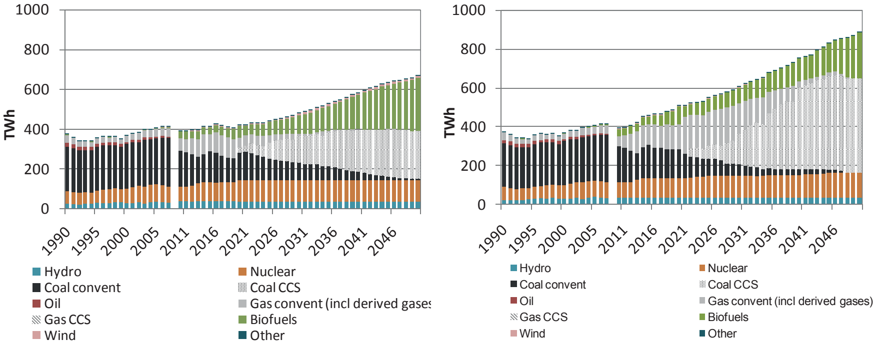


Figure 1.9. Long-term development of the electricity generation system in Eastern Europe (the Baltic States, Bulgaria, Czech Republic, Slovakia, Hungary, Poland and Romania) under the Policy scenario (left) and Market scenario (right) assumptions.

CONCLUDING REMARKS

It can be concluded from the analyses that far-reaching climate policy targets can be fulfilled using, to a large extent, relatively conventional technology. Even though the share of renewables steadily increases over time in the model used here, a very large contribution will be due to fossil fuels in the future. The key to this development is the assumed availability and commercialisation of CCS technology. This is, of course, a very important precondition. If for some reason CCS will not be commercialised in the coming decades, the development of the European electricity generation system will be significantly different from that shown here, given the ambitious climate targets. Other parts of this project deal with the implications of CCS not being available in the future (see Chapter 17).

In the results, renewable electricity generation is entirely made up of hydro, wind and biomass power. The calculated electricity prices do not motivate investments in photovoltaic (PV) cells or wave power (fuel cells are not included in the model). Climate mitigation costs are reflected in the calculated long-term electricity prices (typically 50-70 €/MWh, depending on the scenario). No additional support is included in the analysis besides the specific targets set for renewable electricity by 2020 (in both scenarios) and by 2050 (in the

Policy scenario only). The assumed abundance of wind, hydro, and biomass power meets the required European targets for renewable electricity. Therefore, a small-scale decentralised electricity production system does not appear in this analysis. The advantages that the development of such a system would confer have not been dealt with here. Niche markets (in which, for example, PV cells could have comparative advantages) and technological learning have also been omitted (besides exogenous assumptions as to efficiency improvements in thermal conversion).

Future demand for biomass is likely to be, in some cases, substantial. Even though it may be achievable from a supply-side point of view, this development will undoubtedly involve major logistical and infrastructural challenges. Such infrastructural challenges also apply to other technologies, e.g., CCS, which plays a decisive role in several of the scenarios dealt with in the Pathways project. Large investments in infrastructure are likely to act in part as "inhibitors", meaning that no single option will entirely dominate the future supply. A balanced mixture of technological options and resources is therefore desirable, not only from a security-of-supply perspective, but also due to the fact that large investments in infrastructure will be required for any one of the key technologies identified here (CCS, biomass, wind power etc.) to achieve a substantial share.

For more information:

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Further reading:

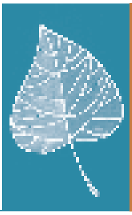
Axelsson, E., Rydén, B., and Colpier, U., 2010, "EMER model results: Two Pathways to Sustainable European Energy System", Pathways Internal report 1/2010. See also www.energy-pathways.org

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.

2

Transforming the electricity supply:

the role of an ageing capacity stock



Approximately 40% of the total installed thermal electricity-supply capacity (fossil, nuclear, and renewable) in the EU is more than 30 years old. It is highly likely that a large proportion of this capacity will be replaced over the coming two decades, which will require massive investments. The age of existing power plants differs widely among the EU Member States. Even if it is assumed that existing power plants have long remaining lifetimes (including aged units), model-based calculations indicate that stringent climate and renewable energy policies in the EU will set an upper limit for the remaining functional life-span of the current thermal fossil capacity.

EXISTING POWER PLANT CAPACITY IN THE EU

The electricity capacity stock differs significantly in terms of age across the European countries and regions. For example, in several Eastern European countries, existing power plants are relatively old, while in other countries, e.g., in Southern Europe, the power plants (mainly gas-fired plants) are considerably younger. Therefore, the prospects for transforming the electricity supply differ widely among the EU Member States. Transforming and adapting the electricity supply towards sustainability involves the replacement of a large share of the existing capacity that fails to meet the new standards. This is, of course, more easily achieved for older power plants. For such plants, replacement costs are generally lower since the investment costs have been recovered while the operation and maintenance costs are higher due to age. Furthermore, environmental benefits of replacements of older plants are greater, since efficiency is lower compared to younger power plants.

Figure 2.1 shows the age distribution of the existing (2010) thermal-power capacity (including nuclear power stations) in the Western, Northern, Southern, and Eastern regions of the EU. The data are taken from the Chalmers Power Plant database (more on that may be found in Chapter 2 in the *Methods and Models* book). The age curves show (right panel) the percentages of the existing capacity in relation to age. For instance, around 60 percent of the existing capacity in Eastern Europe is at least 30 years old. In contrast, only 25 percent of the existing capacity in Southern Europe is at least 30 years old. By aggregating the four regions (not shown in the figure), one may conclude that around 40 percent of the total existing European thermal capacity is at least 30 years old, while more than 60 percent is at least 20 years old.

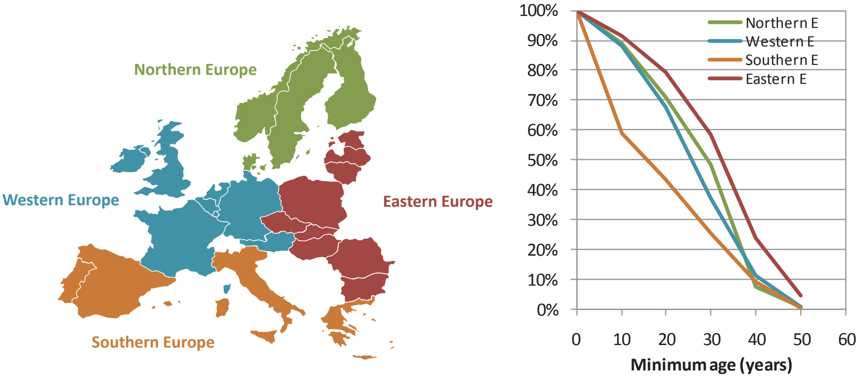
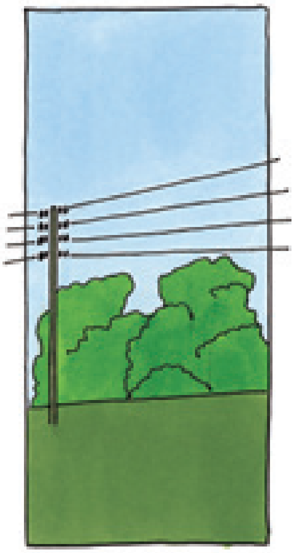


Figure 2.1. The four major regions of the EU, as defined in the present chapter (left), and the corresponding age curves for the existing (2010) thermal power capacity (right). The age distribution is shown as a percentage of the installed capacity of a certain minimum age. Source: Chalmers Power Plant Database.

MODEL CALCULATIONS SET-UP

The model calculations for the long-term development of the European electricity supply system that have been carried out during the Pathways project (see e.g., Chapter 1) generally makes assumptions as to the technological lifetimes of the existing (and new) capacities. These assumptions vary according to technology: 85 years for hydroelectric; 60 years for nuclear; 40 years for coal and lignite; 30 years for gas; and 25 years for wind. This means that once a power plant has come to the end of its technical lifetime, it must be replaced in order to meet demand.

In reality, lifetimes of power-plants are determined by economic, technical, and environmental considerations. Several options to prolong these lifetimes, rather than to invest in new plants, are at hand. However, the remaining lifetime of an upgraded power plant is generally less than the estimated lifetime of a new unit (Kolligs 2003). Life-spans may vary significantly between individual power plants that use the same technology. This may, in some cases, coincide with the assumptions for life-times that have been made here. In other cases, the deviations



may be significant. Studies from the US show, for example, that around 30 percent of the existing coal-fired power plant capacity is more than 40 years old (Battacharya, 2008). As mentioned before, the model calculations in the Pathways project (and in many other studies) have assumed 40 years as the upper limit of the operational time for coal-fired power plants. Consequently, in the Pathways Market scenario, half of the existing fossil-fuelled capacity will be phased out prior to 2025 (reference case). How much of that is due to the assumed lifetimes and how much is due to inferior competitiveness with new technologies available to meet increasing CO_2-reduction targets and increasing fuel prices, remains to be determined. To shed some light on these issues, the ELOD model was run assuming an infinite life-span for the existing capacity (declined here as the ”alternative” case). All other considerations were held constant. This is, in turn, an overestimation of the competitiveness of the existing capacity. In reality, operational and maintenance costs will increase over time, especially if the power plant has reached a certain age. No such considerations have been made in the analysis.

INFINITE LIFETIMES VERSUS LIMITED LIFETIMES – MODEL RESULTS

Figure 2.2 presents the European electricity supply in the reference case (Market scenario), and Figure 2.3 presents the alternative case, in which infinite lifetimes are assumed for the existing capacity. In the latter case, the existing capacity makes a larger contribution when aggregated over the entire period, i.e., the existing capacity is used over a longer time period. However, due to the CO_2-reduction target of 85 percent reduction by 2050, using the existing fossil capacity becomes increasingly expensive. At the same time, new power plants with higher efficiencies and/or with CO_2-leaner fuels will gain in competitiveness. Therefore, half of the existing fossil-fuelled thermal capacity is phased out around 2035 in the alternative case, i.e., roughly ten years after the corresponding phase-out in the reference case. Nuclear power and renewables are not affected in the sensitivity model run, i.e., they are not phased out at all if one assumes infinite lifetimes. This is simply because they are unaffected by carbon costs (in reality, increasing operational and maintenance costs apply also to such plants, as mentioned earlier).

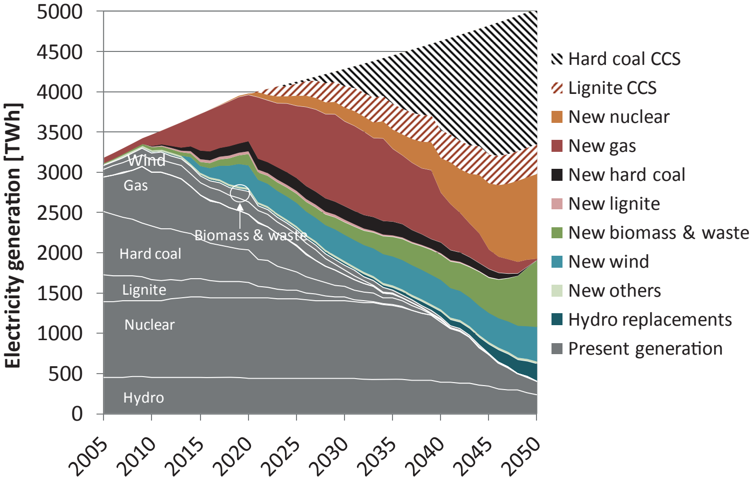


Figure 2.2. European electricity generation in the Market scenario (reference case).

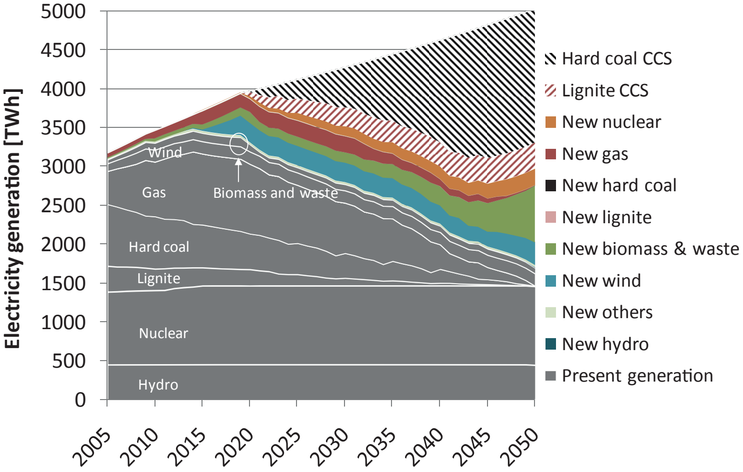


Figure 2.3. European electricity generation in the Market scenario with infinite lifetimes for the existing capacity (alternative case).

The difference in electricity generation between the two cases is attributable to differences in the levels of fossil-fuel based generation (see Figure 2.4). The infinite life-spans of the existing plants imply a greater contribution from the existing supply, as well as, to a certain degree, from new CCS schemes. The reason for this is that the system awaits CCS to be commersialized (from 2020 and onwards), by using existing capacity for a longer period than would be possible if the lifetimes were set by the default assumptions, as in the reference case. Therefore, the total contribution (existing plus new schemes) from natural gas-fired power plants is somewhat lower in the case with infinite lifetimes. New conventional natural gas-fired power plants that act as a bridging measure until CCS is introduced are of less importance if the existing capacity (including gas and coal) can be used for a longer time.

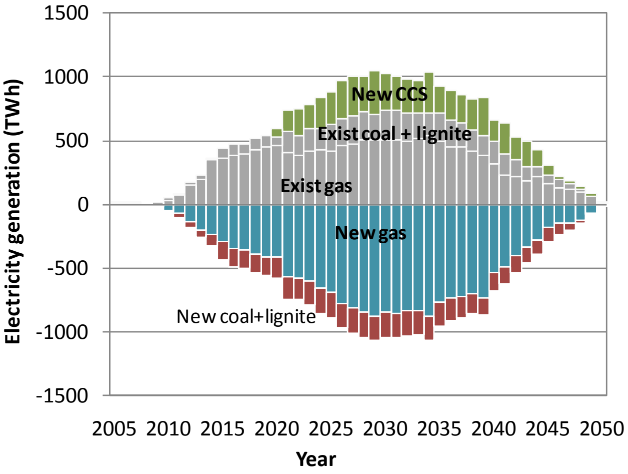


Figure 2.4. Differences in European electricity generation levels between a case in which existing power plants have infinite lifetimes (alternative case) and a case in which default assumptions are made regarding the remaining lifetimes of the existing power plants (reference case).

Finally, a further comparison of the two cases reveals that marginal electricity costs are roughly of the same order. Marginal CO_2-abatement costs are generally somewhat lower in the reference case until 2030. This is due to a relatively larger proportion of new more efficient power plants due to an earlier retirement of existing capacity. In the long run, however, the same type of technology determines marginal costs. Typically, this refers to CCS schemes present in both of the investigated cases (shown in Figures 2.2 and 2.3).

For more information:

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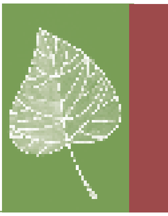
Further reading

Odenberger M., Johnsson F., 2010, “Pathways for the European electricity supply system to 2050 – the role of CCS to meet stringent CO_2 reduction targets”, International Journal of Greenhouse Gas Control, 4(2): 327-340.

Odenberger M., Unger T. and Johnsson F., 2009, “Pathways for the North European electricity supply”, Energy Policy 37:1660-1677.

3

Investment analysis of the cross-border interconnections of the EU power system



The results presented in this chapter are a reduced version of a paper that was presented at the IEEE PES General Meeting in July 2010. The work was done in collaboration with the power systems laboratory at ETH Zurich. The application of the model package developed in the Pathways project to the investment planning analysis of the international cross-border transmission lines within the European transmission system is presented. The investment analysis is based on a cost-benefit analysis (CBA) to optimise the selection of transmission candidates. The results show that the profitability of the investments is influenced by the available production mix and the forecasted CO_2 prices. The avoided congestion costs play an insignificant role in the CBA, which means that many interconnections are inadequate for relieving congestion based on the nodal pricing market structure alone.

Within the Pathways project, a modelling package has been developed for the complete generation of power generation-delivery systems. In this chapter, the application of the modelling package to the investment analysis of the future international interconnections of the European transmission network is presented. More detailed information on the DC Power Flow Model and its linkages to the ELIN and EPOD models can be found in Chapter 11 - 13 and Chapter III of the *Methods and Models* book.

METHODOLOGY FOR TRANSMISSION INVESTMENT ANALYSIS

An integrated iterative process for generation and transmission system planning is presented here. It has been assumed that generation capacity expansion occurs initially, and that a centralised entity is responsible for the optimisation of transmission planning based on proposed strategies for all the system stakeholders. As mentioned previously, using the generation scenarios, the DC Power Flow model can identify possible bottlenecks in the network. Once the long-term network bottlenecks are identified, the DC Optimal Power Flow, which is an optimisation model based on the DC Load Flow model, is used to perform the Cost-Benefit Analysis of the various alternatives for transmission interconnections between countries, in order to remove the network bottlenecks. The next section briefly outlines the results from the cost-benefit analysis. More results can be found in Papaemmanouil et al. (2010).

SUMMARY OF RESULTS

The result of the business-as-usual (BAU) case is presented in Figure 3.1 for the simplified 20-bus European transmission system. During the total period of 25 years, only minor changes in congestions appear, and so the scenarios are based on this picture. Due to congestion lines there is no common price for the entire system. However, three price zones are identified and are coloured in the map as follows: red for expensive; blue for cheap; and green for intermediate price. The most expensive node appears to be node 8, which corresponds to Italy. For this reason, a large amount of power is transferred to the south from the neighbouring nodes, influencing the direct interconnections to Italy, as well as other interconnections, through the produced loop-flows.

The trilateral market coupling of Belgium, The Netherlands, and France is also very clearly recognized, as these three nodes are in the same price zone and there are no congestions between them. The most critical lines of the network are the cross-border connections of node 6, which corresponds to Germany. Germany, together with France (node 3), is the major exporter of the system, providing a large amount of power, mainly to the east. Another important and active exporter of the system turns out to be node 14 (Slovenia), although its production capability is rather limited. The strategic position of Slovenia makes it a significant arbitrator, facilitating the flows from the north to Italy and to south-eastern

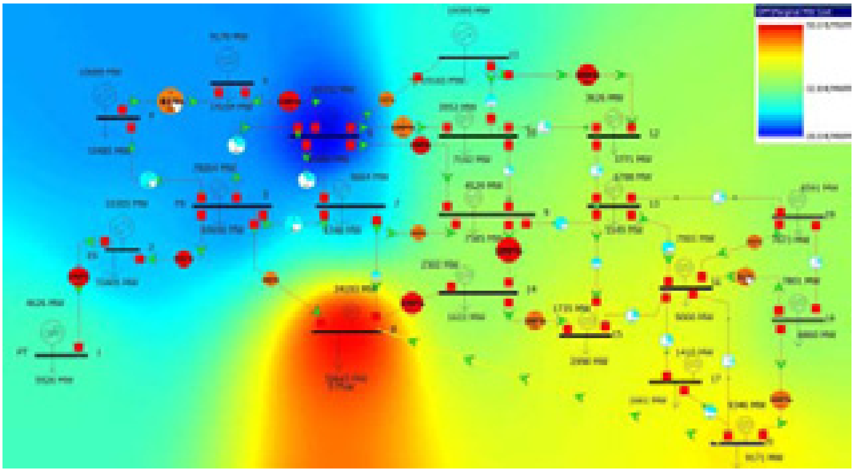


Figure 3.1. Price zones and congested lines (BAU). Source: Papaemmanouil et al. (2010).

Europe. Based on the aforementioned observations, five transmission expansion scenarios have been proposed (Table 3.1).

In Figure 3.2, the calculated cash flows of the five scenarios are presented. From the form of the curve it can be derived that the avoided environmental costs contribute more than the avoided congestion costs to the cost-benefit analysis. During the first 5-6 years, while old and inefficient technologies are still in place, but the integration of renewable technologies is increasing, the avoided environmental costs (which are attributed to the additional transmission capacity) are higher than at the end of the period, when new production technologies have been installed and comprise a higher fraction of the energy mix. This means that more "green" power flows through the additional transmission capacity. In the middle of the period, a peak appears, due to the dispatch of new CCS power plants. As the demand increases, and the dispatched generators do not change significantly, the benefits become negative.

Table 3.1. Candidate transmission expansion scenarios.

	From	To	actual tran. capacity (MW)	additional tran. capa city (MW)	Inv. costs (M €)
scenario 1	7 (CH)	9 (AT)	1200	3000	500
	7 (CH)	8 (IT)	3890	5000	
	6 (DE)	9 (AT)	2000	4000	
	1 (PT)	2 (ES)	1300	2000	
scenario 2	6 (DE)	9 (AT)	2000	3000	365
	14 (SL)	15 (HR)	900	2000	
	6 (DE)	10 (CZ)	2300	4000	
scenario 3	9 (AT)	14 (SL)	650	1300	400
	6 (DE)	5 (NL)	3000	4000	
	6 (DE)	10 (CZ)	2300	4000	
	1 (PT)	2 (ES)	1300	2000	
scenario 4	6 (DE)	10 (CZ)	2300	4000	620
	6 (DE)	11 (PL)	1200	3000	
	1 (PT)	2 (ES)	1300	2000	
scenario 5	9 (AT)	13 (SL)	650	1500	300
	11 (PL)	12 (SK)	550	1500	
	6 (DE)	9 (AT)	2000	4000	

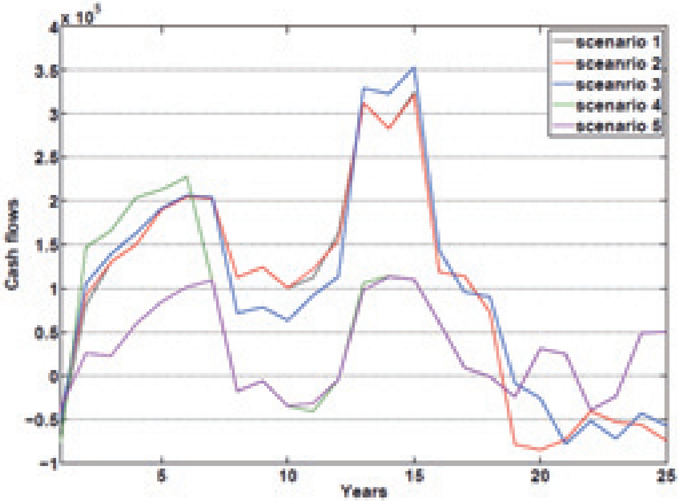


Figure 3.2. Cash flows of the five scenarios (MG).

The cost-benefit analysis shows that all the scenarios are profitable during the whole period. The average benefit to cost index (BCI) is greater than 1 for all of the scenarios, which means that the benefits are higher than the costs. The second scenario is the most profitable for the case of high CO_2 price increases, e.g., from €17 up to €32 per tonne in 2035, although this scenario considers only three transmission lines, and it is not the cheapest one. For the case of lower CO_2 price increases, e.g., from €17 up to €27.5 per tonne, the index provides approximately the same results, despite the lower BCI values. However, a major difference is that the fourth scenario would be in a less favourable position, as the benefits would turn out to be almost equal to the costs. In addition, the fifth scenario would no longer be profitable.

CONCLUSIONS

Two models have been combined in order to study the effectiveness of new transmission plans, regarding their environmental and market aspects. The generation-expansion model (ELIN), which calculates the optimal future generation mix that satisfies a 30% reduction in CO_2 emissions by 2020, and the DC optimal power flow model, which considers transmission network constraints, provide price signals within a nodal pricing market structure. The results show that the profitability of the investments is influenced by the available production mix and the forecasted CO_2 prices, as obtained from the ELIN model. The avoided congestion costs contribute insignificantly to the cost-benefit analysis, which means that many interconnections are insufficient to relieve congestion based on the nodal pricing market structure alone. Due to this, exchanges between the participants are highly promoted and stronger reinforcement of the transmission lines is needed if the target is the reduction of congestion costs. Regarding environmental issues, the proposed investments are beneficial in both types of CO_2 price development for the period of 25 years, supporting generation strategies for greenhouse gas emissions mitigation, except for one of the scenarios, which becomes unprofitable in the case of low CO_2 price development. This analysis is part of the Policy Pathway, which targets both CO_2 emission reductions and demand-side efficiency improvements. The total electricity production will decrease, which in turn will reduce the stress on future transmission systems. Therefore, the need for new investment will be less with the Policy Pathway. The Market Pathway was not implemented in this study. It can however be noted that in the Market Pathway, CO_2 emission reduction is the main target, and with the focus on the supply side, energy production is higher than in the Policy Pathway. Obviously, the need for investment will, in most cases, be greater than that in the Policy Pathway. Regardless of the pathway, the methodology presented in this work will be applicable.

For more information:

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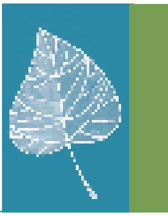
Further reading:

Papaemmanouil, A., Le, T., Andersson, G., Bertling, L., Johnsson, F., 2010, ”A cost-benefit analysis of transmission network reinforcement driven by generation capacity expansion”, IEEE Power & Energy Society (PES) General Meeting 2010, Minneapolis, USA, July 25 - 29.

4

The role of new interconnectors in Europe



Existing bottlenecks in the European interconnector capacities may cause significant differences in electricity prices between regions or countries. Such price differences are the main drivers for investments in additional interconnector capacity. Implementation of the Renewables Directive of the European Commission (EC) is likely to increase further the incentives for new interconnectors. Leading up to 2050, the model runs reported here indicate that total European interconnector capacity may double, as compared to the current level. This in turn will lead to a significant evening out of differences in wholesale electricity prices between the Member States of the EU.

New interconnectors are likely to play a vital role in the ongoing processes of integrating the European electricity markets, and handling the increases in renewable and intermittent sources of electricity production, such as wind power. Strengthening the European electricity infrastructure is identified as an area of priority in a recent communication of the EC (European Commission, 2010).

In the ELOD model used in the present analysis, investments in new interconnectors between countries occur when they are profitable. Thus, if the difference in wholesale electricity price is sufficiently large to motivate investments in interconnector capacity, these investments will be made and, consequently, the price difference will be reduced. In the model, these investments are made until the differences in electricity prices between the countries are reduced to the annualised investment costs for further increasing interconnector capacity. Furthermore, in the model it is also assumed that the electricity that is being exported to a neighbouring country is associated with an efficiency loss in the order of 5%. This is due to model technicalities, but it implies that differences in marginal costs cannot be completely evened out simply by increasing the interconnector capacity between two countries. Nevertheless, the marginal costs may be identical between two countries due to identical production at the margin.

Table 4.1: Investment costs for new interconnectors (cost estimates based on ICF Consulting 2002 and literature survey of existing projects).

Interconnector	Air cable (HVAC), short distance	Air cable (HVAC), long distance	Sea cable (HVDC), short distance	Sea cable (HVDC), long distance
Investment cost (€/kW)	100-150	300	600	800-900
Example	Germany-Denmark	Austria-Czech Republic	Sweden-Poland	UK-Norway

In Table 4.1, assumptions as to typical investment costs for new interconnectors are listed. New interconnectors are divided into four main categories: short- and long-distance on-land (above ground) cables, and short- and long-distance sea cables.

The distribution among "long" and "short" distances is estimated using Google Maps. The typical distances between major load centers in each country of the border determine whether new interconnectors are associated with a long or a short distance. For example, in the case of the Austria-Czech Republic interconnector, the distance between two load centers is relatively long, while the corresponding distance for the Germany-Denmark or France-Spain interconnector is relatively short. In the model, new interconnectors are possible only between countries in which interconnectors already exist or are being planned.

PROFITABLE TO INCREASE INTERCONNECTOR CAPACITY BY 30-40% BY 2020

ELOD model runs indicate that it is profitable for the European electricity system to expand significantly the interconnector capacity between the Member States, from the existing 42 GW (existing interconnector capacities are taken from ENTSO-E online data) to almost 60 GW in the Policy scenario or to 55 GW in the Market scenario by 2020 (Figures 4.1 and 4.2). However, the model does not have any limitations as to the pace of expansion of such capacity. In reality, these investments require substantial lead times. Figures 4.1 and 4.2 include the total interconnector capacity between all EU Member States and Norway. The existing capacity may differ between two Member States depending on the direction of the trade, which may be due to grid limitations within each country. Therefore, the values reported here are the average capacities. For new interconnectors, as estimated in the model runs, capacities are assumed to be identical between two Member States regardless of the direction of the trade.

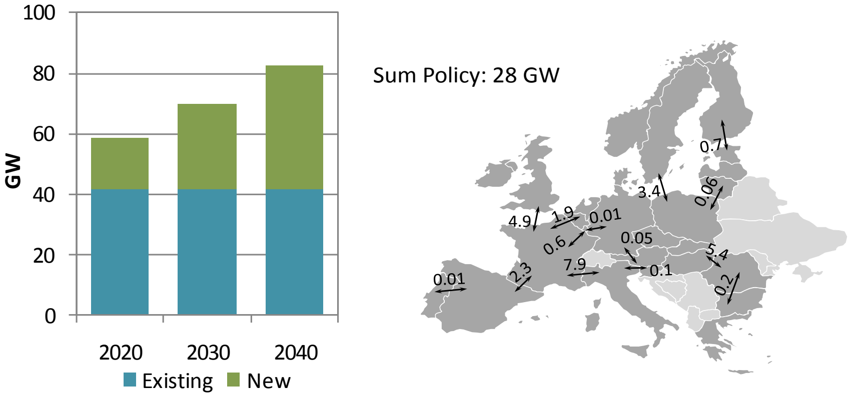


Figure 4.1. European interconnector capacities (the sum of net transfer capacities between EU Member States including Norway) in the Policy scenario in 2020, 2030, and 2040 (left panel), and the regional distribution of *new* capacity (in addition to that existing in 2010) in 2030 (right panel).

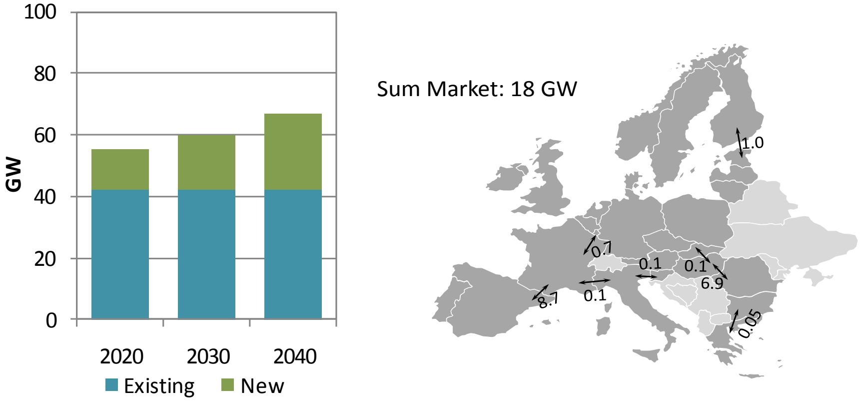


Figure 4.2. European interconnector capacities (the sum of net transfer capacities between EU Member States including Norway) in the Market scenario in 2020, 2030, and 2040 (left panel), and the regional distribution of new capacity (in addition to that existing in 2010) in 2030 (right panel).

The profitability of new interconnectors estimated in the model runs implies a doubling of the interconnector capacity by 2040 in the Policy scenario. In the Market scenario, the corresponding increase is approximately 60%. The results indicate that higher electricity demand, as in the Market scenario, does not automatically mean a greater need for new interconnectors. It is the *differences* in production and demand of electricity between the countries that create the incentives for new interconnectors. These differences do not necessarily become greater if electricity demand increases in general. The Policy scenario, which has a higher share of renewables, especially intermittent production systems such as wind power, and a generally lower electricity demand, seems to generate larger differences between countries. Therefore, the incentives for new interconnectors is greater. The European renewable electricity target, which assumes increases up to 2050 in the Policy scenario (but not in the Market scenario), distributes renewable investments where conditions are most favourable (common European target), and this requires new interconnectors.

In the model, investments in new interconnector capacity are made by several European countries. In particular, France, Spain, the UK, Romania, Hungary, Poland, and Sweden are, depending on the scenario, involved in increasing interconnector capacity (Figures 4.1 and 4.2).

SIGNIFICANT PRICE DIFFERENCES BETWEEN REGIONS WILL BE EVENED OUT

Bottlenecks in the existing interconnectors are the main reason for the differences in electricity wholesale prices between different European countries and regions observed in an integrated and common European electricity market. Implementing the Renewables Directive on a national basis, or jointly among all Member States, is likely to affect the wholesale electricity price in individual Member States. In the present analysis, it is assumed that the target for renewable energy affecting the electricity supply system is implemented jointly across all the European countries.

The impacts of new interconnectors on European wholesale electricity prices (or more precisely, the long-range marginal costs for electricity production) are shown in Figures 4.3 and 4.4 (for model year 2020). The results are obtained from ELOD model runs for two separate cases in which: 1) only existing interconnector capacities between Member States are included; and 2) new interconnector investments are optional. It is shown that "low-cost" areas for electricity generation (e.g., the Nordic countries and France) include regions where the proportion of renewables and/or nuclear power today is very large. "High cost" areas include, depending on the scenario, several Eastern European countries and Italy, where it is assumed that the share of natural gas by 2020 will be relatively large. Furthermore, the existing capacity in many Eastern European countries is relatively old (see Chapter 2), which means relatively low efficiencies and, consequently, high generation costs if CO_2 emission prices are sufficiently high.

Once the model is allowed to invest in new interconnector capacity, wholesale electricity prices are evened out significantly among the Member States. This is clearly shown in the right panels of Figures 4.3 and 4.4. This means that “low-cost” countries, as mentioned above, face somewhat higher prices, while “high-cost” countries face somewhat lower prices. However, in some cases substantial differences between Member States remain. Due to interconnector investment costs, certain price differences will persist (unless supply is identical).

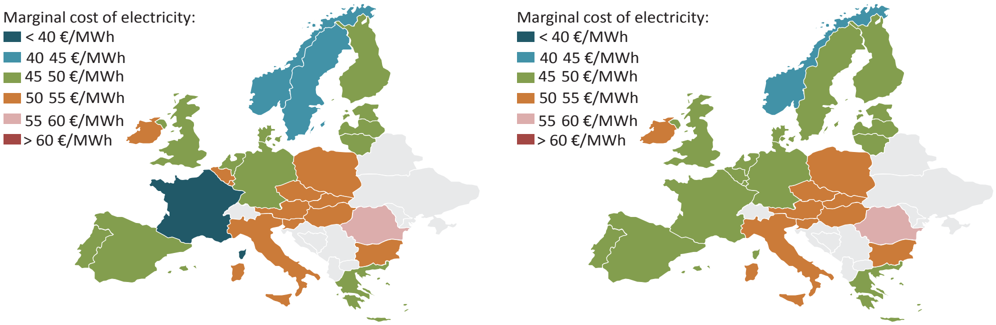


Figure 4.3. Regional distribution of long-range marginal costs for electricity in 2020 with the existing interconnectors (left) and additional interconnectors (right) (Policy scenario).

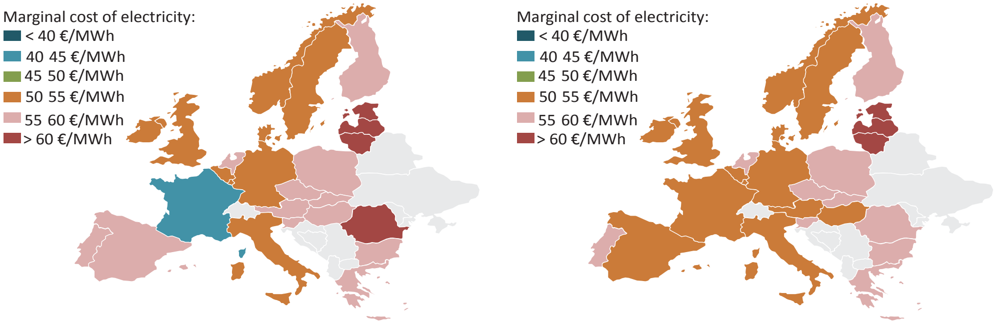


Figure 4.4. Regional distribution of long-range marginal costs for electricity in 2020 with the existing interconnectors (left) and additional interconnectors (right) (Market scenario).

Comparing the Market and Policy scenarios, it is obvious that the Market scenario generally implies higher marginal costs for electricity due to a higher demand forelectricity. However, this is not self-obvious, since the CO_2-reduction commitments in the European electricity supply system are larger in the Policy scenario, i.e., 40% by 2020 for electricity supply (an assumption based on the overall European target of 30% given a global effort), as compared to the Market scenario, i.e., 30% by 2020 (an assumption based on the overall European target of 20% given an exclusively European effort). In the Policy scenario, typical marginal electricity costs are around 45-50 €/MWh if new interconnectors are allowed, while the corresponding cost range is around 50-55 €/MWh in the Market scenario.

For more information:

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Further reading

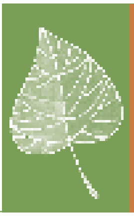
Odenberger M., Johnsson F., 2009, CCS in the European Electricity Supply System – assessment of national conditions to meet common EU targets, Energy Procedia 1(1):4273-4280.

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

5

The social embedding of infrastructure development:

challenges for policy implementation



The concept of path dependence has been used in various fields, including economics, economic history, history of technology, historical sociology, political science, and public administration, to address change and stability in decision making over time. It addresses historical trajectories of reform or policy making and implementation, nested decision making, and co-operation among institutional actors. Path dependence places a focus on the constraints on choice caused by earlier decisions, through returns or incentives, and contributes to an understanding of "bounded rationality" in organizational decision making. A core idea is that the temporal sequencing of events potentially has crucial consequences for consequent decision steps. An important distinction made in the literature is between two types of path dependence: self-reinforcing sequencing and reactive sequencing (Mahoney, 2000). A self-reinforcing sequencing of events tends to produce an institutional pattern by "increasing returns", some form of utility or benefit. Since early events are being reinforced by the reproduction of a mechanism of increasing returns, self-reinforcing path dependence tends to be highly resistant to change (for example, economic subsidies as incentives to homeowners to convert oil-fuelled heating systems to heat pumps). A reactive sequence is different in that late events are driven by reactions to earlier events through repercussive processes that change or negotiate the early events (for example, the Swedish referendum on nuclear power in the past and more recent policies to develop nuclear power).

A comparison of the two modes of facility siting, i.e., policy-driven infrastructure planning (e.g. interconnectors, railways) and market-driven wind farm development, shows that the "public interest" aspect of the facility siting is structured differently. In policy-driven railway planning, the public interest is inbuilt in the facility, which represents a public benefit (by combining the promotion of "green" values, sustainable development, and economic growth), whereas in market-driven wind farm development, the facility can represent a threat to the public interest (in terms of the natural environment, landscape, and public health) posed by a developer acting out of a partial (profit-related) interest (Corvellec and Boholm, 2008).

STATING THE PROBLEM

The overall aim of the Pathways project is to "study and evaluate pathways towards a sustainable energy system with respect to technical, economic, and social issues". The planned development of sustainable energy systems has to respond to many challenges. A major source of complexity is that technical, economic, and social "issues" constitute separate self-producing systems, which are differently constituted and "programmed" (Luhmann, 1989). The interactions between these systems do not automatically align into a simply orchesterated process of convergence, rather the system interactions often display incompatible and contradictory forces and "irrational" outcomes. Swedish wind power policy is a case in point. On the one hand, there exists a government program of economic incentives to producers of electricity from wind power. On the other hand, there are bodies of law and regulatory frameworks for environmental licensing and physical planning. In the public debate on the promotion of "green energy", this incongruence is noticeable. Whereas the government has ambitious planning goals for the development of wind power and provides various economic incentives to support electricity-generating companies to increase the proportion of wind-based energy production in their company portofolios, regulations governing physical planning and environmental licensing systems restrict development (Rönnborg, 2009). These contradictory activities of the institutions of the energy market and of the political and regulatory systems are often described as obstacles to sustainable development, leading to calls for de-regulation or "simplifications" of the regulatory framework, for example withdrawal of the power that municipalities wield regarding land-use planning within their territorial domains (Pettersson, 2008).

THE SOCIAL EMBEDDING OF ENERGY TECHNOLOGY

A theoretical point of departure for this part of the Pathways project is that technology does not exist apart from or independently of social organisation (see, for example, Jasanoff et al., 1994). Technology involves materials, artefacts, and technical assemblies in human-made systems, which are designed to serve purposes and functions of social significance. Technical artefacts build on knowledge of science and engineering; they are designed and constructed within organisations run by people who work and plan together, collaborating to expand on the market, a social institution built on norms, rules, codes, and expectations as to how others will act and react.

The energy sector is no exception to this rule. Energy systems are technical systems for converting energy into a certain form (e.g., electricity, heat or fuel) that can be utilised and distributed according to market or market-like conditions, more or less regulated, and steered by political decisions. Market actors, such as production and distribution companies and consumers, and their preferences, choices, capacities, and strategies are fundamental to the operation of the energy system. The influence of politics on energy systems is twofold: 1) through the steering of market conditions to affect the pricing of energy (through taxes or price mechanisms) so as to influence and direct consumption and demand (for example, away from fossil fuels to renewable cources or by promoting the use of heat pumps in private homes); and 2) through regulating the conditions and requirements for the planning and construction of facilities and installations.

Energy systems comprise industrial facilities, such as power grids, pipelines, distribution centrals, disposal facilities for carbon capture or radioactive waste, power stations, and plants that require substantial investment and physical planning. The siting of power stations and plants, as well as distribution and disposal facilities is regulated by law (the Environmental Code, The Plan and Building Act), and involves specific legal procedures, as well as in some cases, licensing by authorities such as the Environmental Courts and regional county boards. Regulation is essential, since these facilities have impacts within the public domain and should be subject to democratic decision-making processes and consider citizen interests and values. A power plant might encroach on private property, affect municipal expansion and development, entail risks to public health or the natural environment, and might adversely affect public interests other than those related to energy provision. Therefore, formal decision-making procedures that involve municipalities, authorities, and courts are needed (Pettersson, 2008).

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 cooperative 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. Social science research within Pathways uses the concept of "path dependence" as a unifying analytical term to describe the structural and historical continuities that characterize decision processes and organizational arrangements within the energy sector. For a further discussion of the concept of path dependence, see Chapter 4 in the *Methods and Models* book.

This book is accompanied by the **Methods and Models book**, which describes the methodologies used in the Pathways project.

MARKET AND POLICY: RESULTS FROM CASE STUDIES OF INFRASTRUCTURE FACILITY SITING

In the Pathways project, CEFOS has analysed the similarities and differences in cases of market-based and policy/government-based infrastructure facility siting. The concept of path dependence serves as a thematic lens for these observations.

The mode of political steering versus market steering has been discussed in the literature on path dependence, and it has been noted that the role of increasing returns is markedly different in a market context, as compared to that in a political context (Pierson, 2000). Some of the crucial differences are listed in the following table.

In the present chapter, two cases of societal planning and facility siting for a technical infrastructure that are differently regulated and organised, i.e., railway lines and wind farms, respectively are assessed and analysed. In both cases, planning involves complex decision-making processes that actualise many different perspectives and interests, as well as competing aims and diverse expert competencies. Governance interactions are multi-purpose and take place in arenas characterised by multi-level and multi-sectorial governance (Smith, 2003). Communication, co-operation, and continuous negotiation among actors are key features of the interaction (Johansson, 2010; Boholm, 2010).

In Sweden, energy production is de-regulated, and private companies (electricity producers and developers specializing in wind farm technology) are responsible for the planning and building of production facilities, often with the assistance of consultancy firms with expertise in environmental impact assessment and licensing processes. According to the Planning and Building Act (SFS 1987:10), a municipality, which is a politically governed entity, in practice has a planning monopoly within its territorial borders. The municipality has a mandate to make physical plans that designate land use for specific purposes (such as industry, recreation, housing, community functions, transport infrastructure, cultivation, and burial grounds), which are legally binding. The zoning of land for specific uses is legally connected to regulations on building permits and legislation regarding specific types of land and land use, as set out in the Environmental Code. Through zoning, a municipality can effectively block or allow include the facility siting of wind farms. The Environmental Code (SFS 1998:808) regulates the establishment of wind farms, and the county board and the environmental court are the licensing authorities (Pettersson, 2008).

In contrast, the railway infrastructure in Sweden is state-owned, and the national government decides on investments in new lines, upgrading or the closing down of existing lines. The Rail Administration is responsible for the railway system, including the provision of rail tracks, signalling systems, and the

Political steering	Market steering
Many states of equilibrium and possible outcomes	High initial costs (for example in investments in new technology)
Accidental occurrences can play major roles	Learning new is resource demanding
Timing and sequencing of events can be crucial	Coordination requires effort
Inertia due to institutional rigidity (institutions are designed to resist change)	Change is incremental and adaptive

electricity supply for the trains, while the trains are run by companies who hire rail capacity from the Rail Administration. In 2001, the Rail Administration production unit was deregulated and subjected to market competition. Railway planning is regulated by the Railway Building Act (SFS 1995:1649) and the Environmental Code (SFS 1998:808). The Railway Building Act states that consultations with affected real estate owners, municipalities and regional boards, as well as 'others who might have a substantial interest in the matter' (SFS 1995:1649, 2 Ch, 5 §) are mandatory.

The differences in the regulatory and organisational structures of the facility siting process between these two cases seem to have a major influence on the outcome. Railway planning is structured by self-reinforcing co-operation and alliances between key public actors (such as the Rail Administration, the Road Administration, municipalities, and county board), which collaborate to achieve a common goal (a new railway line). In contrast, wind power planning is often characterized as a reactive process, in which a developer or an electricity producer presents an application to a licensing authority that has little incentive to co-operate, but rather concentrates on scrutinising the project as a potential threat to various public interests, and in relation to environmental regulations or conservation law (Corvellec and Boholm, 2008). In railway planning driven by a state agency (the Rail Administration), exploitation interests that encroach upon environmental or conservation values, tend to "win" over conservation interests, since the public interest of a new railway line carries greater weight. However, wind farm planning, which is driven by a private developer or electricity producer, lacks this kind of "in-built" public interest (amalgamated by a co-operation of public key actors and licensing authorities), so it is more likely that conservation values will supersede exploitation interests. The net effect is that infrastructure development within the energy sector with regard to production facilities is somewhat at a disadvantage compared to the building of railways or public roads.

Railway planning	Wind farm planning
Politics	Market
State government (the National Rail Administration)	Private companies/developers
The Railway Building Act, The Environmental Code	The Plan and Building Act, The Environmental Code
The County Board, The National Government	The County Board, The Environmental Court
Co-operative planning among authorities and stakeholder	Private and separate planning
Public interest	Private interest

An overall conclusion of this Pathways sub-project, which resonates with the results of 40 years of policy implementation research dating back to Pressman and Wildavsky’s (1973) seminal work, is that policy and its implementation hardly constitute a linear road from goal to goal fulfilment. Implementation research has shown that this road is often winding and crowded with serious obstacles. It is crucial to have a sense of common direction among the implementation actors, who tend to be driven by diverse goals, using diverging strategies and organisational action logic. The policy itself is sometimes vague and lacks precision, and as a consequence, the implementing actors (public administrators, business representatives, legal or scientific experts) make discretionary decisions based on their interpretations of policy goals. Sometimes, a policy can have complex and even contradictory goals, which means that the implementing actors have to create priorities based on interpretations and organisational (bounded) rationality and inter-actional and inter-organisational negotiations (Winter, 2003).

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Further reading:

Boholm, Å., 2010. Temporality and joint commitment in railway planning. CEFOS Working Paper 10, Cefos, Göteborgs universitet. Available at www.cefos.gu.se (Publications/Working Papers)

6

Large-scale integration of wind power into thermal power systems

Wind power is a key technology to reduce CO_2 emissions from the electricity generation system, as well as to enhance security of supply. As a bridging technology, it has to be integrated into the existing electricity generation systems, which in Europe are generally thermal-based systems. Thermal units are most efficient when run continuously at rated power, whereas the amount of electricity generated by wind varies over time. Thus, depending on the characteristics of the wind-thermal system, part of the decrease in emissions realised by wind power is offset by a reduction in the efficiency of operation of the thermal units as a result of the variations in electricity generation from wind. Measures to improve wind-thermal systems to manage these variations have been investigated within the Pathways project. This investigation is of particular relevance to future scenarios with high proportions of wind power, e.g., as the result of strong diffusion of renewable electricity generation combined with significant efficiency measures, which would result in a low growth in demand, and with remaining generation on base-load plants, such as nuclear and CCS plants (cf. Chapter 1).

In a wind-thermal power system, the continuous power generation in thermal units at high efficiency is influenced by variations in the load and variations in wind power. There are three main alternative ways in which the power system can respond to this variability: 1) by an increase in power plant cycling (i.e., starting/stopping); 2) by an increase in part load operation hours of the thermal plants; and 3) by wind power curtailment. Thus, in a system dominated by thermal base load units, the integration of large-scale wind power might result in increased costs and emissions related to thermal operation.

The choice of strategy for managing the variation depends on the properties of the available thermal units and the duration of the variation. In a power system in which cost is minimised, the strategy associated with the lowest cost is obviously chosen. If, for example, the output of wind power and a base load unit exceeds demand for 1 hour, curtailment of wind power (or possibly some curtailment of wind power in combination with part loading of the thermal unit) might be the solution with the lowest total system cost. If the situation persists for half a day, stopping the thermal unit might be the preferable option from the cost-minimisation perspective.

In addition, active strategies for variation management can be introduced to improve the efficiency of the wind-thermal system by reducing the variations in the total load on the thermal units, thereby avoiding thermal plant cycling and part load operation, without curtailing wind power. Active variation management strategies reduce variations either by displacing power over time or by displacing load over time. Traditional storage forms displace power over time. A transmission grid solution, in which power is imported to and exported from a system, works according to the same principle from a power-generation perspective. A device that displaces power over time is referred to as a 'moderator'. Strategies in which the load is displaced over time are generally referred to as 'demand-side management strategies'.

INTERACTION ANALYSED WITH THE BALWIND MODEL

An optimisation tool, the BALWIND model, was developed to describe the interaction between wind power and thermal units (see Chapter 15 in the *Method and Models* book*)*. This model is a unit commitment model with the objective of finding a least-cost strategy to meet the electric load and the heat load. The model includes start-up costs and minimum load level, as well as the part load costs of all large thermal units within the system under study. The variation management strategy of the system is thus part of the optimisation. Different moderators, designed to displace power over time, have been investigated. The particular demand-side management strategy of shifting load over time, which is considered here, involves the integration of a fleet of Plug-in Hybrid Electric Vehicles (PHEVs) into the wind-thermal system. The electricity generation system considered is an isolated system that contains the thermal units of western Denmark.

DECREASED COSTS AND EMISSIONS

In general, the described integration of variation management strategy decreases the system generation costs. Reductions in the number of start-ups and in part load operation, as well as in wind power curtailment also imply decreased system emissions, whereas the effect on system emissions of a shift from peak load to base load generation depends on the specific peak load and base load technologies. System benefits (i.e., reductions in costs and emissions) reaped from the integration of active variation management have been compared to costs and emissions related to the operation of storage technologies and costs related to Plug-in Hybrid Electric Vehicles (PHEVs) demand-side management.

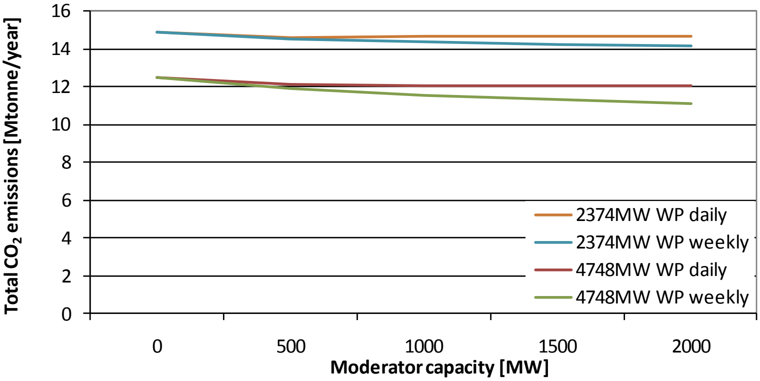


Figure 6.1. Impact of moderator power rating and capacity on total system emissions. The electricity generation system considered is an isolated system that contains the thermal units of western Denmark and two levels of wind power (2374 MW, generating 20% of the total electricity demand; and 4748 MW, generating 40% of the total electricity demand if no wind power is curtailed). Charging and discharging of the storage is balanced on a daily and weekly basis. Source: Göransson and Johnsson, 2010.

Figure 6.1 illustrates an example of the impact of a general moderator (i.e., loss-less storage or loss-less transmission capacity) on power system emissions. The ability of a general moderator to displace power over time depends on the power rating of the moderator and the storage capacity of the moderator (i.e., the time basis on which the charging and discharging of the moderator is balanced). As indicated in Figure 6.1, the advantage of a weekly balanced moderator, as compared with a daily balanced moderator, is more significant in a wind-thermal power system with a high level of wind power grid penetration (in this case, 40%) than in the wind-thermal power system with a lower level of wind power grid penetration (in this case, 20%). This is explained by the following observation; at 20% wind power, variations in wind power are in the same range as variations in load for the system investigated, whereas variations in wind power dominate the power system at the higher level of wind power generation. In the system with 20% wind power, wind power does not compete with base load units during peak hours, and wind power curtailment is rare. With a moderator, wind power generated at off-peak hours can be used during the subsequent peak in load, and emissions are mainly reduced through load variation management. A daily balanced moderator is thus sufficient in a system that has up to 20% wind power. In a system with high wind power grid penetration (i.e., 40%), the variations in wind power generation dominate over the variation in load, and wind power curtailment is substantial. Since there may be several subsequent days with good wind conditions, a weekly balanced moderator is more efficient at reducing emissions in this type of system.

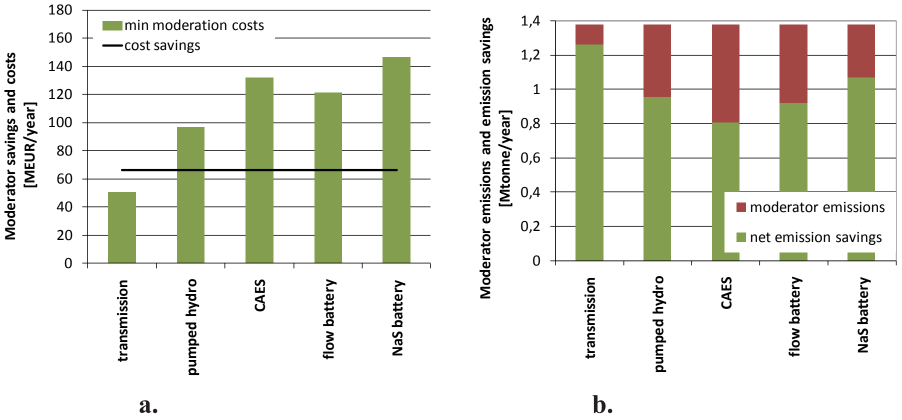


Figure 6.2. Costs for different moderators and their emissions (using a weekly balanced moderator as example). a) Cost savings (solid line) compared with costs for moderation (bars). b) Emission savings reduced by emissions associated with moderation. Sources: (Rydh, 1999; Nourai, 2002; EC, 2003; Denholm and Holloway 2005; IEA, 2005; Kuntz, 2005; Rydh and Sandén, 2005; Ravenmark and Normark, 2006; Göransson and Johnsson, 2010). Abbreviations: CAES - Compressed Air Energy Storage, NaS - Sodium sulphur.

Figure 6.2 compares the reductions in emissions and costs due to the introduction of a weekly balanced moderator in a system with 40% wind power and the total life cycle costs and emissions of possible moderators. Applying existing moderator technology, a net reduction in emissions of 7.5% to 10.3% is possible. However, assuming a CO_2 emission cost of 20 €/tonne (corresponding to the solid line in Figure 6.2a), overhead transmission lines is the only moderator that lowers the total system costs. With overhead transmission lines, system costs can be reduced if the imported power can be bought at prices that do not exceed the yield from exported power by more than about 4 €/MWh and assuming that it is sufficient to invest in 1000 km of transmission line. However, using transmission as a moderator requires either the construction of transmission lines to a region with excess flexible capacity (e.g., high hydroelectric power capacity) or to a region that is sufficiently far away to make wind speeds and/or demand uncorrelated with wind speeds and/or demand in the region seeking variation management.

Finally, it should be noted that when comparing different moderator technologies, the preferred order of moderator technologies depends on the average emissions associated with the power system into which the moderator will be integrated. Since major rearrangements of present power systems are under consideration, it is important to take future developments of the system into account when choosing a moderator technology.

DEMAND-SIDE MANAGEMENT

Another way to maintain the generation in thermal units at the desired level is to displace some of the load, rather than some of the generated power, using demand-side management. An example of how demand-side management is implemented by choosing appropriate charging strategies for PHEVs is described below.

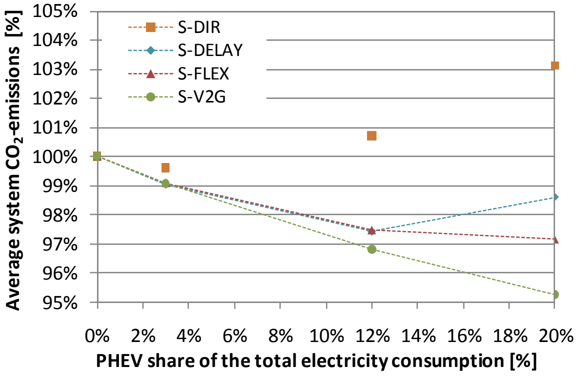


Figure 6.3. Impact on CO_2 emissions of PHEV integration, as deduced from simulations of an isolated wind-thermal power system (vehicle emissions are not included). The average level of emissions in the system without PHEVs is 649 kgCO_2/MWh. Thus, in the plot, 1% is equivalent to 6.49 kg CO_2/MWh. Source: (Göransson et al., 2010)

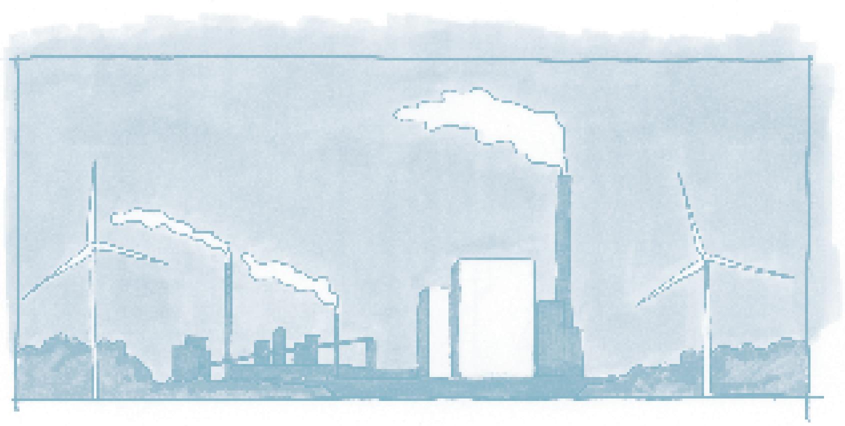
The load managing ability of the PHEVs depends on the PHEV share of total electricity consumption, as well as the limitations on the power system to allocate the PHEV load. A comparison of the PHEV impact on power system emissions for four different integration strategies is presented in Figure 6.3. In Figure 6.3, PHEVs are integrated into the system at three implementation levels (3%, 12%, and 20% of the total electricity consumption). The four integration strategies are as follows:

– S-DIR, in which the charging of the PHEVs occurs immediately after driving and the PHEVs are charged as soon as they return home (it is assumed that the PHEVs will always be recharged due to the relatively low cost of driving on electricity as compared to gasoline).

– S-DELAY, in which the charging of the PHEVs is delayed (i.e., with a timer) to minimise average correlations with demand.

- S-FLEX, in which the charging of PHEVs takes place when it is most favourable from the power system perspective, although the entire PHEV fleet has to be charged during the night and a part of the fleet is charged during the workday.
- S-V2G, in which the power system is free to dispatch the PHEV load and to discharge PHEVs as desired. However, charging and discharging are restricted to the PHEV capacity available to the grid and the power level of the batteries. The power level of the batteries depends on the charging and discharging history and the daily driving pattern, for which electricity could have been used.

As shown in Figure 6.3, the lowest emissions are obtained for the S-V2G strategy at 20% PHEV share of the total electricity consumption, and a 4.7% reduction in power system emissions is achieved. In contrast, when the charging of the PHEVs occurs immediately after driving and the PHEVs are charged as soon as they return home (S-DIR), there is a clear increase in CO_2 emissions from the power system as the share of PHEV electricity consumption increase. The other integration strategies produce emissions that are intermediate to those observed for the S-V2G and the S-DIR strategies.



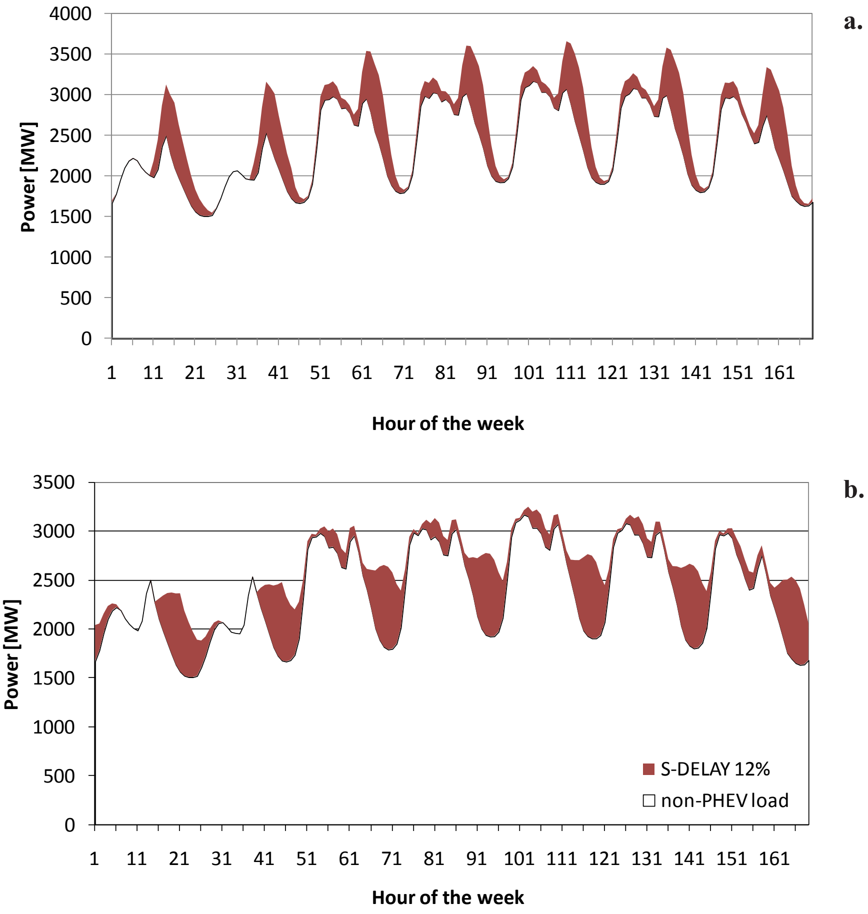


Figure 6.4. Total electricity consumption in the system modelled by Göransson et al., (2009), divided into consumption by households and industry (white) and consumption by PHEVs (red). The example shown is for a 12% PHEV share of electricity consumption. **a)** The S-DIR integration strategy, in which electricity consumption by households and industry is strongly correlated with electricity consumption by vehicles. **b)** S-DELAY strategy, in which a shift in charging start time decreases the correlation and evens out overall electricity consumption. Source: (Göransson et al., 2010).

What mechanisms underlie the increase/decrease in emissions seen for the four different integration strategies? Figure 6.4 shows a weekly time series of the total consumption of electricity divided into consumption by households and industry (white) and consumption by PHEVs (red). In Figure 6.4, PHEV consumption is 12% of the total electricity consumption, and the household and industry consumption is scaled down to 88%. As shown in Figure 6.4a, in the

S-DIR strategy (i.e., vehicles are charged as soon as they return home), PHEV integration into the system does not imply a smoothing of the total load, but rather accentuation of the peaks. As PHEVs are integrated under the S-DIR strategy, there is a decrease in the number of thermal units that can run continuously, and most units also have to cover the peak load. The result is an increase in emissions from the power generation system compared to the reference case without PHEVs (cf. Figure 6.3). Applying the S-DELAY strategy (i.e., vehicle charging is delayed with a timer), PHEV consumption is shifted so that it occurs at times of low non-PHEV load, and the overall load is evened out, as shown in Figure 6.4b. This simple adjustment proves to be an efficient way to smooth out the overall load, and the integration of PHEVs will reduce the average system emissions under this strategy (cf. Figure 6.3).

Table 6.1. Reduction in total system costs (as compared to the case without PHEV integration) per vehicle compared with implementation cost (right-most column) for different PHEV integration strategies and implementation levels. Negative values represent increases in system costs due to PHEV integration. Source: Göransson et al., 2010.

[€/vehicle and year]	Reduction in cost 20% PHEV	Reduction in cost 12% PHEV	Reduction in cost 3% PHEV	Implementation cost[1]
S-DIR (fixed load - no control)	-17.16	-11.58	-4.00	0
S-DELAY (fixed load - timer)	1.54	11.23	20.85	4
S-FLEX (free load distribution)	6.29	15.25	28.76	14
S-V2G (free load, V2G allowed)	12.57	19.39	32.07	52

1) (Capital costs*r/(1-(1+r)^-lifetime))
A 10-years lifetime is assumed. r =0.05 as in one of the IEA cases (IEA (2005). *Projected Costs of Generating Electricity*, OECD/IEA). Costs for S-FLEX (US$150) and S-V2G (US$550) are from Tomic, J. and W. Kempton (2007). ”Using fleets of electric-drive vehicles for grid support.” *Journal of Power Sources*168(2): 459-468. The cost for S-DELAY is 298SEK at standard hardware store (2007 average exchange rate from the Swedish central bank).

The choice of PHEV integration strategy obviously depends on the cost to implement the strategies. If the majority of vehicle charging takes place at home (as is assumed in the work by Göransson et al., 2010), there is an implementation cost associated with each vehicle. The implementation cost then simply corresponds to the cost of the device for connecting and controlling the PHEVs at the charging point (e.g., in a garage). There are significant differences in implementation costs between the strategies, and the cost of a sophisticated controlling system (i.e., S-V2G) is particularly high. However, when a more sophisticated controlling mechanism is used for a fleet of PHEVs, the improvements in power system efficiency (which reduce costs) are greater than when a less-sophisticated controlling mechanism is used. Table 6.1 compares the costs of implementing PHEVs with the changes in cost of supplying the electricity generation system with power as PHEVs are integrated into the wind-thermal system. As shown in Table 6.1, the reduction in costs is always smaller than the implementation cost for the S-V2G strategy, whereas the implementation costs of the S-FLEX and S-DELAY strategies are compensated for at a 3% and 12% PHEV share.

Thus, from a maximum CO_2 reduction perspective, the S-V2G strategy is preferred. However, the implementation costs of this strategy are relatively high (see Table 6.1). Furthermore, it may prove difficult to reach agreement for a strategy in which the transmission system operator has full control over the charging and discharging of the vehicle and the car owner has no say in the state in which he/she will find the car (charged/discharged). In the S-FLEX and S-DELAY strategies, the car owner will always find the car charged at a specified/contracted time, so these strategies would probably be more convenient to implement in reality.

TIME SPAN DECIDES MANAGEMENT STRATEGY

From a wind power integration perspective, there is no difference if variations are managed by shifting power over time compared to if they are met by shifting load over time, since the objective is to match load to power generation. More important is the time span over which the shift can be implemented. Demand-side management implies a shift in load within a 24-hour period, since most loads are recurrent on a daily basis. This corresponds to daily balanced storage. By shifting the power or load over the day, it is possible to avoid competition between wind power and base load units, which means that the efficiency of generation will be improved (resulting from a decrease in start-ups, part load operation and/or wind power curtailment). In addition, the daytime peak can be reduced and some associated start-ups can be avoided (although such “peak shaving” is of secondary importance, since the peak load units generally have good cycling ability). The results of the simulation of the western Denmark system indicate that it is sufficient to manage the variations in load over the day (by shifting power or load), so as to accommodate efficiently wind power generation that corresponds to 20% of the total demand for electricity.

With wind power generation in the range of 40% of the total demand, the variations in wind power exceed the variations in load and, since the variations in wind power often are of longer duration (i.e., strong winds may affect a region for more than 12 hours), power or load has to be shifted over longer periods of time. In this case, a weekly balanced moderator (typically pumped hydro or transmission) would be suitable for a wind-thermal system. Some flexible generation, such as hydro power or co-generation, might also be applicable. However, since it is not easy to find a demand for electricity that can be delayed for a week, demand-side management could be difficult to apply for wind power variation management at these grid penetration levels. Nevertheless, this chapter illustrates that there are significant possibilities for applying smart control systems to a system with high proportions of intermittent power generation, such as wind power.

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Further reading:

Göransson, L., 2008, Wind power in thermal power systems - large-scale integration, Thesis for the degree of licentiate of engineering, Chalmers University of Technology.

Göransson, L., Johnsson, F., 2010, Large scale integration of wind power: moderating thermal power plant cycling. Wind Energy, n/a. doi: 10.1002/we.405

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