All CO$_2$ molecules are equal, but some CO$_2$ molecules are more equal than others

Stefan Grönkvist

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KTH - Royal Institute of Technology
Department of Chemical Engineering and Technology
Energy Processes
SE-100 44 Stockholm, Sweden
This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that participate in the Energy Systems Programme are the Division of Solid State Physics at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Department of Heat and Power Technology at Chalmers Institute of Technology in Göteborg as well as the Division of Energy Processes and the Department of Industrial Information and Control Systems at the Royal Institute of Technology in Stockholm.

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Stefan Grönkvist
Department of Chemical Engineering and Technology, Energy Processes
Royal Institute of Technology – KTH, Stockholm, Sweden

Abstract
This thesis deals with some challenges related to the mitigation of climate change and the overall aim is to present and assess different possibilities for the mitigation of climate change by:

• Suggesting some measures with a potential to abate net greenhouse gas (GHG) emissions,
• Discussing ideas for how decision-makers could tackle some of the encountered obstacles linked to these measures, and
• Pointing at some problems with the current Kyoto framework and suggesting modifications of it.

The quantification of the net CO₂ effect from a specific project, frequently referred to as emissions accounting, is an important tool to evaluate projects and strategies for mitigating climate change. This thesis discusses different emissions accounting methods. It is concluded that no single method ought to be used for generalisation purposes, as many factors may affect the real outcome for different projects. The estimated outcome is extremely dependent on the method chosen and, thus, the suggested approach is to apply a broader perspective than the use of a particular method for strategic decisions. The risk of losing the integrity of the Kyoto Protocol when over-simplified emissions accounting methods are applied for the quantification of emission credits that can be obtained by a country with binding emissions targets for projects executed in a country without binding emission targets is also discussed.

Driving forces and obstacles with regard to energy-related co-operations between industries and district heating companies have been studied since they may potentially reduce net GHG emissions. The main conclusion is that favourable techno-economic circumstances are not sufficient for the implementation of a co-operation; other factors like people with the true ambition to co-operate are also necessary.

How oxy-fuel combustion for CO₂ capture and storage (CCS) purposes may be much more efficiently utilised together with some industrial processes than with power production processes is also discussed. As cost efficiency is relevant for the Kyoto framework, this thesis suggests that CCS performed on CO₂ from biomass should be allowed to play on a level playing field with CCS from fossil sources, as the outcome for the atmosphere is independent of the origin of the CO₂.

Language: English

Keywords: climate change mitigation, abatement of GHG-emissions, co-operation, district heating, waste-heat utilisation, GHG accounting, CO₂ accounting, emissions accounting, CO₂-crediting, marginal power, rebound, market-based leakage, CDM, oxy-fuel combustion, oxygen combustion, carbon capture, cement kiln, lime kiln, biomass, carbon capture and storage, CCS.
Alla CO₂ molekyler är jämlika men somliga CO₂ molekyler är mera jämlika än andra

Stefan Grönkvist
Institutionen för kemiteknik/energiprocesser
Kungliga Tekniska Högskolan

Sammanfattning

Denna avhandling behandlar vissa av de utmaningar vi står inför när det gäller att dämpa den pågående förändringen av klimatet. Det övergripande målet är att presentera och värdera olika möjligheter ämnade att åstadkomma en sådan dämpning genom att:

• Föreslå åtgärder som potentiellt kan minska nettoutsläppet av växthusgaser
• Diskutera förslag gällande hur beslutsfattare kan hantera vissa av de hinder som finns för att de föreslagna åtgärderna skall komma till stånd
• Belysa vissa problem med det nuvarande ramverket kring Kyotoprotokollet och samtidigt föreslå modifieringar till det


Avhandlingen diskuterar också hur syrgasförbränning för insamling och lagring av CO₂ kan utföras betydligt effektivare när tekniken appliceras på vissa industriella processer än på kraftproduktionsprocesser. Eftersom kostnadseffektivitet är ett ledord inom ramverket för Kyotoprotokollet föreslås också att insamling och lagring av CO₂ av biologiskt ursprung skall ges samma förutsättningar som insamling och lagring av CO₂ av fossilt ursprung. Motivet till förslaget är att koldioxidens ursprung inte spelar någon roll för atmosfären.
List of appended papers


Contributions to the appended papers

The development of the ideas behind each paper is briefly described in section 1.3, but the actual work resulting in the papers may also be summarised as follows:

Paper I
I was responsible for the empirical findings in Gävle, Hofors, Lindesberg, Mariestad, Norrtälje, and Sandviken, while Peter Sandberg was responsible for the cases in Göteborg and Sundsvall. The planning and writing of the paper were made together.

Paper II and Paper III
These papers were written together with Jörgen Sjödin, who did most of the work on Paper II while I did most of the work on Paper III. Mats Westermark provided us with useful ideas and comments for Paper III.

Paper IV
I was involved in the discussion leading to the concept presented in this paper and have also contributed to the literature search and the creation of the paper.

Paper V
I did most of the work on this article, but the ideas were partly developed together with Mats Westermark. Mårten Bryngelsson did some fundamental research for data used in the article.
Paper VI

I did the major part of the writing of this article, but the fundamental ideas behind it were worked out together with Kenneth Möllersten. Still, the paper would not have resembled the way it looks today without the help of Kim Pingoud, who wrote some of the passages, but, more importantly, helped us with his knowledge about greenhouse gas reporting and accounting.

Related publications not included in this thesis


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1 Introduction

By paraphrasing the famous proclamation in George Orwell’s novel Animal Farm, I have tried to reveal the scope of this thesis in the title. I got the idea for the title from one of my co-authors, Kenneth Möllersten, who thought about using it on one of his papers, but desisted. The original sentence

“All animals are equal, but some animals are more equal than others”,

uncovers the hypocrisy of a government that declares the unconditional equality of all citizens in the country while giving privileges and power to a few. In this thesis, the title indicates mainly two things: once in the atmosphere, the origin is irrelevant for how a carbon dioxide molecule will influence the earth’s radiative balance, and, when considering the net greenhouse gas (GHG) balance, it is always the overall effect of a certain action that counts.

Energy processes and their relation to CO₂ emissions are the targets for this thesis and a general view is that different components are looked upon from a certain distance with no previously decided methodology as the starting-point. Whether this is some kind of systems research may be discussed, but, nevertheless, it is different from much of the traditional engineering research performed on energy processes. The traditional research referred to usually has its starting-point in different components, such as a particular type of technology, or methodologies, which may be a certain technical or economic method. In energy research with components as the starting-point, the surroundings are rarely considered and, if the surroundings are taken into account, it is common to investigate whether the components fit somewhere. On the other hand, when the methodology is the starting-point a number of different components may frequently be studied simultaneously, but similar general characteristics from the methodology are applied to various types of energy systems. Another way to express it is that the more traditional research is component or method-oriented while the attempt here is to be problem-oriented.

A metaphorical illustration of this is to examine my wife Moa and me when we are doing a jigsaw puzzle, which happens occasionally. Moa takes a piece and tries to find out where this piece can fit while I have a look at an empty space and try to find a piece that fits there. Moa’s method has most of the time turned out to be the most efficient way to do the jigsaw puzzle, or she is just more skilful than I am, but for the research related to finding out about the most efficient ways to mitigate climate change, I think my approach is the better one. Though, in reality one might have to construct new pieces, as the jigsaw puzzle always will be the same with the old. To find the piece that fits exactly in the empty space might, thus, not be enough to build a new sustainable future.

1.1 Climate change and the connection to the use of energy

The international concerns about climate change are most clearly manifested in the United Nations Framework Convention on Climate Change (UNFCCC, 1992) and the Kyoto Protocol (UNFCCC, 1997). The first by being an international agreement that agrees upon

“Acknowledging that change in the Earth’s climate and its adverse effects are a common concern of humankind”,
and the latter by setting binding targets for GHG emissions. The Kyoto Protocol (KP) refers to six different GHGs, but the GHG carbon dioxide (CO₂) is generally the main focus when climate change is discussed because of the enormous amounts released by human activity. The relation between climate change and the use of energy is also apparent considering that about three-quarters of the anthropogenic emissions of CO₂ are due to the burning of fossil fuels (IPCC, 2001a) and that the greater share of the fossil fuels is used for energy purposes (IEA, 2004).

Without being excessively detailed, some basic characteristics of the Kyoto Protocol will be explained here, as they are relevant for this thesis; or more accurately, they are the basis for parts of the performed research. In addition to this brief presentation, these characteristics of the KP will also be touched upon in other parts of the thesis. The Kyoto Protocol entered into force on 16 February 2005 and it defines legally binding GHG emission targets for the Annex I Parties that ratified it. Annex I Parties of the Convention include industrialised countries that were members of the Organization for Economic Co-operation and Development (OECD) and some economies in transition to market economy from the former East Block. Individual emissions targets for the Annex I Parties are defined in Annex B of the Kyoto Protocol.

Apart from reducing national GHG emissions, the KP also allows for Annex I Parties which have ratified the KP to perform other climate change mitigating measures that will give emission credits equally valuable as national GHG emission reductions. Emission credits can be earned through, for example, the so called flexible mechanisms and through some specified activities related to land use, land use change and forestry (LULUCF). The three flexible mechanisms are labelled Emissions Trading, Joint Implementation (JI), and Clean Development Mechanism (CDM). Emissions Trading allows for the trading of emission credits between Annex I countries and JI provides a possibility for an Annex I country to earn emission credits for a climate change mitigation project performed in another Annex I country. CDM, on the other hand, allows an Annex I country to earn emission credits for a climate change mitigation project performed in a non-Annex I country, i.e. a country without binding GHG emission targets; this is primarily relevant for Paper IV.

The possibilities to offset GHG emission by some LULUCF activities are limited to some eligible activities that either are compulsory or non-compulsory. The compulsory activities set out by the KP are afforestation, reforestation, and deforestation while the countries with binding emission targets may choose to consider forest management, cropland management, grazing land management, and revegetation, which are additional eligible LULUCF activities specified in the Marrakesh Accords (UNFCCC, 2001). The possibilities to offset GHG emissions by these eligible LULUCF activities are linked to whether the activities result in removal of CO₂ from the atmosphere through carbon sinks. These carbon sinks are measured by stock changes in terrestrial carbon stocks where an increase in the carbon stock is considered as a corresponding removal of CO₂ from the atmosphere and a decrease in the carbon stock as a corresponding emission of CO₂ to the atmosphere. The compulsory activities (and theoretically also the non-compulsory) can therefore result in either GHG emissions or GHG removals. However, as soon as the biomass is removed from the terrestrial area, it is also removed from the terrestrial carbon stock, and, accordingly, the use of the

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1 The non-compulsory cropland management, grazing land management, and revegetation are actually measured in accordance with a net-net approach that measures possible removals or emissions as changes in carbon stocks in comparison with changes in carbon stocks during a base-year.
biomass cannot affect the GHG accounting for the Kyoto Protocol any more. This part of the GHG accounting is essential for the ideas leading to Paper VI.

1.2 Aim

An overall aim with the energy-related fields of research in this thesis is to suggest and assess possibilities for the mitigation of climate change and to put forward tools for how to tackle some of the encountered obstacles linked to these possibilities. Furthermore, a predominant view throughout the thesis is that the mitigation of climate change should be performed in the most efficient way, in terms of most climate change mitigation per money spent. The work has been carried out within the multi-disciplinary Energy Systems Programme with the fundamental goal

“to create knowledge making it possible to establish sustainable and resource-efficient energy systems” (Energy Systems Programme, 2001).

As the mitigation of climate change can be considered as a part of the goal to create sustainability, the aim of this thesis can be seen as a part of the greater goal of the Energy Systems Programme.

1.3 Research journey and special contributions of this thesis

Stemming from the affiliation with the multidisciplinary Energy Systems Programme, my first research topic was to investigate energy-related co-operations between district heating companies and process industries in Sweden. Two types of co-operation were studied, the deliverance of industrial waste heat to a district heating network and the common operation of a jointly owned plant that delivers heat to both an industry and a district heating network. This study finally resulted in Paper I, which was written together with Peter Sandberg who also had studied energy-related co-operations, but in other locations. Examples of energy-related co-operations comparable to the ones described in Paper I can be found in various parts of the world, but the literature addressing this subject is limited. Most of the literature that, nevertheless, may be found describes the co-operation as an ordinary techno-economic phenomenon, despite the fact that the technology necessary for the co-operations is neither state-of-the-art nor complicated. The special contribution of Paper I is that it describes driving forces and obstacles with regard to the co-operations from various perspectives. It highlights the value of favourable techno-economic factors as well as the importance of personal determination for the successful realisation of co-operations where cultural differences may be a major obstacle.

The goal for the parties involved in the co-operations described in Paper I is to make a profit, but given that the co-operation also can be a way to reduce net CO₂ emissions, my intention was to quantify the net CO₂ emission reduction that can be achieved by different co-operations. Initially, this seemed to be a relatively easy task, but soon I discovered that there were problems with several common methodologies for estimating net changes in CO₂ emissions. In most cases, it is impossible to isolate the change of technology or other kinds of dynamics from the surroundings and a fair prediction of the net changes in CO₂ emissions resulting from a specific project is difficult, if not impossible, to obtain. Still, to estimate the net CO₂ emissions resulting from some measure, which commonly is called emissions accounting, ought to be a key tool for the decision making process related to the mitigation of climate change and, as such, it is relevant for the Kyoto framework. The problems with
different methodologies for emissions accounting had also concerned Jörgen Sjödin and our discussions led to Paper II, in which different methodologies for emissions accounting related to the use and supply of electricity are presented and discussed, and Paper III, in which the results from applying different methodologies for emissions accounting on district heating technologies are demonstrated. My supervisor Mats Westermark was also involved in the development of some of the ideas relevant for emissions accounting, i.e. that biomass cannot be seen as an unlimited resource, presented in Paper III.

In Paper II, the presented methodologies can be found elsewhere, but some are also based on new ideas. Yet, the main focus is on bringing ideas about emissions accounting together. Different ideas from professionals such as economists, engineers, and scientists in the field of life cycle assessment rarely converge, even if they all struggle with emissions accounting. The discussion in Paper II embraces viewpoints from these different professions and a conclusion is that some marginal type of methodology probably is the most feasible for emissions accounting for use and supply of electricity, as a marginal methodology is able to capture some important dynamics in the power system.

Paper III demonstrates how much the selection of methodology for emissions accounting affects the results in a comparison between different technologies and it emphasises the importance of not choosing one methodology exclusively and to believe in it as the truth. Four different methods are presented and applied on different district heating technologies. The methods have in common that they all are based on a marginal generation approach, but they often yield the most diverse outcomes when applied to a given technology. The results from this comparison demonstrate how essential it is not to over-simplify reality by choosing a method and using it as the only tool to evaluate different measures related to, for example, climate change mitigation projects.

Of the, in section 1.1, described possibilities to receive emissions credits for projects carried out abroad, the CDM enables a country with binding emission targets to receive emission credits for a project performed in a country with no binding emission targets. If the predicted GHG emission reduction in this project is overestimated, the country with a binding emission target will be allowed to increase their GHG emissions with no compensation by a corresponding GHG emission reduction elsewhere. Furthermore, as many of the possible host countries for CDM projects are, or have the potential to become, high growth economies, the question might even be more significant than when first pondered, as different CDM projects possibly could result in indirect effects that could increase instead of decreasing net GHG emissions. Thus, this will lead to a risk of losing the integrity of the Kyoto Protocol and these issues are discussed in Paper IV. The connection to Paper II and Paper III is obvious, as the question relates to emissions accounting, but the basic ideas for Paper IV emerged in a discussion with Kenneth Möllersten, while Mårten Bryngelsson joined the discussion and took charge of the work shortly after that.

Carbon dioxide capture and storage (CCS) is one of the most frequently discussed methods for reducing global carbon dioxide emissions and oxy-fuel combustion is one of the possible technologies for CO₂ capture. The focus for CCS is usually the energy sector due to the enormous amounts of CO₂ emissions emerging from this sector, but, in Paper V, it is demonstrated how oxy-fuel combustion for CCS can be used much more efficiently together with some industrial processes than in the energy sector. To utilise oxy-fuel combustion together with, for example, cement kilns or lime kilns, is far more energy efficient than to use it in combination with power production processes. The basic idea behind this paper was
developed together with my supervisor Mats Westermark, but there is a hitch with this efficient capture of CO₂. Some of the CO₂ that can be captured from lime kilns at kraft pulp mills is of biological origin. This CO₂ would, if released, affect the atmosphere’s radiative balance in the same way as fossil CO₂ and the benefit of keeping this biological CO₂ away from the atmosphere is in other words equal to keeping fossil CO₂ away from the atmosphere. Nevertheless, there seems to be no possible way to earn emission credits for captured and permanently stored CO₂ of biological origin during the first commitment period of the Kyoto protocol, i.e. 2008-2012. This is the main theme in Paper VI, in which a method to allow for emission credits for captured and permanently stored biological CO₂ within a future accounting framework is also suggested. It would enable CCS of biological CO₂ to compete on a level playing field with other options for mitigating climate change. The structure and ideas in Paper VI are, to a large extent, the result of discussions with Kenneth Möllersten and Kim Pingoud.
2 Methodologies - How this thesis is an example of systems research

2.1 What is a system and what is systems research?

As this thesis is a work within the Energy Systems Programme, it ought to include a discussion of the concept system. However, in today’s society, the word system is so commonly used that most of us rarely ponder the term at all and a brief reflection could be valuable along with a presentation of the methodologies applied in this thesis. The concepts system and systems research will be discussed below, both from a historical perspective of proposed approaches for systems research and from my own views of what systems research can be and how it may be applied. At first, to answer the question of whether a system view is applied in this thesis is partly a matter of definition. How have the words system and systems research been defined previously?

To begin with the first part; what is a system? The answers given by pioneers in the field of studying sets of constituents, not by isolating the constituents as much as possible, but by keeping the interactions, have some basic features in common, see, e.g., Wiener (1961), Ashby (1964) and von Bertalanffy (1973). A general idea is that a system consists of a number of components, or elements, that interact with each other and that the system is separated from the environment by a system boundary. The system still interacts with the environment and these interactions between the system and the environment are often referred to as input, stimulus, output, response, disturbances, etc. A system can, for example, be a computer, an animal, a human being, a family, a company, a country, or a process industry, and a common feature is that the systems usually behave differently than the sum of the components, i.e. something more is added with the interactions and these new characteristics are sometimes called emergent characteristics.

“It does in fact very commonly happen that when the system becomes large, so that the range of size from part to whole is very large, the properties of the whole are very different from those of the parts. Biological systems are thus particularly likely to show the difference. We must therefore be on guard against expecting the properties of the whole to reproduce the properties of the parts, and vice versa.” (Ashby, 1964, pp. 111-112)

Other common thoughts are that the principles that regulate systems often are independent of the system in question and, thereby, transferable between systems of the most varying kinds. However, there are also discrepancies among these pioneers. Wiener in his “Cybernetics – or control and communication in the animal and the machine” (1961) describes systems from the perspective where the systems are controllable, as the title indicates. Most of the discussed features of presented systems are therefore of a relatively simple kind where the characteristics can be mathematically described. The word cybernetics is also used by Ashby (1964), who, among other things, has in common with Wiener that they both define the behaviour of systems from an essentially scientific, i.e. primarily mathematical, perspective. In contrast, von Bertalanffy (1973) and Boulding (1956) describe systems as being ruled by relationships that cannot always be mathematically modelled. Cybernetics is, indeed, by these two scholars only defined as a part of the general system(s) theory that was coined by von Bertalanffy, but which also Boulding was partly involved in the development of.

Relevant for the above-mentioned scientists’ view of systems is that they share the idea of systems as being given by nature, i.e. the system boundary and the behaviour of systems
are pre-defined and something we can learn about if we observe them\textsuperscript{2}. In this way the systems exist and the world or the universe is full of natural systems that we can study the characteristics of as they are. Others define systems and the behaviour of systems in a less rigid sense. Churchman (1968), for example, defines systems very much from the overall objective and uses this objective to identify the resources as the assets that you can use and control, the components as subsystems with defined sub-objectives (which Churchman calls goals), and the environment as the given things that you cannot control, which includes basic characteristics and limitations of the resources and the components. Systems are in this way something applied on different existing things, i.e. the systems are not natural by themselves and it is often hard to define the system boundaries.

What is then systems research? A simple answer to this question is: systems research is the application of theories related to the understanding and control of systems. But, can the different theories be generally characterised? A number of approaches exist in the literature and examples of different labels are cybernetics, general system(s) theory, systems approach, systems thinking, systems science and systems analysis. A key thread in these different methodologies is that the focus is on the interactions and the arrangement between components in a system and between the system and the environment. This view can be compared with the traditional analytical analysis commonly applied in scientific research, where components are studied as isolated phenomena.

The principles needed for controlling systems constitute an important part in most systems research methodologies, but for one of them, cybernetics, the principles may be described as the explicit core of the methodology. The word cybernetics does directly indicate this, as it emerges from the Greek word for steersman. In the control of a system, the information about a deviation from an intended performance is important to enable a corrective response. This information about a deviation from an intended performance is called the feedback and it is a central issue in cybernetics. Wiener (1961), for example, uses a thermostat that regulates the temperature in a house as an example of a feedback chain. Other systems research methodologies, such as the general systems theory, are more linked to the understanding of the behaviour of systems than the mere control of them.

The above-mentioned idea that systems of the most diverse origins, such as computers, human beings and societies, may be described by some common principles has often been the basis for theories about systems. These common principles are in some cases defined as universal and superior to the principles developed within the traditional disciplines. As such, this view is used as an argument for why theories about systems should form their own scientific discipline with universal principles and laws that transcend the traditional disciplines. This view of systems research can be called interdisciplinary, which is a term used by, e.g., von Bertalanffy (1973) and also by Boulding (1956), but then to denote all different kinds of mixtures of different disciplines. The interdisciplinary view is favoured by, for example, Wiener, Ashby, and von Bertalanffy. Another view is to use the knowledge gained in many scientific disciplines when a system is studied. The principles that control the behaviour of some kind of system studied within one discipline could be the same as for a different kind of system studied within another scientific field of research. The understanding, methodologies, concepts, and principles could in this way be borrowed from different

\textsuperscript{2} Ludwig von Bertalanffy’s (1973) definition of systems is, however, at times a bit hard to grasp. He discusses systems in the way presented above, but he also describes the problems with defining the boundaries of a system and, in a discussion about mathematical system theory, he states: “It is generally agreed that ‘system’ is a model of general nature, that is, a conceptual analog of certain rather universal traits of observed entities” (p. 251).
disciplines when a system is studied and this view could be called multi-disciplinary, which is a translation of a term used by Ingelstam (2002). Boulding (1956) and von Bertalanffy (1973) also describe this multi-disciplinary methodology, but do not use a specific term to denote it. Boulding (1956) points out two approaches for the general systems theory. The first is to find general models by picking out

“certain general phenomena which are found in many different disciplines, and to seek to build up general theoretical models relevant to these phenomena”.

This can be considered to be an interdisciplinary view and he also gives some examples of general phenomena that can be found in different disciplines, but he then concludes:

“These various approaches to general systems through various aspects of the empirical world may lead ultimately to something like a general field theory of the dynamics of action and interaction. This, however, is a long way ahead.”

He also states that:

“It (General Systems Theory, author’s comment) does not seek, of course, to establish a single, self-contained ‘general theory of practically everything’ which will replace all the special theories of particular disciplines. Such a theory would be almost without content, for we always pay for generality by sacrificing content, and all we can say about practically everything is almost nothing.”

Boulding’s second approach is to

“arrange the empirical fields in a hierarchy of complexity of organization of their basic ‘individual’ or unit of behaviour and try to develop a level of abstraction appropriate to each”.

The second approach to General Systems Theory is more linked to the organisation of knowledge from different disciplines into a “system of systems” (ibid.) and not to find a universal theory. This can, thus, be considered a multi-disciplinary methodology. Boulding’s argument for the second approach is that it can give us an idea where the major gaps are in human knowledge and that it, therefore, can be an efficient tool for the direction of research to fill these gaps3.

Churchman (1968) moves towards various problems in a methodical, or systematic, order, but he favours the multi-disciplinary view of solving problems via the argumentation against the belief of an ‘all applicable solution’ to all kinds of different problems. This includes the arguments against the application of a pre-defined systems approach to every encountered problem and he point out the importance of gaining and using experience from different fields when the systems approach is applied.

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3 I find this view of directing our limited research resources very questionable. This standpoint has much in common with the idea that large resources should be concentrated to fundamental science because we do not know what will be useful in the future. With that type of reasoning, one could actually defend the counting of grains of sand in the Sahara Desert.
2.2 What methodologies are applied in this thesis?

In this thesis, the overall aim has been to suggest and assess possibilities for the mitigation of climate change and to put forward tools for how to deal with some of the encountered obstacles linked to these possibilities. Thus, the overall aim is clearly problem-oriented, but what tools are used for the research? The answer is that several methodologies and theories are borrowed from other disciplines than my own, which is energy engineering. Examples are the interviews that are the source of information for Paper I and the economic theories that are used in Papers II, III, and IV. These methodologies have simply been used because of the limitation of the methodologies traditionally employed within energy engineering. Moreover, this has been done without a specific plan to apply an already defined systems theory as the basis for the research. In this way, the systems research performed in this thesis has been multi-disciplinary in accordance with the classification used above.

Churchman (1968) describes different problems that could theoretically be solved with what we know today (which, in fact, was 1968). The problems are related to starvation, world poverty, environmental problems, and so forth. What is characteristic is, however, that these problems cannot be solved in a simple way, because so many factors related to the problems are interconnected. What Churchman points out is the necessity of not being tied to a certain methodology when problems should be solved. The best approach is to let the problem define the type of problem-solving method that should be applied in each specific case. The problems described by Churchman have much in common with mitigating climate change, because this problem cannot be solved by a sole method either. The global nature of the greenhouse gas problem will make national solutions ineffective and politics, legislation, public awareness, economic issues, media, present and future technological possibilities, international agreements, and many other factors are interconnected in a way that prohibits a single solution to the whole problem.

The different phenomena encountered in this thesis have been studied with several perspectives in mind, but my background has naturally also influenced me. In any case, when I have studied an energy system and its relation to the GHG balance, the following questions are examples of issues that have been considered more than others:

- How is a specific service, for instance, residential heating, linked to different energy carriers such as electricity, district heating, or fuel oils?
- How do changes in the use of a service and changes in the supply of an energy carrier affect the overall GHG balance?
- What are the mechanisms by which we can control or tune the energy system in a desired direction to mitigate climate change?

Unsurprisingly, there are numerous questions tied to these questions, for example:

- Is the service or the supply of the energy carrier tied to certain types of technologies or could the technologies be changed?
- How do economic measures such as subsidies, fees and taxes affect the supply of the energy carrier and use of the service?
- How can public awareness affect the use of the service and the supply of the energy carrier?
- How do the cultural differences affect decisions relevant for the energy system on, for example, an international, a national, or a company level?
What are the technical possibilities today and how may the technical possibilities in the future be affected or affect the situation?

How will different kinds of markets, i.e. regulated or liberalised, affect the supply and use of energy as well as the ability to control the situation?

It is obviously not possible to be an expert on all these issues and the construction of a complete model encompassing all possible components and interactions of, e.g., a national energy system, would not be achievable. Simplifications to discard most things except for some key features are essential for the construction of a model relevant for estimates of, for example, GHG emissions, but the usefulness of such a model for predictions is limited. A reason for a simplified model not being perfectly useful for energy systems, such as the electrical system in northern Europe, is that different components and the interactions between them steadily change in an unpredictable way. It can be the shutdown of a major power source, high or low precipitation, and the irrational behaviour of consumers. A real energy system comprising more than a very limited number of components will perhaps not even produce the same change in the output from a given change in the input two times in a row. The consumers and suppliers would have gained information from the first change of input that could change their behaviour the next time or their response to a certain change could be a matter of chance. Furthermore, the local and time-bound factors are so essential for the response of a system to a specific change that the transfer of a given model to another time and geographical area is quantitatively extremely questionable. Another argument for why models should be used with care is the possibility of being deceived by the seemingly precise quantification resulting from the use of a model. Even von Bertalanffy that generally favours mathematical models and expressions recognises that:

"It may be preferable first to have some nonmathematical model with its shortcomings but expressing some previously unnoticed aspect, hoping for future development of a suitable algorithm, than to start with a premature mathematical model following known algorithms and, therefore, possibly restricting the field of vision" (1973, p. 24)

A model that could predict the behaviour of different energy systems with certain accuracy would perhaps be an eminent tool for most decision-makers with the intention of mitigating climate change, but would that solve the major problems for the decision-makers? Even with a very good knowledge of the outcome from particular actions, there will be a number of obstacles against carrying out certain measures. It could be public opinion, international agreements or, more likely, the lack of international agreements, political inability to enforce certain changes, and many other obstacles. On the other hand, is a complete understanding an absolute necessity for achieving the desired goals for a system, and, more specifically, for the energy system? The answer to this question is no. The reduced dependence on oil in Sweden during the last thirty years is an illustrative example of what may be achieved with rather blunt tools, such as taxes and subsidies. The knowledge of how the system would react to a given action was even more limited in the 1970s than now, but the political desire to reduce the dependence on oil had the effect that the energy supplied from oil has been reduced from 350 TWh in 1970 to 210 TWh in 2003 (Swedish Energy Agency, 2004). The entrance of nuclear power played an important role in the shift away from oil, but this is certainly not the whole answer. See more about this change in Paper I.

The applicability of a model for energy systems is very restricted and it is questionable whether models are unsurpassed sources of information when making decisions that will affect the future energy systems’ link to GHG emissions. My view is that systems research is
a multi-disciplinary tool and that it should be used as such. Furthermore, the real usefulness of the different kinds of systems theory is not the possibility of applying an all-purpose model that may be applied to different studied fields, but rather to widen the horizon of the observer; this despite the possibilities to constructive generalisations claimed by the advocates of the interdisciplinary view. An elementary broad knowledge concerning technical, economic, and institutional mechanisms is valuable when making decisions with the intention of mitigating climate change and this knowledge ought to be combined with the information that may be gained from different models. It is crucial not to become trapped in a field-specific paradigm and believe in it as the only true way of investigating a system. I have borrowed ideas from various fields of knowledge in the search for knowledge applicable to energy systems and their relation to the GHG balance, and, in this sense, this thesis is an example of systems research. To summarise with “some principles of a deception-perception approach to systems” given by Churchman (1968):

1. The systems approach begins when first you see the world through the eyes of another
2. The systems approach goes on to discovering that every world-view is terribly restricted.
3. There are no experts in the systems approach.
4. The systems approach is not a bad idea.
3 Reflections on Paper I: Co-operation, is it important and, if so, how can it be carried out?

The title of Paper I is “Driving forces and obstacles with regard to co-operation between municipal energy companies and process industries in Sweden” and, as the title indicates, it deals with matters linked to co-operations between two types of organisations that culturally are very far apart. This chapter summarises some of the findings in Paper I along with a discussion about the development in Sweden and a brief reflection on whether the knowledge about the Swedish co-operations can be used abroad. First, however, we must deal with the question: Why do these organisations co-operate at all?

Process industries for the production of pulp and paper, petroleum, cement, aluminium, steel and other metals, industrial gases, etc., commonly generate waste heat with limited usefulness because of the low temperatures compared to the temperatures needed in the processes. However, there is one major exception to the restricted applicability and that is when the heat is used for residential heating, either directly, if the temperature is high enough, or indirectly, if the temperature is so low that heat pumping to increase the temperature of the heat is necessary. The transfer of waste heat from a process industry to buildings does, however, require some kind of distribution method and this is normally a district heating system, even if some tests have been made transporting the heat by trains (Breuer, 1993). The district heating systems in Sweden are usually owned and operated by municipal energy companies and the utilisation of waste heat for residential heating purposes thus requires that the process industry and the municipal energy company agree on what to do. The mutual agreement between these parties and all the procedures needed to start, carry out and deal with the daily operation of the waste heat utilisation unit is here referred to as co-operation. Yet, the term co-operation is, in Paper I, rather generally used for a variety of arrangements, ranging from a seller-to-buyer relation with modest mutual commitments to jointly owned and operated plants for the production of district heating and process steam, where the connection and mutual dependence between the two parties is very strong. The latter example of co-operation is the, technically, second type of co-operation studied in Paper I, where the discussion is focused on the driving forces and obstacles on the way to accomplished co-operations.

The mere existence of the co-operations is a reminder of a not always obvious way to solve things and it reveals much about the people behind the ideas and the implemented solutions. The main conclusion in Paper I is, in fact, that people with a true desire to co-operate seem to be crucial for successful co-operations and that these people have to be present on both sides of the co-operation. This type of co-operative phenomenon, as such, is not very well spread around the world, as illustrated by the difficulty to find information about, for instance, the utilisation of industrial waste heat in the literature. The centre of attention in Paper I is the less complex type of co-operations, i.e. waste heat utilisation, and, in Sweden, this is also more common than the jointly owned and operated plants for the production of district heating and process steam. A figure for Sweden is that around 8% of the 59.5 TWh primary energy for district heating and non-industrial combined heat and power (CHP) production supplied in 2003 had its origin in industrial waste heat (District Heating Association, 2005). Comparable international figures are hard to obtain and figures from

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4 The reported figures are for district heating and non-industrial CHP taken together and the share of industrial waste heat would be even higher for the primary energy supplied for district heating production alone. The reason for this is that none of the waste heat is used for the CHP production, because of the low temperatures of the waste heat, and a part of the primary energy supplied for CHP contributes to the electricity production.
different locations are also difficult to compare because of problems related to the definition of waste heat. A commonly used definition is: Waste heat is the heat that is left over after a process has been internally optimised. This definition immediately leads to difficulties, as it is very hard to define what an optimised process is. Relevant questions to ask are:
- May the pinch temperature difference be decreased even more?
- May another type of equipment be used to lower the energy demand in this process?

I have used another definition of waste heat and that is: Waste heat is heat that cannot be utilised directly in the (industrial) process. This is also problematic, depending on whether the definition implies ‘as the process is today’, thereby including heat from terribly un-optimised industrial processes and even from CHP plants lacking the ability to produce power in condensing mode, or if it also implies that the process should be optimised, which will lead us back to the problems with the first definition. It is therefore necessary to use some kind of ‘fair’ judgement from case to case and the familiar answer to what waste heat is ought to be: it depends!

3.1 What is the foundation for the co-operation?

The technological framework necessary for co-operations of the kind studied in Paper I are district heating networks. The district heating networks function in much the same way as the electrical grid and most engineers, economists, business people, politicians, and others, would consider it lavish if excess electricity were produced as an unintended by-product by an industry isolated from the grid. There would simply not be anyone on the other side to receive and make good use of this electricity and it would be both a loss of a good business opportunity and a waste of physical resources. On the other hand, the fact that only a tiny fraction of the enormous amounts of industrial waste heat is utilised does not attract particular attention. The comparison is relevant in the sense that both electricity and heating are necessary energy products for the residential sector. Space heating is, in fact, the largest end-use of energy in the building sector in the developed countries and in the economies in transition (IPCC, 2001b) and a direct comparison between the two forms of energy is at times relevant as long as electricity is used for low-temperature heating purposes. However, the comparison is less relevant when the quality of electricity and district heating is compared. Electricity has a higher ‘thermodynamical value’, which is another way of expressing the characteristic that electricity can be transferred to other forms of energy without any losses, which is not the case for heat, and especially not for low-temperature heat. Electricity is by all means much more versatile than heat in the technical infrastructure of today and the need for residential heating, and thus for district heating, is more connected to local climate and season than is the need for electricity. Yet, the link to local climate and season has in some areas become less pronounced and the situation could supposedly change in other areas as well, given that district heating may be used to produce comfort cooling by absorption chillers. Other major arguments for the comparison between district heating and electricity being unreasonable are that it is only in theory that an energy-intensive industry would be isolated from the grid and that there are (not that I know of) no industrial processes that produce electricity as an unintended by-product. Nevertheless, there are energy-intensive industries that may produce excess electricity as a by-product, such as kraft pulp mills, but then this production is intended.

The pinch temperature difference is the minimum allowable temperature difference between hot and cold streams in a network of heat exchangers. More heat can be internally recovered by decreasing the pinch temperature difference, thereby decreasing energy consumption and optimising the process, but the heat exchanger network will be more costly.
The district heating networks are also the technical foundation for the other type of energy-related co-operation studied here: the jointly owned and operated CHP plant. The co-operation is there because the primary energy can be more economically exploited if heat is produced for both process steam and district heating, but also because the specific capital investment decreases with the size of the plant. There would be no reason to co-operate if electricity were the only product, since there is a virtually unlimited sink for this product with the connection to the grid. Typically for the cases studied in Paper I is that the jointly operated and owned CHP plant produces steam for the industrial process, low temperature heat for the district heating network, and electricity to the grid, but there are also other types of co-operation that resemble this kind of arrangement. An example of a similar type of arrangement may be that the CHP plant could be owned and operated by one of the parties or by a third party. Another example could be that the plant only were to produce process steam and district heating without any electricity production. CHP co-operation is a more profound type of co-operation than the utilisation of waste heat in several respects; for example, the capital investment is higher and the co-operation affects the daily operation of not only the district heating network, but also of the process industry.

A district heating network could, as described above, work in a similar fashion as the electrical grid, but in reality the connection to a district heating network is much more restricted than the connection to the electrical grid. Because of this reality, there are discussions about facilitating the access to Swedish district heating systems for external parties (Directive, 2002; Official Governmental Investigations, 2005). At present, this does not seem to become a reality, but if realised, such a liberalisation would resemble the liberalisation of the electrical markets in northern Europe. Nevertheless, most industries are currently not connected to a district heating network and it is not up to the industry or any other external party by itself if it wants to connect to the district heating network for delivery of heat. It is up to the owner of the district heating network if the heat is wanted, which may not always be the case, see Paper I and below for details about different barriers against co-operation.

3.2 What are the benefits of co-operation?

What are the basic benefits of co-operation? This answer to this question depends on the perspective, but we may concentrate on the techno-economic and environmental aspects. The most obvious benefit for both the industry and the district heating company is the profitability of the co-operation, and none of the co-operations described in Paper I would have been carried out without this benefit. For waste heat utilisation, the profitability may be linked to both decreased production costs, associated with decreased costs for primary energy and, in some cases, labour, but also to lower investment costs in comparison with many of the alternatives. Of these benefits, the most essential is the decrease in the cost for primary energy otherwise necessary for the production of district heating; the gain thereby generated may be shared in different ways depending on the configuration of the contract, see Paper I. However, there are examples of when the reduction in cost due to a reduced need for primary energy is not so certain; one such example is related to CHP while another is linked to the disposal of refuse.

The amount of district heating that may be produced from a CHP plant is, in energy units, very large in comparison with the extra amount of electricity that could be produced if the same plant were to be shifted into condensing mode, i.e. work as an ordinary thermal
power plant. The heat produced from the CHP plant could hence be considered quite inexpensive, provided that the plant is still running to produce electricity, and this naturally affects the profitability of waste heat utilisation. A comparable situation may arise when the disposal of domestic or industrial refuse becomes expensive because of legislation. The cost for primary energy may in such a situation turn out to be negative for plants incinerating this refuse and negative costs for primary energy will make it difficult for any other kind of solution to compete; waste heat utilisation is no exception.

Both these examples of waste heat utilisation not being profitable depend on both the size of the district-heating supplier and on the timing of the investment. The investment costs for a refuse-incinerating plant or a CHP plant are large, but the specific investment costs decrease with the size of the plant. This usually excludes both these options for smaller district heating networks, but will often affect possible waste heat utilisation in larger district heating networks. In addition, the timing is important, because waste heat utilisation is rarely an alternative when either refuse incineration or a CHP plant is in place, provided that these options still are profitable.

The techno-economic benefits with a jointly owned and operated plant are not as obvious as the benefits with waste heat utilisation, although they are linked to both the investment costs and the production costs. As the specific investment costs decrease with the size of the plant, the co-production decreases the individual parts of the investment costs in comparison with two separate plants for the production of district heating and process steam. Furthermore, a lower temperature in the district heating in comparison with the process steam will permit a higher total efficiency than with the individual CHP counterpart for process steam, and the production of process steam will allow for an increased annual operation time in comparison with the individual CHP plant for district heating. Both these aspects allow for better profitability for the co-operative solution in comparison with the individual counterparts.

Possible environmental benefits resulting from both kinds of co-operation are predominantly linked to the possible overall reduction of emissions of CO₂, but also to other possible favourable effects that depend on the technological circumstances, such as reduced emissions of sulphur oxides (SOₓ) and nitrogen oxides (NOₓ). At a cursory glance, it seems possible to work out a fairly ‘objective’ estimate of the environmental effects from a given co-operative project, at least in some cases. One such example could be when we have a boiler fired with oil that is replaced by waste heat from an industry. When first looked upon, it seems obvious that the environmental achievement with this co-operation is that we have reduced the CO₂ emissions and other pollutants by the amount that would have been released with a continued operation of the oil-fired boiler. However, even this very restricted example gives rise to a number of questions, for example:

- What would or could the invested money have been used for, if not invested in the waste-heat utilisation?
- Could perhaps the profitability for an alternative technology have become so decent in comparison with the oil-fired boiler that the district heating company would have chosen this alternative, if the waste-heat utilisation had not ‘interfered’?
• Linked to the above questions; should the comparison be made with the oil-fired boiler or the likely alternative and, for the latter comparison, how should this alternative be judged environmentally\(^6\)?
• Does the ‘not used oil’ have an effect on the surrounding energy system from a short-term or a long-term perspective?
• Does the waste heat utilisation affect other pending investment plans in the industry?
• Does the possibility to earn money on waste heat stop future process optimisation measures that would lessen the amount of waste heat\(^7\)?
• Does the project have an effect on the surrounding economy that, in turn, will have an environmental effect?

Most of the questions above are correlated to market mechanisms of which some are discussed in Papers II, III, and in chapter 4. These questions illustrate some of the difficulties with regard to emissions accounting for a given project. Nevertheless, all these questions are linked to the ability to estimate the environmental impact of the project and these are just examples of questions that ought to be considered. The environmental effects that may be achieved with waste heat utilisation are linked to the reduced need for primary energy for the production of district heating, but, given all the uncertainties, it is hard to quantify the true effects specifically and, even more so, generally\(^8\). The environmental effects from a jointly operated CHP plants are even more difficult to estimate, since the production of electricity is added to the picture and the situation is so different in different projects that general estimates in this case are of low value. Some illustrative examples of the extreme outcome from the use of over-simplified models may be found in Paper III, where different models for emissions accounting are applied to district heating technologies.

Given the advantages discussed above, why are not all possible energy-related co-operations of the two kinds discussed here carried out? The answer is that there are both disadvantages with, as well as barriers against, the co-operations that may explain much of this. The major disadvantage is the need to co-operate with all the drawbacks, such as restricted freedom, that follow from this kind of commitment. The barriers against co-operations of this kind, on the other hand, are more related to the location and are harder to generalise, but a discussion about different barriers against energy-related co-operations in a Swedish context may be found in Paper I.

3.3 How did the co-operations start in Sweden?

The CHP types of co-operations are rather few and, as described previously, hard to generalise. Thus, the following description of the development of energy-related co-operations in Sweden concentrates on the utilisation of industrial waste heat. Today, there are around 60 comparable waste heat co-operations in Sweden (Wrangensten, 1999) and the first emerged in the mid 1970s. The expansion of the utilisation of waste heat has been a steady increase in capacity without any extreme stepwise changes. Even so, there are a number of factors that have affected the development during different periods and one of these factors is

\(^6\) Say that this alternative utilises a different primary fuel and is connected to the electrical grid. The questions that can be raised in such a case are numerous and some of them are discussed in subsequent parts of this thesis.

\(^7\) In this case it can be discussed whether the heat still is true waste heat, see the discussion about definitions above.

\(^8\) Even if the factual environmental effect is difficult to quantify accurately, the true effect of most waste heat utilisation projects is in most cases probably a reduction in net GHG emissions, locally and globally.
the expansion of the district heating networks. There are examples of district heating networks in Sweden from the years after World War II, but the real expansion came in the 1970s when the totally supplied amount of district heating increased from 14.6 TWh in 1970 to 34.5 TWh in 1980 (Swedish Energy Agency, 2004). This development has naturally influenced the implementation and expansion of waste heat utilisation positively in many locations, but the influence has also been reversed in some places, i.e. the district heating network has been built because of the possibility to utilise industrial waste heat. Other factors that influenced the establishment of waste heat co-operations were the two oil crises, in 1973 and 1979, and the political programmes with the ultimate intention to reduce the dependence on oil that followed. One of the earliest signs of a political desire to utilise industrial waste heat for residential heating through district heating networks may be found in a governmental proposition from 1975:

“*A more efficient use of energy may, among other means, be achieved through a system where a public energy supply is developed and through the utilisation of waste heat from process industries for residential heating*” (author’s translation) (Governmental Proposition 1975, p. 341).

Other examples of political measures are the conferences that were arranged to discuss technical and business-related possibilities for utilising industrial waste heat for district heating as well as the technical, economic, institutional and mental barriers against the accomplishment of the co-operations (Nordic Industrial Fund, 1976; Royal Swedish Academy of Engineering Sciences, 1978). The following examples of obstacles against the co-operations were identified:

- *Unfamiliarity with the problem,*
- *Lack of technology,*
- *Prestige,*
- *Lack of confidence in the durability of the deliveries,*
- *Lack of capital,*
- *Waste heat is not considered as primary energy,*
- *Waste heat will eliminate the ability to utilise CHP,*
- *Both parts do want to have as large a part of the gain as possible,*
- *Too slow expansion of the district heating systems*  
  (authors’s translation) (Royal Swedish Academy of Engineering Sciences, 1978).

These obstacles may be compared with the discussion about obstacles in Paper I, as most of the problems identified prior to the breakthrough for waste heat utilisation are no different today. An exception is the lack of technology, which is not a problem today. Two of the other obstacles may still be found internationally, but not in Sweden, and these barriers are: unfamiliarity with the problem and too slow expansion of the district heating systems. Another indication of the political focus on how to overcome some barriers against energy solutions such as waste heat utilisation and industrial and non-industrial CHP, may be found in a governmental report from 1977 (Industrial Department/Energy Commission, 1977). This governmental report is mainly focused on economical barriers and the economic measures to defeat these barriers.

Many fundamental questions linked to the possibilities to utilise industrial waste heat had to be answered initially and the government-founded National Swedish Board for Energy Supply Research was involved in finding out about some essentials. This organisation performed surveys of possible Swedish industrial waste heat sources (1978a, 1978b), and was
also commissioned to evaluate and plan for the development of industrial waste heat utilisation in Sweden (1977). Another political measure that certainly has influenced the growth of waste heat utilisation in Sweden is the law of local energy planning of which the first version came in 1977 (Swedish Statute Book, 1977). The municipalities are, according to the law, required to

“assess the possibilities to co-operate with other municipalities or other significant entities within the energy field, such as process industries or power production companies, to solve questions of importance for the saving of energy or for the energy supply co-operatively” (author’s translation).

This quotation clearly indicates that energy-related co-operation, for instance industrial waste heat utilisation or the joint operation of a CHP plant, is a solution that is encouraged, even by law. All these political measures to investigate the possibilities for utilising industrial waste heat in district heating networks and for promoting this technology may be seen as a platform for the upcoming co-operations in Sweden. Still, these political instruments are not mentioned as the major factors that affected the co-operations in any of the cases in Paper I, but the crucial ideas about the co-operation might not have developed without these early political efforts. The first Swedish waste heat co-operation was, however, established in Helsingborg in 1974, consequently before the political efforts could have had an effect (Lindell, 2005). Even so, the political measures that were mentioned as vital for the development for the co-operations were the high oil taxes and the subsidies for environmentally friendly energy solutions and oil substitution, see more about this in Paper I.

Other, non-political, driving forces that have affected the establishment of waste heat co-operations in these cases are the technical momentum for this kind of co-operative solutions, i.e. the positive outcome of the experience from other cases, exceptional techno-economic circumstances, and decision-makers from both sides of the co-operation with the true ambition to co-operate because of the benefits this may bring about for the community and for the environment. The main conclusion from Paper I is that while favourable techno-economic circumstances are the foundation for both kinds of co-operations studied here, this is not enough for the carrying out of a co-operation. People with the genuine ambition to co-operate from both parties are essential for the co-operation to emerge.

3.4 May the experience gained in Sweden be useful in other countries?

The discussion in Paper I is mainly focused on the factors influencing the situation for energy-related co-operative solutions in Sweden, but may the experience gained be applied in other countries as well? The plausible answer to this question is sometimes, but to get a comprehensive answer is beyond the scope of this work. Still, if energy-related co-operations, and waste heat utilisation in particular, are useful tools to reduce net GHG emissions, it is worthwhile to investigate whether experience from one case may be useful for another case. The basic principles related to the co-operative part of the co-operation are most likely the same around the world, i.e. the need to have people with the intention to co-operate on both sides of the co-operation is crucial, no matter where the co-operation takes place. An exception to this could perhaps be in dictatorships, where the parties do not decide what to do by themselves. Physical realities that make the situations comparable is that process industries are often located close to cities in industrialised countries and that the need for residential heating is common, even if the domestic hot water part of it might be greater part than in the Nordic countries. A cold climate and, thus, a comparatively long season for district heating, is
naturally beneficial for the large investments related to district heating systems, but this situation could change with the possible introduction of comfort cooling through district heating combined with absorption chillers. Heat-driven comfort cooling is in use today, but the breakthrough for this technology has yet to come, see e.g. Rydstrand (2004) and Lindmark (2005). A significant difference between Sweden and continental Europe is the well-developed district heating networks in the former in contrast to the well-developed networks for the distribution of natural gas in the latter. Sweden had a comparatively late, 1985, and limited introduction of a natural gas along the West Coast and this has probably affected the development of district heating, and therefore the ability to co-operate, positively. The existence of natural gas networks might have limited the development of district heating networks in continental Europe, and a reasonable deduction ought to be that the internationally considered major barrier to these kinds of co-operations is the lack of district heating networks. Yet, there are examples where district heating and waste heat utilisation co-exist with natural gas networks. Examples can be found in Göteborg and Helsingborg, where natural gas has become available after the establishment of two of the largest waste heat co-operations in Sweden. This, however, does not say anything about the possibilities of introducing district heating after the establishment of natural gas networks. Another issue that has to be resolved before any generalisations on waste heat co-operations are possible is how well known the possibility to utilise waste heat is among decision-makers internationally. Given the limited amount of literature that discusses this subject the answer seems to be that it is hardly known at all. An example of this limited knowledge on the subject may be found in the editorial foreword by Turner to an article by Zebik et al. with the title “Heat Recovery From Industry” in Energy Engineering (1997). Two quotations from this editorial foreword are:

“I read the article upon returning home and was astounded with the freshness and excitement of the idea” and

“Yet, no one to my knowledge has proposed using industry waste heat as a source for district heating (and potentially cooling through absorption)”.

This article was published in 1997, in other words more than twenty years after the first Swedish establishment of industrial waste heat utilisation in district heating systems. The previously mentioned National Swedish Board for Energy Supply Research noticed in their international work as a part of the international IEA/CRD Working Party on Waste Heat that:

“The work within the group demonstrated that Sweden, in an international perspective, has advanced a long way” (1977) (author’s translation).

This, on the other hand, indicates that the International Energy Agency (IEA) was aware of the possibility to utilise waste heat at a rather early stage. Today, the IEA provides promotional information about district heating as a technology that, among other benefits, has the advantage of enabling waste heat utilisation (2002). It is difficult to assess the real effect of these promotional efforts, but as the international awareness about climate change has increased, solutions such as waste heat co-operations might not be overlooked in the future.
4 Reflections on Papers II, III, and IV: Emissions accounting, price flexibility, and rebound effects, and how they affect the clean development mechanism

In the previous chapter about co-operations, the difficulties in estimating the environmental effects of a very simple project were illustrated. The simple project used as an example was an oil-fired boiler that is replaced with waste heat from an industry and, in this case, the effects on the electrical grid may be neglected. Even if the environmental effects are limited to the effect on net global CO\textsubscript{2} emissions, it was illustrated how difficult it is to perform a fair quantification of the effects due to the number of factors affecting them.

On the other hand, when a project does have an impact on the electrical grid, either through electricity consumption or production, the net CO\textsubscript{2} emissions resulting from the project will be even more complicated to estimate. The project will in this case have an effect on the dynamics in the electrical grid and, thereby, directly affect possible emission sources elsewhere. The sum of direct and indirect effects on net CO\textsubscript{2} fluxes to the atmosphere attributed to a given project is generally referred to as emissions accounting; this chapter mainly focuses on emissions accounting linked to dynamics in the electrical grid, even if most of the discussion may also be generalised to other energy carriers.

This subject is also the centre of attention in Papers II and III. The aim of Paper II is to discuss how changes in the use or supply of electricity may be accounted for with various kinds of emissions accounting methods and to present arguments for and against these methods. The aim of Paper III is to demonstrate the vast difference in the results from four emissions accounting methods when they are applied to energy projects. In addition, these papers briefly consider how CO\textsubscript{2} emissions from fuels of different origin may be regarded. Paper IV discusses how erroneous predictions of the net CO\textsubscript{2} emission reductions resulting from a project aimed at mitigating climate change may be a problem for the integrity of the Kyoto Protocol. This is essential seeing that a critical problem with the currently applied emissions accounting methods is that they do not consider some market effects that might be significant.

4.1 When is emissions accounting a relevant issue?

As countries have agreed to reduce GHG emissions through the Kyoto Protocol (KP), forecasts of a given project’s GHG emissions are relevant as a tool for decision-makers. If a country generally wants to encourage or discourage a specific technology, or specifically decide between different projects for climate change mitigation reasons, it is necessary to have a broad understanding of the direct and indirect effects of an action to predict the real outcome with respect to GHG emissions. In addition to this, there are, within the Kyoto framework, possibilities for a country with binding GHG emission targets to earn emission credits for projects performed abroad through the project-based mechanisms Joint Implementation (JI) and Clean Development Mechanism (CDM). Here there is a need to explicitly assess the true effects of a given project, since the emission credits are based upon the estimated net effects of GHG emissions. JI is a mechanism that enables a country with binding emission targets to carry out a project in another country with binding emission target, while in CDM, the project is to be executed in a country without binding emission targets. In practice, this means that with a wrong estimate of the true effects, a JI project will lead to a later on measured, and globally accounted for, deviation, while a CDM project will lead to a deviation in GHG emissions that not will be accounted for globally. The wrong
estimate in the JI case will, negatively or positively, affect the recipient of the project, but in the case of the CDM, it may lead to a loss of integrity for the emission reduction targets of the KP. The main topic of Paper IV is how the problems with accurate emissions accounting for different CDM projects may actually be a problem for the climate mitigation target of the Kyoto Protocol. Hence, reliable emissions accounting is a tool that may solve many problems related to strategies to manage GHG emissions.

Another application for emissions accounting is within the life cycle assessment (LCA) performed on different products to assess the environmental performance of the products during their lifetime. An assessment of the environmental effects resulting from the energy use related to the production, use, and disposal of a given product is a key part of judging the total environmental performance for most products in use today and this is a direct application of emissions accounting.

4.2 Different methods applicable for emissions accounting

When electricity is supplied to, or consumed from, the electrical grid, this will affect other units connected to the grid and these units may, in turn, have an effect on the net global GHG emissions, i.e. an indirect effect. Different ways to account for this indirect effect are discussed in both Paper II and Paper III; below is a brief survey of different possibilities of accounting for the net global effects resulting from dynamics in the grid. The basic feature of the methods presented here is that they are intended to assess the net indirect affect on CO₂ emissions resulting from adding or removing electricity from the grid.

A principal method is to use average emission figures for all power-producing units during a given period in a specific region. For the Nordic electricity region, this would lead to relatively low emissions of CO₂ per used unit of electricity due to the abundance of CO₂-lean power production units, for instance, hydropower, nuclear power, and biofuelled CHP plants. An argument against this way of accounting is that it is often hard to define the units to be included in the calculations. The Nordic countries are, for instance, electrically connected to many surrounding countries and a relevant question to ask is: which countries or regions should be included and to what extent? Still, the main argument against the method of using average figures is that it does not give a fair estimate of the emissions caused by the use of electricity since it does not reflect the changes that occur when electricity is used or not used, i.e. dynamics in the grid. The different kinds of power supply are not turned on and off in accordance with their average share of the total power supply, i.e. a power demand increase of 1 % does not render a 1 % increase in capacity of all the different kinds of power supply already in production. This is a very relevant argument against the average way of accounting, since it is the changes from an already specified situation, whether it is today’s situation or a forecast that should be focused. It is to estimate changes in net CO₂ emissions as a result of a given action inflicting changes in electricity use or supply that is of interest for decision-makers striving to construct strategies for managing GHG emissions.

Another in principle different approach to emissions accounting for use and supply of electricity is to represent all changes by a certain type of ‘marginal’ power producing technology. This marginal power producing technology will then be considered as the technology that is turned on or off depending on the dynamics in the grid. Two of the methods
that use this principle are termed marginal coal method (MCM) and marginal new technology method (MNTM) in Paper III.

The basic idea behind the MCM is that the type of generation with the highest variable cost supplying the grid is the marginal power that is turned on or off depending on the dynamics in the grid. With the above-mentioned integration of the electrical grids in Northern Europe, this marginal power is in the Nordic countries, as well as in continental Europe, often considered to be produced in a coal condensing plant, see Paper II. Moreover, a given amount of used electricity is considered to cause CO₂ emissions corresponding to the emissions created when the same amount of electricity is produced in this marginal coal condensing plant and vice versa. Historical data have been used to argue that coal condensing power should be considered marginal power production in Sweden, at least in a short-term scenario, i.e. commonly within a 10 year horizon (Swedish Energy Agency, 1999; 2002). The arguments that are used are that coal condensing power fills the gap in years when precipitation has been low and that the net power import from fossil power-dominated Denmark to hydro and nuclear power-dominated Sweden usually starts when the electricity price is about the same as the variable costs for coal condensing power.

The MNTM, on the other hand, takes a forecasted technology change into account. In Paper III, two possible scenarios are presented, and it is only in one of these scenarios that a new technology will act as a marginal power in the same way as the coal condensing power in the MCM. It is in this scenario presumed that some kind of new technology, for instance, natural gas combined cycles (NGCC), have taken over the role of coal condensing power as the marginal power production technology. The assumption in the other scenario is that some kind of new technology, such as the NGCC, has become the primary, or standard, choice for new investments when new power production units are put into operation. It is also assumed that new power production units are regularly becoming operational because of an increased demand for new power production units in the future, which, in turn, is a result of an increased demand for electricity in combination with a need for replacement of power plants due to age or high production costs. Hence, the investments are made to fill a gap and the new power production units will operate as base load production rather than as marginal production. When applying emissions accounting to different kinds of power producing technologies, they should, with the assumptions applied in this scenario, reasonably be compared with the standard new technology, since the increased demand for electricity otherwise would be met by an investment in the standard new technology. Thus, this scenario is not applicable to a marginal power production method in accordance with the description above. The two scenarios for the future new technology will often yield the same estimates when, for example, the emissions accounting for a new power producing unit is assessed. Yet, a major exception to the equivalent estimates is when price flexibility is taken into account, see below.

The methods using the concept marginal power presented above, do take one economic factor into account and that is the variable cost, which is used to define the marginal power production. In a regulated electricity market, it might be a reasonable approach not to consider other economic factors, because the price of electricity may be set independently of the market, which makes the market highly static. To assume that one unit of produced electricity is replaceable by another unit of produced electricity might therefore under certain circumstances be a sensible approach to emissions accounting. The assumption that one unit of

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9 The terms method, methodology, and model are often used synonymously here and in the papers, even if the more common nomenclature is to use model for a specific case, while method and methodology are used more generally.
added or saved electricity will reduce the production of another unit in full, and vice versa, may be called a one-to-one approach, and this is a common feature for the average accounting, the MCM, and the MNTM, as presented above. However, in liberalised electricity markets such as the Nordic Nord Pool, there are other economic factors of importance for emissions accounting. If supply to, or removal from, the grid is affecting not only producing units, but also the behaviour of consumers due to price changes, we have a situation that cannot be described by any of the one-to-one approaches. The intersection between the demand curve and the supply curve for electricity will, in a liberalised electricity market, decide the momentary price for electricity, which at Nord Pool is called the spot price.

How will then the liberalised market affect the indirect emissions when, for example, an additional amount of power is added to the market? Given that the rest of the supply side and the demand side react as before, the additional power will adjust the supply side curve from what in figure 1 is called the ‘Initial supply curve’ to the ‘New supply curve’. A new lower price will be established and the demand side will, because of the lower price, use some more electricity. Thus, the additional power will still replace some kind of marginal power on the market, but not to the full extent of the added power, see figure 1. A method that takes these effects into account is the Price Flexibility Method (PFM) described in Paper III.

![Figure 1. A schematic description of the price flexibility mechanism when new power production capacity is added to a liberalised electricity market](image)

The demand side’s sensitivity to changes in the price is in economic literature called the price elasticity. Different estimates of price elasticities for electricity presented in the literature may be found in, e.g., Nesbakken (1999), and an international survey of international energy elasticities has been performed by Atkinson and Manning (1995). These two reviews of different price elasticities reveal that the estimates found in literature show large variations, but this may both indicate that it is difficult to measure the effect and that the price elasticities vary greatly depending on the energy carrier in question, the timing of the measurement, the geographical area, the kind of sectors included, etc. In Paper II and Paper III, the term price flexibility is used to denote the aggregated changes on both the demand and the supply sides due to added power to the grid. The price flexibility effect is in figure 1 illustrated as an effect caused by a market-wide change in the price equilibrium resulting from
the added power, but there are also other factors, such as macro or economy-wide effects, that may be significant for the price flexibility, see the discussion about different rebound effects below.

4.3 Taking the rebound effect into account

The price flexibility, as illustrated in figure 1, and as used in Paper II and Paper III, is more or less a mirror of the rebound effect, which is a term that is frequently encountered in literature discussing energy efficiency and energy conservation measures. The same basic principles are used in both concepts, but a difference is that the PFM, as described in Paper III, is used to assess the net CO₂ emissions resulting from the addition of energy to a market, while the rebound effect commonly is used for energy conservation and energy efficiency measures. The discussions about the rebound effect are usually focused on the demand side, but most of the concepts are also applicable for energy efficiency improvements on the supply side. Before continuing this discussion, some basic definitions for terms used in this text are given to avoid confusion:

- **Supply side energy efficiency** = energy output<sup>A</sup> / energy input<sup>B</sup>
- **Demand side energy efficiency** = physical service<sup>C</sup> / energy input<sup>D</sup>
- **Energy conservation** is used in the text to indicate a reduced energy demand without any reference to a specific output.

A: For example, electricity, district heating, mechanical work, cooling, etc.
B: For example, oil, coal, electricity, natural gas, uranium, etc.
C: For example, light, mechanical work, comfort heating or cooling, transportation, etc.
D: For example, electricity, oil, coal, natural gas, district heating, etc.

The rebound (also referred to as the take-back, snap-back, or set-back) may be defined as the difference between potential and the actual energy savings because of energy efficiency measures. A milestone for this kind of thinking was when Khazzoom (1980) pointed out that a common view when energy conservation measures were discussed by authorities was that an energy efficiency increase for a commodity of, say, 1 % would automatically lead to a 1 % drop in the energy demand. He then argued that this was an in principle erratic view, since increased energy efficiency, in fact, might lead to an increased demand for energy. A similar argumentation can be found in Brookes (1990) who claimed that:

"Reductions in energy intensity of output that are not damaging to the economy are associated with increases, not decreases, in energy demand at the macroeconomic level".

Both these authors published a number of papers with the same theme and this triggered Saunders (1992) to coin the Khazzoom-Brookes Postulate that, in summary, declares that energy efficiency improvements might not decrease, but rather increase, energy consumption on a macro-economic level. This over-unity rebound is also labelled backfire, see, e.g., Khazzoom (1980).

Jevons (1906) described historical examples of what certainly was actual backfire in the 19th century. In one example, he outlined how the energy efficiency of different steam engines had steadily increased, with the Watt steam engine as an example of a significant step in energy efficiency improvement. The gains in energy efficiency did, however, not result in a diminished consumption of coal, since the invention was an important step in the industrial
revolution. The efficiency improvement actually led to an extended use of the steam engine in many applications where it had not been used before and the result was an enormous increase in the use of coal. As Jevons himself describes it:

“It is wholly confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.”

He also makes another illustration:

“Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each.”

Later on in the book, this example is illustrated by the production of pig-iron in Scotland. While the consumption of coal used in blast furnaces was reduced from seven to two tons of coal per ton of cast iron from 1820 to 1863, the production of pig-iron increased from 20,000 tons to 1,160,000 tons. The consumption of coal used in Scottish blast furnaces increased by almost a factor of ten during this period when the fuel was much more efficiently used.

Jevons also describes the fuel savings per ton of steel made possible by the Bessemer process for the conversion of pig iron into steel, but he does not specifically use this invention among the examples regarding backfire. Though Jevons does not directly refer to it, others have used the consequences of the invention that Bessemer put forward in 1856 as an illustrative example of backfire. Rosenberg (1994), outlines it:

“The Bessemer process was one of the most fuel-saving innovations in the history of metallurgy. However, the innovation made it possible to employ steel in a wide variety of uses that were not feasible before Bessemer, bringing with it large increases in the demand for steel. As a result, although the Bessemer process sharply reduced fuel requirements per unit of output, its ultimate effect was to increase, and not to reduce, the demand for fuel.”

These two historical examples of significant rebound are both demonstrations of the effect on an economy-wide level, but there are different types of rebound effects on different levels of economy. Classifications of different kinds of rebound effects are given by, for example, Berkhout et al. (2000), Greening et al. (2000) and Frondel (2004) and the classification of different types given here can be seen as a modified summary of these classifications with a different terminology, as I have found that the dissimilarities in terminology used is sometimes confusing. The reasons that various kinds of rebound effect are discussed at all in this chapter about emissions accounting, are that the classification may illustrate in what market situations the different kinds of rebound could be valid and whether the rebound effects might affect one or several kinds of energy carriers. Regularly encountered examples of energy efficiency measures used for ease of illustration of different kinds of rebound effects are improved fuel efficiency in cars and improved insulation in buildings. These examples will also be used here, even if the discussion in this chapter mainly considers dynamics in the electrical grid.

The Law of Demand is an economic principle of special importance for the rebound effect and it is a general principle emerging from the frequently observed regularity that if the price for a service or a product decreases the demand for it will increase and vice versa. This
is due to both an income-effect, i.e. more of the service can be purchased as the purchasing power increases with the decreased price for the service in question, and a substitution effect, i.e. consumers may consume more of a service that has become less costly at the expense of other services or products.

Physical services like transportation by car and residential heating may, for example, become less expensive by an increase in the energy efficiency for the service or through a drop in the price for the energy carrier needed for the service. We may start by examining some of the effects that are directly related to an efficiency improvement. The increased purchasing power that possibly will be the outcome of an efficiency improvement may result in both what will be denoted direct service rebound and indirect service rebound. The direct service rebound effect is that some part of the money saved on an energy efficiency improvement is used for an increased consumption of the service in question. The direct response to the potential amount of money saved because of increased fuel efficiency in a car could, for example, be more travelled kilometres and, similarly, an improved insulation for a house could result in an increased indoor temperature instead of taking out the full potential as lower energy bills.

The money saved on the energy efficiency measure may, on the other hand, be used on other commodities and services, of which some demand energy. This response to the energy efficiency measure is the indirect service rebound and it could obviously affect both the energy carrier linked to the energy efficiency measure and other energy carriers. Money saved from the fuel-efficient car may, for example, be used for other petrol-demanding services or for services that use more electricity. There is also what may be called the service-related substitution effect that may, just as the indirect service rebound, affect a variety of different energy carriers in different ways. Using the fuel-efficient car to illustrate the service-related substitution effect, the car rides could have become so much less expensive that we have chosen to take the car for the holiday instead of the planned flight or train ride.

A price change for an energy carrier may also trigger a behavioural response of consumers, as the price for different physical services may change this way too. On an aggregated level, this is actually the slope of the demand curves found in figure 1 and figure 2. This slope is, as explained when describing the Law of Demand above, also due to both an income effect and a substitution effect, but now for a changed price for the energy carrier. In a liberalised market, a diminished demand resulting from efficiency improvements may alter the demand curve which, in turn, may change the market-wide price equilibrium. The energy efficiency improvement could, thus, inflict changes in the overall supply and demand that partly offsets possible energy savings due to the efficiency improvement and this rebound effect may be called the price equilibrium rebound effect. This rebound effect is only directly applicable to liberalised energy markets such as the free electrical markets that are the main focus of this chapter, seeing that the price does not have the same direct impact on the electricity trade in a regulated market as it has in a liberalised market. Another type of rebound on an economy-wide level is attributed to changes in the behaviour of society caused by the energy efficiency measure. Here this effect is called the indirect economy-wide rebound effect, but in the literature discussing different rebound effects, this effect is also called the transformational effect and the macroeconomic rebound effect.

As illustrated by the two historical examples above, the indirect economy-wide rebound effect might be the spin-off effects from an energy efficiency improvement that changes the general behaviour of society or the general economic growth which, in turn, has an effect on the consumption of a variety of services, including services that consume energy. Going back
to the examples with the improved insulation or the increased fuel efficiency for cars to illustrate the price equilibrium rebound effect, the overall use of energy could possibly be affected by the adjustment in the demand and supply balance caused by the energy savings resulting from these energy efficiency improvements. The indirect economy-wide rebound effect may, on the other hand, be effects on the use of energy caused by increased profits for the motor manufacturer or insulation manufacturer who delivers the products behind the energy efficiency measure or that more people can afford buying and driving a car with the new lower mileage cost, which in turn may result in increased economic growth and increased use of energy in various sectors in society.

The direct and indirect service rebounds as well as the service-related substitution effect, which all affect the demand curve, and the price equilibrium rebound effect, which is brought about by a demand-supply readjustment, are schematically illustrated for a liberalised electricity market in figure 2. The indirect economy-wide rebound effect is, however, difficult to illustrate schematically, in view of the fact that the appearance of the demand and the supply curves could be changed either way because of this effect. The indirect service rebound and the service-related substitution effect may, as explained above, affect a variety of different services and, therefore, also a variety of different energy carriers. Yet, as figure 2 only deals with electricity, it is only the possible effects associated to electricity that are schematically illustrated. Another thing to be noted about the presentation in figure 2 is that the new potential demand curve and the new demand curve probably ought to diverge as the price decreases. The reason for this is that the gap between these curves is present because of the lower price for the service due to the efficiency improvement and that a lower price for the energy carrier, i.e. in this case electricity, will affect the price for the service correspondingly.

**Figure 2** A schematic representation of different rebound effects due to a demand side electrical efficiency improvement in a liberalised electrical market.
It should be noted that, at least in theory, most of the rebounds can be either positive, i.e. the potential energy saving is reduced, or negative. The new improved insulation or improved fuel efficiency could make people more aware of the problems associated with the use of energy and thereby even decrease the use of energy more than expected from the potential energy conservation measure. Furthermore, the money saved could be spent on other energy saving commodities, et cetera. The most likely outcome is, nevertheless, that the different rebounds are positive, that is the net energy saving is less than the potential. A feature that is not hard to imagine is that the time factor is significant for different kinds of rebound effects. Economists, for instance, usually refer to both short-term and long-term price elasticities, and

“Given the long-term nature of the environmental consequences of global warming, as well as policies designed to mitigate such warming, estimates of very-long-term energy elasticities (i.e. periods of more than twenty years) are clearly of more relevance than estimates of short-term energy elasticities” (Barker et al. 1995).

This deduction is directly applicable to the relevance of different kinds of rebound or price flexibility effects, i.e. it is the effects that exist over an extended period of time that are most relevant to be aware of in the struggles to mitigate climate change. In the long-term perspective, the indirect economy-wide effect is, if present, likely to be more and more pronounced in comparison with other rebound effects, especially in the case of transformational changes of society. Another scenario would, however, be that the market’s response to a change will lessen the rebound or the price flexibility effects over time. For example, Vennemo and Halseth (2001) assume that the short-term rebound effect for an electricity conservation measure in Norway is 60 %, i.e. the overall demand will only drop 40 % as a result of the conservation measure, but that a new large hydro-power production project in the long-term perspective will entirely replace other capacity expansion elsewhere, because

“Alternative producers will have time to adjust their investment plans to the coming of a new hydro project”.

An argument that could be used against this view that new power production capacity will totally replace other power production capacity in the long term, is that the large-scale introduction of nuclear power in Sweden between 1975 and 1985 most likely is a reason for the Swedish per capita use of electricity today being roughly twice that of the average among the OECD countries (IEA, 2004). However, the hydropower dominated Sweden was, during this extremely rapid expansion period for nuclear power, not as electrically integrated with other countries as today and the amount of existing or planned power production units with high variable costs that could be removed was limited.

4.4 The debate about the rebound effect

As a subject of importance, but with no clear answer, the rebound effect has triggered a considerable debate and a simple literature survey may occasionally feel like jumping into a minefield. In fact, Energy Policy devoted a whole issue to questions about the rebound effect and this might have sorted out some of the more qualitative question marks, as most of the debate after this usually does not consider the mere existence of the effect, but rather the extent of it (2000).
One opinion in the debate has been claimed by, for example, Lovins and Grubb, who strongly argue that improving energy efficiency is a powerful tool to reduce energy use and thereby have an effect on the mitigation of climate change. Lovins (1989, 1996), as a matter of fact, does not even mention the rebound effect, or any of its synonyms, when discussing efficiency improvements. He considers every saved amount of power as an equal amount removed on the supply side, thereby explaining the use of the term negawatt, which was coined by Lovins:

“Think of such a compact bulb, with 14 watts replacing 75, as a 61 watt negawatt power plant” (1989).

Grubb (1990), on the other hand, does not take such a firm position, but still argues that energy efficiency undoubtedly decreases overall energy use, with the possible exception of a situation when the energy supply or price is a constraint in the economic activity, which, according to Grubb, should not be a common situation in mature economies. Grubb (1990; 1992) had a major confrontation with Brookes (1990; 1992; 1993) about the importance of the rebound-effect in a series of articles. Brookes, as previously mentioned, in these articles argued for the significance of the economic effects leading to an increased overall use of energy, i.e. backfire, as a result of energy efficiency measures. The aforementioned views of Khazzoom (1980) and Saunders (1992) are in this case very close to those of Brookes.

While the discussion in some cases is very polarised, others have taken a less resolute position about the rebound effect. Herring (1998; 1999; 2000) reviewed the debate and also discussed many arguments for and against the rebound effect. His own view in these papers is that the rebound effect is an important aspect and that governments cannot rely on energy efficiency as the sole measure to mitigate climate change. The view that some kind of constraint for CO₂ emissions, for instance, in the form of a physical limit₁⁰ or a carbon tax, is necessary to tackle the greenhouse gas problems is common among authors who study the rebound effect, see also Brookes (1992), Greening et al. (2000), or Binswanger (2001). A number of surveys and empirical studies with the intention of quantifying the rebound effect have also been accomplished more recently, see, e.g., Schipper and Grubb (2000), Greening et al. (2000), and Binswanger (2001). It is, nevertheless, difficult to accurately quantify the magnitude of the rebound effect, because of the almost impossible task of measuring the effect, the small possibilities to fruitfully generalise the findings from different investigated cases, and the very disparate assessments in the studies. However, Schipper, as the guest editor of the previously mentioned Energy Policy issue, summarises the empirical studies by suggesting that

₁⁰ A nearby example of such a physical limit is the Kyoto Protocol and the European Union Greenhouse Gas Emission Trading Scheme (EU ETS), which is a sub-system of the KP for the trading of emissions permits based on Directive 2003/87/EC (EU, 2003). The EU ETS is operational since January 2005 and it deals with the trading of GHG emission permits during two periods, a three year period beginning 1 January 2005 and a five year period beginning 1 January 2008, the latter being the first commitment period of the KP. This cap on GHG emissions raises some questions related to emissions accounting. For example, does energy conservation or an increased use of energy have an effect on GHG emissions at all, as the cap on total GHG emissions is already set? Will a reduced demand only lead to increased GHG emissions somewhere else, provided that the emission permits are not destroyed, and will an increased demand have to be met by zero-emission supply? Or will a reduced demand release some pressure from the system and thus safeguard it, while a large increase in demand will ruin the EU ETS?
“... rebounds are significant but do not threaten to rob society of most of the benefits of energy efficiency improvements. That is, depending on the initial conditions, end user incomes, and energy price changes, micro rebound effects focusing on the end-uses whose efficiencies improve might eat up 10–40 % of the energy savings otherwise realised from a given decline in energy to output ratios. Macro-effects caused by the stimulating of the economy and re-spending of savings from lower energy bills seem to be small, too” (2000).

The micro rebound effects mentioned by Schipper focus on the direct feedback between energy efficiency and energy use related to a specific end-use, activity, or sector, while the macro effects focus on effects beyond this. This is not in an obvious way transferable to the classification of different rebound effects described here, as there will be questions related to whether, for example, the price equilibrium rebound effect belongs to the micro or the macro rebound effect. Anyhow, an odd thing with this statement is that 10 to 40 % for a fraction of the total rebound is considered a small value, for the reason that, even if this is far from the real backfire predictions, it is still a substantial error for most applications related to emissions accounting.

An author that seems to have adjusted his view with the progress of the debate is Saunders (2000), who still argues for backfire, although now only in selected instances. He also recognises the empirical work of some authors who have found that the rebound effect commonly is small in many instances. Nevertheless, some of the controversies about the rebound effect might be easier to understand if we consider different situations in which the effect may or may not appear. Grubb (1990), for example, argues that the rebound effect ought to be much more pronounced in circumstances when energy supply or price is a constraint on economic activity than when end-use of energy approaches saturation, and this is likely to be relevant. The aforementioned historical examples with backfire probably caused by the Bessemer process and the Watt steam engine did happen in a situation very far from being comparable with a mature industrialised economy. The economic growth only needed a spark to set off and the need for different services and commodities to increase the average standard of living was almost desperate. It is not hard to imagine that inventions that could provide these services and commodities at a lower price would have considerable spin-off effects on the economy and thereby, subsequently, increase the total use of energy. However, Grubb also describes a situation when the need for more services and commodities is limited. Going back to the two examples with better house insulation and better fuel efficiency in cars, one could envisage a situation when houses are so warm that an increased temperature does not increase the comfort, but more readily the opposite, and when the need or willingness for transportation is not restricted by economic factors. Such saturation would have an effect at both the individual and the aggregated level, for the reason that the needs for more energy on both these levels thus would be limited.

Another major issue of importance for the rebound effect, and also for the price flexibility, is the difference between liberalised and regulated markets for energy. Except for these differences, the markets for different kinds of energy carriers vary considerably in other ways, such as the response to changes, e.g., time and magnitude, and constraints, e.g., power and energy constraints, etc. Still, Paper II and Paper III focus entirely on the electricity markets and the discussion about differences between liberalised and regulated markets for electricity is relevant given that both types of markets exist in parallel today. Electricity is, therefore, well suited to illustrate the differences between a regulated and a liberalised energy market. The major difference is in the price-setting; in a liberalised market, the price is set from an equilibrium point trading based on participants from both the supply and the demand
sides, while the price setting in a regulated market is based on some other mechanism. As a consequence, the quick responses leading to the price flexibility and price equilibrium rebound effect as illustrated in figure 1 and figure 2, will not occur in a regulated electricity market. The conclusions that can be drawn from this is that the price flexibility and the rebound effects, theoretically, ought to be more pronounced in a liberalised than in a regulated electricity market. Discussions about how different types of markets will affect the rebound effect is, in spite of this, uncommon in the literature.

4.5 Problems with the emissions accounting methods for use and supply of electricity

The different methods for emissions accounting that have been presented here are average accounting, the marginal coal method, the marginal new technology method, and the price flexibility method. Of these methods, the method using average figures for emissions has the obvious problem of not reflecting dynamics in the grid at all, and, hence, it can hardly be used as a realistic method for emissions accounting.

Different emissions accounting methods that apply a one-to-one marginal approach, as the MCM and the marginal production approach of the MNTM, are more suitable for reflecting actual changes in the supply and use of electricity than the average accounting approach. But, given the discussions about the price flexibility and the rebound effect, it becomes clear that these approaches disregard several economic features at various levels of the economy. These ‘economic’ difficulties perhaps constitute the major argument against the one-to-one marginal approaches, but there are also other economic realities that may cause problems for different kinds of marginal approaches. A common feature in both regulated and liberalised electricity markets is that power producers schedule their production units in accordance with a least variable-cost dispatch to choose the merit order of power production units. This scheduling of plants is for a company, in a perfectly competitive market, combined with a profit maximising ruled by the controlling of its supply so that the short-term marginal costs equals the market price (Tennbakk, 2000). However, if a power production company (or a number of companies making a deal) has a dominant position in a market, they may increase their profit by abandoning the basic mechanisms ruling the perfect market in the exercise of market power. The exercising of market power might in this case be to reduce production to force the price up and this might, for any of the marginal approaches to emissions accounting, increase the difficulties in defining what the marginal power really is. Halseth (1999) has performed a study about potential market power in the Nordic electricity market.

The control of the supply from some different types of electrical power production sources will not be scheduled as the thermal power production sources that dominate most electrical markets, because of external conditions and inherent characteristics. One such example is wind power\(^\text{11}\), which due to extremely low variable production costs, normally should produce when the wind allows for this. These changes in the supply will, principally, affect a liberalised electrical market in the same way as the added power in figure 1. Another example is hydropower, which is a significant power production source in many electrical markets\(^\text{12}\). The control of the power supply from hydropower is affected by many factors, but the major difference between the control of thermal power and hydropower lies in that the first may be categorised as power constrained and the latter as energy constrained. Simplisti-

\(^\text{11}\) The share of wind power was in the Nordic countries (except Iceland) 2 % of the total 363 TWh power produced in 2003 (Nordel, 2004), and Denmark is the dominant producer.

\(^\text{12}\) The share of hydropower was in the Nordic countries (except Iceland) 46 % of the total 363 TWh power produced in 2003 (Nordel, 2004), and Norway and Sweden are the dominant producers.
cally described, thermal power can go for a full, albeit limited, power load during the whole year, while hydro power only occasionally delivers full load due to the limited amount of available water during the year. High or low precipitation has, in the past, affected the reservoir levels and, in the forecasts it will affect the expected reservoir levels; both have an impact on how the control of the hydropower production is managed. The energy constraint for hydropower also leads to the situation when as much water as possible is saved for periods when electricity prices are expected to be high, as during the winter season in the Nordic region. Furthermore, hydropower is, despite low variable costs, often used for short-term regulation purposes, because of the trouble-free possibilities for rapid regulation in comparison with thermal power. All these factors affect the electrical market in a similar way as the wind power described above, but it is mainly the short-term regulation of hydropower that may be used as an argument against the one-to-one emissions accounting methods. If a change in the use or supply of electricity is not met by a response of the power with the highest variable costs on the grid, but by hydropower, this means that the hydropower has an equal amount of less or more electrical energy in the reservoirs that will have an effect at a later stage. It is, however, unlikely that this amount subsequently will be met by exactly the same quantitative response of an equivalent marginal power, as at the time for initial change in the use and supply of electricity.

When different regions with different kinds of power supply configurations are connected, problems with defining the marginal production will arise when the connections are operated at full capacity, i.e. when bottlenecks appear. An illustrative example is when Finland and Denmark, dominated by fossil fuel power, are connected to Sweden, dominated by nuclear and hydropower, and Norway, almost exclusively dominated by hydropower. Electricity is traded between these countries via the common Nordic marketplace for electricity, Nord Pool, but the connections between different areas may be bottlenecks that limit more electricity being transferred from one area to another in response to a change. An increase, or a decrease, in the power demand or supply as a response to a change, may thus be met by power with lower or higher variable production costs than what normally is considered marginal power production, taking into account the whole area without bottlenecks.

Another difficulty for the one-to-one marginal approaches is the grid-related transmission and distribution losses that will be more pronounced if the marginal plant is remotely located. This will not make a major difference in most cases, since average transmission and distribution losses are commonly below 10% in many regions of the world. Approximate average figures are: 7.2% for the USA in 1995 (DOE, 2003), 7.4% for the U.K. in 1998 (Powerwatch, 2000), and 6.8% for Sweden in 2003 (Statistics Sweden, 2005). Still, it might have an impact on emissions accounting when a marginal plant is far away.

4.6 What may be achieved by improvements in energy efficiency?

The only clear conclusion that may be drawn from the discussion about the rebound effect is that it may not safely be ignored. The same can most certainly be said about the price flexibility mechanism for added supply of energy, even if this issue is not at all as vigorously discussed as the rebound effect. The significance of these effects will, nevertheless, be crucial for the possibilities to answer the question: What could presumably be achieved by energy efficiency and energy conservation measures? Yet, this could not be answered without taking into account the perspective: for whom is energy efficiency beneficial and in what way? Even if we can depict the perspective, the answer has to be: it depends. Some examples of different perspectives are given below. The basis for the discussion about different perspectives is that
the rebound effect is present, that the energy efficiency improvements are profitable in comparison with alternative investments, and that the rebound is not above unity, i.e. backfire.

For an intermediate\textsuperscript{13} energy supplier such as a power producer, an energy efficiency improvement on the supply side will lead to lower energy input needs per energy output and, hence, it will presumably lead to lower variable costs and higher profits. In this way, the energy efficiency is beneficial for this energy supplier. Nevertheless, in the long-term, competitors may have increased the efficiency so much that a part, or all, of the higher profits earned through the efficiency improvements has been eaten up by the lower overall electricity prices resulting from the overall efficiency improvements. The efficiency improvement may, therefore, not be entirely beneficial for the energy supplier, but the energy supplier would perhaps suffer even more if only the competitors carried out the efficiency improvements.

If the perspective is the demand side and considers an individual citizen or a company, the answer is that demand side energy efficiency improvements are beneficial. There are possibilities to save money and increase profits through the lower costs for energy and also to improve the standard of living through all the well-being and comfort gains that are the foundation for service-related rebounds. Possible overall energy-efficiency improvements will, in this view, be beneficial too, since these might lead to lower energy prices.

For a decision-maker such as a politician with the ultimate goal of stimulating economic growth in, for instance, a country or a region, there are many indications that efficiency improvements are apt to be beneficial. Over, say, the last 100 years, the energy efficiencies on both the demand and the supply sides have been vastly improved along with the economic growth of the industrialised countries. Nevertheless, it is difficult to confidently tell to what extent this economic growth has depended on energy efficiency improvements. The previously mentioned historical examples with the Watt steam engine and the efficiency improvements in the iron and steel processes occurred concurrently with rapid economic growth; it is highly plausible that these energy efficiency improvements actually had something to do with the economic growth. Still, this is only an assumption, even in these extreme cases. Intuitively though, it is not hard to imagine that money released due to energy efficiency improvements on both the supply and the demand sides ought to spur economic growth. Economic theories, such as the neoclassical growth theory used by Saunders (1992), also indicate the same. Hence, it is realistic to assume that energy efficiency improvements are beneficial for the decision-maker with the ultimate goal to stimulate economic growth. An exception could be for a region or country that is dependent on the supply and export of primary energy. Demand and intermediate side efficiency improvements may, in this case, harm the possibilities to sell primary energy.

When a decision-maker, on the contrary, has the mitigation of climate change as the primary ambition, the answer to whether energy efficiency is beneficial cannot be given with utter confidence in this case either, as may be seen from the discussions above about the rebound effect. The scholars who argue that the rebound effect is strong are, as previously discussed, commonly arguing that measures to promote energy efficiency must be followed by different constraints, for instance, green taxes and/or physical limits, to be meaningful in national GHG abatement programmes. Others that do not believe in a strong rebound effect claim that energy efficiency is a powerful tool to solve the problems associated with GHG

\textsuperscript{13} Here a distinction is made between the intermediate energy suppliers who convert one form of energy to another, for example, a power producer, a petrol producer, and a district heating supplier and the primary energy suppliers who deliver unprocessed energy products such as coal, crude oil, and biomass.
emissions. The individuals who believe in a strong rebound still consider energy efficiency as a good thing, but particularly as a tool to stimulate economic growth and not as a tool to abate GHG emissions. Thus, it is hard to objectively assess the impact of energy efficiency as a tool in the mitigation of climate change and these controversies do not make it easier for the decision-maker. The previously mentioned empirical studies that were summarised by Schipper (2000) do, nevertheless, indicate that energy efficiency certainly can be a tool in the fight to reduce GHG emissions. Hence, a reasonably safe point of view for the decision-maker is that measures to promote energy efficiency ought to be a tool in the battle against climate change, but that these measures cannot be used without other constraints that limit GHG emissions.

Closely related to the discussion about energy efficiency as a possibility to bring GHG emissions down, is the discussion about ‘decoupling’ of economic growth from its environmental impact. The observation that emissions of some pollutants such as chlorofluorocarbons (CFC), sulphur dioxide, or particulates may have decreased even with continuous economic growth in industrialised countries provides evidence that decoupling sometimes may occur. The thought that there can be decoupling between energy use, and thereby CO₂ emissions, and economic growth also finds support in the energy intensity patterns in the industrialised countries during the last decades. The total primary energy supply per unit of Gross Domestic Product (GDP) fell by a third between 1973 and 2000 (IEA/OECD, 2004). The total CO₂ emissions, however, increased during the same period (ibid.) and, for the atmosphere, the economic development in various countries is irrelevant. There is also a major physical difference between most pollutants and CO₂: the magnitude of the emissions. Hence, it much more difficult to reduce CO₂ emissions than the release of most other pollutants. Azar et al. (2002) put forward that trends have revealed partial decoupling of CO₂ emissions from GDP in several major economies of the world, but

“Currently, CO₂ emissions are increasing in most countries of the world. The increase is primarily driven by an increase in income per capita and population” (ibid., p. 56).

They also conclude:

“CO₂ emissions have to be decoupled much more rapidly than has been the case in the past, and it is extremely unlikely that this will happen by itself. Policies are required.” (ibid., p. 7).

Decoupling between CO₂ emissions and economic growth must be an almost irresistible concept for a politician making policies, since the trade-off between economic growth and mitigation of climate change then may be avoided. Hence, it is not surprising that it also has rendered some political interest and an example of this is a letter sent jointly by the Prime Ministers of the United Kingdom and Sweden to the European Commission (Blair and Persson, 2003) declaring that:

“New technologies and processes can contribute to the goal of decoupling economic growth from environmental degradation “ and

“To speed up the replacement of old technologies there is a need to set clear targets, develop stronger market based incentives and make more use of the instrument of public procurement. We will need to consider carefully the most appropriate ways of pursuing this at national or at EU level”.
4.7 An all-applicable method for emissions accounting would be very useful, but can we construct one that gives reliable estimates?

All larger models intended to predict the behaviour of systems are created with a number of assumptions and limitations, of which some are based on theory and others on empirical studies. For a regional, national or international energy system, these assumptions and limitations may be with regard to: physical and economic constraints, rational behaviour of the residents, the perfect market, a strict least variable cost dispatch of power sources, demand side price elasticities, technical development, economic growth, etc. When these factors have been defined, there are perhaps possibilities to create a model that may predict changes in a confined energy system, which is bound to time as well as geographical and demographical limits, with reasonable accuracy. The practical usefulness of such a model is, however, limited because of the sensitivity to changes in the assumptions and the limitations. Even within the same system, the response to a change is probably different from time to time and to generalise the findings to another part of the world is generally not feasible. The extreme variation in quantified price elasticities on energy carriers (electricity and fuels) previously referred to, constitute an argument for why it is inept to generalise the results from one case to another. Adding the difficulty to reasonably assess the rebound, the price flexibility, the effect of unpredicted events, the effects of the general technical and economic development etc., will make the task even more unachievable.

The methods for emissions accounting presented here, such as the average accounting, the MCM, the MNTM, PFM and the rebound accounting, are all in principle very simple in their basic forms. These methods do not consider most of the factors that can be applied in large models and, hence, these methods probably give less accurate estimates of the true outcome resulting from a given measure. Moreover, their basic function is perhaps not to give generally reliable estimates for changes in GHG emissions resulting from an energy project, even if they in many cases unfortunately are used as such, see, for example, Paper IV and section 4.8 below. To a certain extent, the real benefit of these methods is to provide the insight that the task of estimating how a given measure will affect the GHG emissions is not as straightforward as it may seem at a first glance. A method based on assumed relationships that do not exist and fabricated assumptions may certainly give a correct estimate during specific circumstances, but the method does not give correct estimates in other situations.

A drawback with a very strong belief in some method is that many poor decisions may be made because of it. For decision-makers who should decide between different measures to mitigate climate change this is crucial, as different measures in many cases will presumably not deliver the expected results if the estimates are based on, for example, one of the above-presented methods. In Paper III, CO₂ emissions were estimated for different energy projects using different methods, and the results vary considerably depending on the method. Taking a natural gas combined cycle (NGCC) operated as CHP as an example, the estimated net CO₂ emissions varied from roughly -660 kg CO₂ / MWh (produced heat) to 80 kg CO₂ / MWh (produced heat), just depending on the choice of method. However, in most cases it is not even possible to measure the true outcome of a particular project or measure, so a decision based on a faulty estimate might not even be discovered.

The emissions accounting methods taking the price flexibility and the rebound effect into account might be theoretically more sound than the methods that do not, but as it is impossible to estimate the true price flexibility or rebound effect for generalisation purposes, this is not enough to construct an all-applicable method for emissions accounting. The larger
models mentioned above may take many factors into account that are not treated by the simple methods, but they still rely on some basic assumptions and limitation that, firstly, limit their ability to predict a true outcome of a given measure and, secondly, restrict the possibilities to use them for generalisation purposes. The answer to the question of whether it is possible to construct an all-applicable emissions accounting method that gives accurate estimates in different times and geographical areas, must therefore be no.

4.8 The relevance of economic effects for CDM projects

The previously described likely difference for the rebound effect in economies where the supply or price for energy is or is not a constraint to economic development is highly relevant for differences in how to perform emissions accounting for measures aimed at mitigating climate change in developing versus industrialised countries. The rebound effect, or the corresponding price flexibility effect for added power supply, is probably much more pronounced in high-growth, or potentially high-growth economies than in mature industrialised economies, and many of the countries that could be host countries to CDM projects are either high-growth economies or have the potential to be so. Schipper and Grubb (2000) who, for example, conclude that rebound effects generally are relatively small in mature economies, also state that:

“We must emphasise that our findings are based on examining the high-income countries. In low income countries, energy and energy costs are often a constraint to industrial activity... This is particularly true if there are power outages, droughts, or other factors that make supply unreliable. And for more than a billion consumers who rely on gathered firewood and other renewables and no electricity whatsoever, the time alone required to gather energy and to carry out tasks without any mechanical assistance means little time for participation in a commercial economy. As households hook up to the formal economy, we would expect a significant burst of commercial energy use both because of its efficiency in saving time and because higher incomes permit purchase of more appliances that use this energy...Our generalisations about the low impact of rebound effects can not, therefore, be easily extended to low income countries.”

Thus, one could expect that discussions about emissions accounting for the project-based mechanisms in the Kyoto Protocol, and especially for the CDM, ought to be heavily influenced by how the state of development in various countries affects different price effects, but they are usually not. Nevertheless, this is the main topic of Paper IV.

Before continuing the discussion about how differences in the state of development affect emissions accounting, a brief overview of three fundamental concepts used for the project-based mechanisms is given. The concepts are additionality, baseline, and leakage and they capture much of the complex nature of the quantification of the GHG effect resulting from a specific project. For a CDM project, the KP uses the term additional to exclude business as usual projects:

“Reductions in emissions that are additional to any that would occur in the absence of the certified project activity” (UNFCCC, 1997, article 12 paragraph 5 (c)).

It is a criterion that is added to protect against attempts to obtain emission credits for projects that would have been realised even without the CDM, as, naturally, there are strong economic incentives for this. To determine the additionality of a project is, as can seen from
above, directly linked to the ability to assess what would have happened in the absence of the project, and this absence of the project is called a baseline scenario. This concept is not used directly in the Kyoto Protocol, but in the Marrakesh Accords\textsuperscript{14} (UNFCCC, 2001) some of the problems with establishing which projects are truly additional were addressed; the baselines are important here:

“Recognizing the need for guidance for project participants and designated operational entities, in particular for establishing reliable, transparent and conservative baselines, to assess whether clean development mechanism project activities are in accordance with the additionality criterion” (ibid., chapter J.3, p 68).

In practice, a project’s possible emission reduction is, within a project boundary, assessed through the difference between a baseline scenario and the scenario with the proposed project. The establishment of a project’s possible emission reduction, therefore, involves several difficult tasks, such as the prediction of the business as usual emissions, the prediction of emissions with the proposed project, and the establishment of project boundaries. The Marrakesh Accords gives some advice on how to set the project boundary for a CDM project:

“The project boundary shall encompass all anthropogenic emissions by sources of greenhouse gases under the control of the project participants that are significant and reasonably attributable to the CDM project activity” (ibid., chapter J.3, Annex G. 52).

While it is clear that this advice leaves much for interpretation, the Marrakesh Accords also state that the estimated emission reduction also should consider changes of emissions outside the project boundary attributable to the project, which are referred to as leakage:

“Leakage is defined as the net change of anthropogenic emissions by sources of greenhouse gases which occurs outside the project boundary, and which is measurable and attributable to the CDM project activity” (ibid., chapter J.3, Annex G. 51).

The word measurable is in this case problematic, as many of the effects that, potentially, could generate significant leakage effects, are not measurable. This includes most aggregated and economy-wide effects related to price flexibility and rebound discussed above. Not to consider possibly significant, but not measurable, effects is a dubious approach in many ways, but especially for CDM projects since, as explained earlier, the erroneous estimates will not have to be corrected for at a later stage in the GHG accounting. Moreover, it is quite likely that, for example, the economy-wide effects could be of significant importance for the net GHG emissions resulting from a CDM project and this is discussed in Paper IV.

The organ that issues emission credits for CDM projects is called the CDM Executive Board. They also approve methodologies for how emissions reductions from different projects should be estimated and these approved methodologies subsequently work as precedents for future projects. Guidance for how to estimate emission reductions may also be found in the Marrakech Accords, when applicable, and in other guiding documents from the CDM Executive Board (UNFCCC, 2004; 2005a).

\textsuperscript{14} The Marrakesh Accords was the document resulting from meeting number 7 of the Conference of the Parties, which is the organ that can make decisions about the climate change mitigation framework. This meeting sorted out a number of questions related to the Kyoto Protocol.
To what extent do the approved methodologies discuss and consider rebound or price flexibility effects? The answer to this question is: not at all. Two examples of approved methodologies for energy efficiency measures, AM0018 and AM0020 (UNFCCC, 2005b), and two approved methodologies for projects that will add electricity to a grid, AM0004 and AM0005 (ibid.), may be used as examples. Direct savings of fossil fuels is only found in AM0018, and in this case no rebound effects are considered. However, all of the projects consider removal or addition of power to a grid and the resulting changes in emissions are estimated in accordance with a blend of different one-to-one approaches, with no considerations of the rebound or price flexibility effects. The emissions accounting methods used are varieties, or blends, of the one-to-one emissions accounting methods average accounting, MCM, and MNTM previously presented, and this is also recommended by the CDM Executive Board (UNFCCC, 2004; 2005a). An example of a recommendation in one of these documents is that added power from renewable power generation can be assessed to replace other types of power generation sources on a one-to-one basis, either through an average of an approximate operating margin and a build margin or through the weighted average for the current generation mix. The approximative operating margin is the weighted average emissions of all generating sources supplying the grid, excluding hydro, geothermal, wind, low-cost biomass, nuclear and solar generation. Thus, this may be regarded as a mixture of average accounting and the MCM, as it is an average but only for the generating sources that probably have the highest variable costs of the operating units. The build margin is the weighted average emissions of recent capacity additions to the system, which in essence is the same as the MNTM with regard to the scenario when a new technology has become the standard choice for new investments. An illustrative example of how far away the discussion is from rebound and price flexibility effects may be found in AM0004:

“The operating margin (i.e. based on existing production, author’s comment) usually is more relevant for grid-connected biomass generating units even if the demand for electricity is growing rapidly because:

- The relatively small size of the biomass power generation project means that it has little impact on plans for constructing major new power stations;
- Due to the priority accorded renewable energy sources by the energy policies of many host countries and the small size of the biomass project, the project is unlikely to cause the cancellation of another planned renewable energy plant of similar size (build margin displacement). They will both be built.”

To conclude, the added power will thus, even in a situation with rapidly growing demand, be considered to entirely displace existing power production. This is certainly very far from deliberating the economic issues discussed in this chapter, such as different kinds of rebound and price flexibility effects.

The economic situation in many developing countries that could be targets for CDM projects resembles the economic situation in 19th century England when the Watt steam engine and the Bessemer process caused what certainly was backfire. The addition of, for example, carbon-leaner power production to such an economy would probably lead to many different economic effects of which most are positive for the country in question, but that also may lead to increased GHG emissions which are not compensated for by reductions somewhere else. The risk is, thus, a loss of integrity of the Kyoto Protocol and, with the current Kyoto framework, this has to be judged against the positive effects resulting from the CDM projects. However, since progress in developing countries is a positive thing and so is
the mitigation of climate change, it would be better to change the accounting framework than to, in reality, encounter the risk of having to choose between them.

4.9 How can decision-makers retrieve useful information, if no method gives an answer?

The overall aim of this thesis is to suggest and assess possibilities to mitigate climate change and to put forward tools for how to overcome some of the encountered obstacles linked to these possibilities. Thus, it would be fair to come up with at least some general idea of how to choose between different measures intended to mitigate climate change, instead of only demonstrating the problems with every approach. Many decision-makers will probably feel very uncomfortable with the inability to make an ‘objective’ judgement of how a given energy project will affect global CO2 emissions, because of the, at a glance, easily quantifiable situation. This might be even more pronounced if the decision-makers have an engineering background with the worldview based on the measurability and possibilities to quantify that usually follow with this schooling. To hold on to a single restricted view by, for example, strictly believing in one of the methods presented here may lead to decisions that will not lead in the desired direction and, even more severe, the inability to discover that the decisions lead in an unintended direction. An example of such a restricted view is common among engineers and it may be called the supply-oriented view. In summary, this belief is based on the assumed existence of a certain demand for energy in society that has to be met in one way or another. The focus is on the supply side and questions are usually related to what may be done on the supply side to meet the demand. Other features are that this energy demand may grow with the technical and economic development as time goes by and that historical trends could be followed to establish forecasts for supply and demand. The connection between the supply and the demand sides’ responses to changes in the price are, however, missing in the supply-oriented view, i.e. price elasticities are not considered at all, and examples of emissions accounting methods that are derived from this kind of view are the average accounting, the MCM and the MNTM. Another example of a restricted perspective is the view that may follow from an overly firm belief in the rationality assumption, which is common in economic models. One interpretation of the rationality assumption is that individuals seek to reach a specific goal, for instance, keeping the house warm during the winter months, at minimal cost, other things being equal (ceteris paribus), etc. However, this principal assumption does not consider a number of human values, such as environmental concern without any economic gains, and much human behaviour cannot be explained with the rationality assumption. An example from Paper I is some of the cultural and human-related barriers that may result in a failure to carry out a co-operation in spite of good ‘rational’ arguments, for instance, knowledge of beneficial technical and economical conditions. The relevance of keeping one’s eyes open for new insights and not getting caught in a specific worldview is, therefore, a central idea concerning how to deal with the problems related to mitigation of climate change.

Because of the difficulties of making predictions of the outcome resulting from a given measure, the subsequent observation and, if possible, measure of the true outcome is necessary both for the success of this measure and to gain information that may well be used to succeed with other, not yet realised, measures. Hopefully, the information will be used to make corrective measures to ‘get back on track’ and it is essential not to be deceived by the beliefs leading to the measure initially. Here, we are directly back to thoughts used in systems research. The corrective actions are the basis for the cybernetic loop described in section 2.1, which is to use the new information gained to correct a deviation from the planned course. The feedback of information is essential, but there are problems with feedback from such a
complex system as a large energy system. We have only one future and it is very hard to find out what would have happened in the absence of an accomplished action. The deviation from a planned outcome is often possible to measure, but it is frequently not possible to measure how a given measure has affected this deviation and, consequently, how the corrective actions should be dealt with. Another systems approach-related feature is the significance of not being deceived by a single restricted view, as was pointed out by Churchman (1968). To constantly examine and to permit correction of a given view ought to be as fundamental for the success in mitigating climate change as for any complex problem.

The field of emissions accounting is a relatively new research area, as the recognition of the need to do something about the greenhouse gas emissions is also relatively new. Many of the principles are, nevertheless, the same as for measures with the ultimate goal to save primary energy resources that partly were discussed as a result of the oil crises in the 1970s, see, e.g., Khazzoom (1980). The development of emissions accounting methods are, even apart from the disputes about, for example, the rebound effect, not a linear development. An example of this is the varieties of average accounting, MCM, and MNTM used for the estimates of net CO₂ reductions resulting from CDM projects, see above. The general trend should, however, be that the increased insights in emissions accounting have to lead to a development of ideas and an example of a possible evolution is illustrated in figure 3, which is influenced by a Swedish or Nordic context. The first three methodologies for emissions accounting may all be said to be all-applicable and based on ideas emerging from some physical and economic realities, while the last two methodologies cannot be used for fast generalised estimates. A physical reality that may have influenced the view in Sweden is the increased exchange of electricity with neighbouring countries and an economic reality that might change the general view in the future is the transition from a regulated to a liberalised market for electricity. Even if figure 3 is influenced by the Swedish or Nordic context, parts of these tendencies may also be found in various fields where emissions accounting is applied. In studies related to LCA for instance, it is still common that emissions accounting is performed in accordance with Box 1, but discussions about emissions accounting in accordance with Boxes 2 and 3 are also common, see, for example, Weidema et al. (1999), Ekvall (1999), EPA (2002) and Hondo (2005). As was previously discussed, the recommended and approved baselines for CDM projects apply emissions accounting methods according to one of, or a combination of, Boxes 1, 2 and 3 (UNFCCC, 2004; 2005a; 2005b). In Sweden, the general development has regularly lead to Box 2, but more recently also in combination with Box 3, i.e. the MCM or the MCM together with the MNTM are often used as the basis for emissions accounting (Rydén et al., 1993; Swedish Energy Agency, 1999; Kågeson, 2001; Werner, 2001). Several Norwegian studies of the Nordic electricity market would fit best within Box 4, although most of the considerations are purely economic with the main purpose of describing market behaviour rather than emissions accounting (ECON, 1994; Haugland, 1996; Halseth, 1999; Vennemo and Halseth, 2001).

The pragmatic methodology in Box 5 is suggested because of the inability to obtain accurate estimates from models and emissions accounting methods. This methodology does not rule out the use of models, actually quite the contrary, as it does recognise the use of models as a tool for retrieving information that may assist, for example, decision-makers in their work. However, the methodology excludes the firm belief in methods or models as the only way of retrieving information when estimating changes in CO₂ emissions due to a measure with an effect on an energy system. Experience from previous energy measures ought to be used as well as experience from other large systems in society. Another vital
A feature to facilitate the practical usefulness of the methodology is the openness to amendments with the retrieval of new insights, i.e. adjustment by feedback.

**Figure 3.** A possible process of development of methodologies for predictions of estimated CO₂ changes due to dynamics in the electrical grid (Swedish or Nordic context).
My belief is that with such a complex system as a national or the global energy system, it is impossible to find the best way to approach and reach a given goal, for example, an X % reduction in national anthropogenic GHG emissions during a specified year in comparison with a base year. Yet, I still believe that there is a major potential to find out more about how to find some way to approach and reach this goal, and that these findings could be used practically to guide decision-makers to achieve real progress. I believe that the most efficient approach to find out about these advances ought to be to use a pragmatic, experience-based, and anti-dogmatic methodology of the kind described in Box 5 in figure 3. Here we are back to the systems research idea again; the most valuable is to have a good general idea of basic mechanisms and to draw conclusions and make decisions based on this understanding.
5 Reflections on Papers V and VI: All CO₂ molecules are equal

In chapter 4, the focus of attention was issues related to emissions accounting for use and supply of electricity. The difficulties with defining the indirect effects of a given measure were discussed and large parts of this discussion may also be valid for emissions accounting from other energy sectors, for example, the transport sector and the district heating sector. An issue that was left out from the discussion in chapter 4 was how a shift from one form of primary energy, or energy carrier, to another will affect emissions accounting. The shift from one energy carrier to another may affect the market situation for different kinds of primary energy and for both demand and supply sides’ energy technologies, locally as well as globally. A major shift from coal to uranium or natural gas in one country will, for example, certainly influence both the markets for several primary energies and different supply and demand technologies nationally, but also internationally. Another issue is how to account for CO₂ emissions from fuels with different origins, such as fossil or biological, and this is the main topic of this chapter.

5.1 The carbon cycle

Carbon is naturally transferred between the terrestrial ecosystems, the atmosphere, and the oceans as part of the natural carbon cycle. Other reservoirs involved in the carbon cycle are geological reservoirs, consisting of fossil organic carbon, rock carbonates, and ocean sediments, but the natural fluxes to and from these carbon reservoirs are almost negligible in comparison with the carbon fluxes between the atmosphere and the terrestrial ecosystems or the oceans. A detailed description of the reservoirs and the different fluxes between them may be found in IPCC (2001a), and, notably, the gross natural fluxes are much larger than the fluxes caused by human perturbation. However, the major net flux is the carbon flux from the geological reservoirs to the atmosphere and this is, most importantly, due to the anthropogenic burning of fossil fuels (ibid.). The net carbon fluxes from the atmosphere to terrestrial ecosystems are currently positive, but this net flux is small in comparison with the gross fluxes between these two reservoirs. About half of the carbon uptake in these terrestrial ecosystems is directly respired by plants, while nearly all of the remaining part either is respired back to the atmosphere through some form of decay process or through oxidation by combustion. One part of the detrius will be converted to a modified soil carbon, which decomposes slowly, but it is only a small fraction of this modified carbon that, together with a tiny amount of black carbon produced through combustion, will be converted into a carbon pool that is resistant to decomposition, i.e. an inert carbon pool (ibid.).

Within the framework of the Kyoto Protocol (UNFCCC, 1997), two different approaches to assessing the fluxes of GHGs from a particular system and the atmosphere are applied. One is to estimate the actual fluxes and this approach is used for CO₂ from fossil sources and for non-CO₂ GHGs. The other is to estimate the fluxes through changes in a specific reservoir and this principle is called stock change when it is applied on CO₂ fluxes to and from terrestrial ecosystems. More specifically, the stock change principle is that a net decrease in a predefined carbon stock (or carbon pool) is considered as a corresponding CO₂ emission to the atmosphere, i.e. a source, and any net increase is considered as a corresponding CO₂ removal from the atmosphere, i.e. a sink. A forest where the total carbon content does not decline over time will, in accordance with the stock change principle, not yield a net positive flux of carbon to the atmosphere and it may thus be called sustainably
A possible and common view is that the release of CO$_2$ from biomass harvested from this sustainable forest gives no net contribution to the global GHG emissions, but there are some arguments for why this viewpoint may be pondered:

1. The only alternative for the harvested biomass is not to release the CO$_2$ to the atmosphere, but carbon may be stored in this harvested biomass for a short, long, or very long period.
2. The harvesting of the biomass will lead to less stored carbon in the forest than with a pure sequestration strategy for the forest (see, e.g., IPCC, 2000, Ch. 4.5.2).
3. The view that CO$_2$ emissions from biomass from sustainably grown forests do not render any net GHG emissions have spilled over to all types of biomass, sustainably grown or not.

The history of the sources of the CO$_2$ emissions is rather uninteresting, as it, for instance, is what occurs with the biomass if it is not combusted, or what will occur with the land area from where it is taken, that are the interesting issues for the discussions about gross and net CO$_2$ emissions. This perspective is frequently missed when biomass for energy and other purposes is discussed as a means to mitigate climate change. The earth’s radiative balance is affected equally by the release of a given amount of CO$_2$ independently of the origin of the CO$_2$ and this ought to be considered in these discussions. To use biomass from sustainably grown forests for energy and other products is a measure with great potential for mitigating climate change (ibid.), but not in all cases and not without other system aspects taken into consideration, as discussed in previous chapters. If the release of a given amount of CO$_2$ affects the atmosphere equally independently of the origin, so is the avoided release of a given amount of CO$_2$, and this is the main theme in both Paper V and Paper VI, but from different perspectives.

Carbon dioxide capture and permanent storage (CCS)\(^{16}\) is often discussed as a potent and realistic method to mitigate climate change because of the compatibility with current and upcoming large fossil-based energy infrastructures, see, for example, Parson and Keith (1998), DOE (1999), IPCC (2002) and OECD/IEA (2002). These fossil-based energy infrastructures might, however, not always be the first targets for CCS if cost-efficiency is in focus, and this is discussed in both Paper V and Paper VI, which both discuss CCS from different emission sources where the origin of the CO$_2$ may be either fossil or biological. The possibilities to capture and permanently store CO$_2$ from biomass has not received nearly as much attention as when the CO$_2$ is of fossil origin, but it has been suggested by, for example, Ishitani and Johansson (1996), Ekström et al. (1997), Obersteiner et al. (2001) and Möllersten and Yan (2002).

In Paper V, the significance of considering how carbon capture methods could be utilised in the most efficient way is pointed out and this is illustrated with an example on how a certain carbon capture method could be more efficiently utilised in some industrial applications than with fossil-based power production. Paper VI deals with the, for cost-efficiency reasons, problem that there seem to be no possibilities to receive emission credits for CCS from biological sources within the current Kyoto framework. An approach that could solve this problem in a future accounting framework is also presented.

\(^{15}\) The forest should not be depleted of other substances/elements than carbon either to be sustainably grown.

\(^{16}\) Carbon capture and sequestration, CO$_2$ capture and permanent storage, etc. all denote the same thing in the literature discussing this subject, and the acronym is in all cases CCS.
5.2 Treatment of GHGs within the Kyoto accounting and the UNFCCC reporting

A basic understanding of the principles for the accounting of GHGs within the Kyoto framework is necessary for understanding why CCS from biomass, i.e. biotic CCS, cannot receive emission credits currently. A brief presentation of the basic principles will therefore be given below.

Guidelines for national GHG inventories are developed within the United Nations Framework Convention for Climate Change (UNFCCC) with assistance from the International Panel on Climate Change (IPCC). These guidelines are subsequently accepted, or rejected, by the Conference of the Parties (COP). The UNFCCC reporting\(^{17}\) of GHGs is accomplished by most countries, while the Kyoto accounting only applies to the Annex I countries with binding emission targets set in Annex B\(^{18}\) of the Kyoto Protocol (KP). Due to these binding emission targets, it is only the GHG accounting linked to the KP that is legally binding, thereby giving true incentives to mitigate climate change. However, even though the UNFCCC reporting does not give any true incentives to mitigate climate change, it is still important as the first stage before the possible inclusion in a future binding accounting framework similar to the Kyoto Protocol.

National reporting and Kyoto accounting of fossil CO\(_2\) and non-CO\(_2\) GHGs are based on atmospheric flows. This means that the reported and accounted GHG emissions are based on estimates of the fluxes in the country when and where they actually occur. The non-CO\(_2\) GHGs that are accounted for in the KP are, as listed in the Annex A of the KP: methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. The UNFCCC reporting and KP accounting for CO\(_2\) emissions and removals linked to terrestrial ecosystems, i.e. Land Use, Land Use Change and Forestry (LULUCF) activities, are, on the other hand, based on national stock changes. For the UNFCCC reporting, five carbon pools are considered, above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter. Changes in biomass carbon pools removed from the forests, such as harvested wood products (HWP) and biomass used for energy purposes, are thus not yet included in the reporting. The use of, for example, biomass for energy purposes, as a result, only indirectly affects the UNFCCC reporting by the harvesting that will influence the five carbon pools.

Within the Kyoto accounting on the other hand, only some specified activities within the five carbon pools are accounted for. Article 3.3 of the KP defined the direct human-induced activities that are compulsory to account for, and these are afforestation, reforestation, and deforestation, while article 3.4 opened up for some un-defined additional human-induced activities that an Annex I Party may choose to account for. These undefined additional human-induced activities under article 3.4 were in the Marrakesh Accords (UNFCCC, 2001) subsequently defined as revegetation, forest management, cropland management, and grazing land management. The CO\(_2\) emissions and removals resulting from the 3.3 activities and forest management are estimated by the stock change principle, while the CO\(_2\) emissions and removals from the rest of the 3.4 activities are estimated according to a net-net approach. The net-net approach is also based on stock changes, but it is the net change of carbon stocks in a base year that should be compared with the net stock change during the first commitment period of the KP, i.e. 2008-2012 (divided by five to compensate for the

17 The reporting accomplished by non-Annex I Parties only has to be in a relatively general form.
18 Annex I countries (or Parties) are the 36 industrialised countries and economies in transition listed in Annex I of the UNFCCC (1992). This list of countries is, with some exceptions, similar to the list of 39 countries that have individual emissions caps specified in Annex B of the KP.
longer period). In summary, the use of biomass for, for example, energy purposes will only be indirectly accounted for in the Kyoto accounting as well, given that all of these human-induced activities are accounted for by stock changes linked to a certain land area. The difference is, however, that these activities only consider some parts of the five terrestrial carbon pools regarded in the UNFCCC reporting.

The carbon in biomass products may be released almost directly after harvesting, if the biomass is used for energy purposes, or be stored for hundreds of years in construction materials. As a result, the earth’s radiative balance will be differently affected, but this is, as explained above, not considered in the UNFCCC reporting and in the Kyoto accounting. This is also the reason why it does not seem to be possible to receive emissions credits for biotic CCS for the first commitment period of the Kyoto Protocol, since this measure does not affect the compulsory and optional measures eligible for the Kyoto accounting. Another central issue for this discussion is that biotic CCS cannot be considered in the current UNFCCC reporting either. This is essential for forthcoming possibilities to receive emission credits for biotic CCS, as it is the first step prior to the possible inclusion within a future accounting framework.

5.3 Why is the possibility to receive emission credits for biotic CCS beneficial?

The basic principle that has governed the implementation of the flexible mechanisms in the Kyoto Protocol, i.e. Joint Implementation, Clean Development Mechanism, and Emissions Trading, is that the overall costs to mitigate climate change could be reduced if measures are carried out where this can be done in the most cost-efficient manner. This principle is sound and, therefore, in Paper VI, arguments are put forward that it also should be applied by allowing for the inclusion of emission credits for biotic CCS within a future accounting framework. To enable biotic CCS to compete with other climate change mitigation options is sensible, given that there are several indications that it could be a cost-efficient measure to mitigate climate change, especially given ambitious GHG stabilisation targets. Several studies presented in Paper VI point out the importance of biotic CCS as a cost-efficient means to reach stable low CO\textsubscript{2} concentrations in the atmosphere, but there are also other arguments for why biotic CCS ought to be eligible for emission credits. In countries with few large point emission sources of fossil CO\textsubscript{2}, abatement costs may locally become very high. If, however, the capture and permanent storage of CO\textsubscript{2} from large point emission sources of biomass CO\textsubscript{2} could generate emission credits, this situation might change by lowering the abatement costs considerably. There are also cases in the biomass-based industries, for example, the pulp and paper and the sugar/ethanol industries, when biotic CCS can be very cost efficiently carried out, provided that emission credits can be received and traded, see Paper V and Paper VI. A final argument in line with the principal argument for flexible mechanisms above is that a level playing field for many different climate change mitigation options is beneficial for decreasing the overall costs of achieving specific stabilisation targets and it may also stimulate the development of new strategies and technologies to mitigate climate change.

5.4 A possible approach as to how biotic CCS can be eligible for emission credits

In Paper VI, we discuss a number of issues related to biotic CCS. The review of the possible importance of biotic CCS is together with the absence of possibilities to receive emission credits for biotic CCS mentioned above. Other issues that are discussed are the desirable characteristics of a possible accounting approach for biotic CCS and how such an
approach could be implemented within future accounting guidelines. The desirable characteristics for an accounting approach for biotic CCS were identified as:

- An approach that gives a reward for captured and permanently stored CO₂ of biomass origin,
- An approach without the need to keep track of the origin of the biomass, because biomass used for industrial or energy purposes at one site can have many different origins, such as different landowners and different countries,
- An approach that is rewarding to the entity that captures and permanently stores the CO₂ from biomass,
- An approach that does not discourage the use of biofuels for the replacement of fossil fuels, and
- An approach that does not interfere with other accounting principles that encourage the storage of biomass carbon in carbon pools such as forests and harvested wood products (HWP).

In an ideal situation for the optimisation of cost efficiency, equal gains in climate change mitigation would yield equal rewards within the accounting guidelines. In reality, this is not possible to accomplish for all possible climate change mitigation options, since most possible options to mitigate climate change are very hard to quantify and because the size and the complexity of the accounting framework must be kept at a reasonable level. Given the potential significance of CCS as a mitigation option, this option will have to be clearly addressed in any future accounting framework, but there are still several question linked to the potential escape of stored CO₂ and cross-border projects that are not solved in the present accounting framework, see Bode and Jung (2004). Their solution to this issue would be to use the same rules and modalities as are used for sequestration in the LULUCF sector for CCS, as many of the issues regarding non-permanent storage and cross border projects are similar for CCS and LULUCF. Other arguments are that it is good for simplicity and consistency to use the same type of guidelines in several different fields and that the experience from the development of guidelines within the LULUCF sector should not be neglected. To treat CCS as a removal activity, i.e. a sink, in a similar way as other sinks within the LULUCF sector, is, however, not consistent with the UNFCCC definition of a sink, which is

“any process, activity or mechanism which removes a greenhouse gas, an aerosol or a pre-cursor of a greenhouse gas from the atmosphere” (UNFCCC, 1992).

To remove CO₂ from flue gases or even prior to that is not the same as removing it from the atmosphere and this is why CCS could not be treated as a removal activity within the present accounting framework. Thus, if the UNFCCC definition cannot be changed, CCS has to treated as an emissions reduction, i.e. the captured CO₂ is treated as if it has never left the stack, rather than as a removal activity, in spite of the good arguments for doing the contrary.

In Paper VI, a possible approach to account for biotic CCS is presented. It is to create a carbon pool for captured and permanently stored CO₂ from biomass within the accounting framework and that removal units (RMUs) should be assigned to the country that collects CO₂ in this pool. RMU is a term used for emission credits that might be earned through domestic sequestration within LULUCF activities eligible by the Kyoto accounting. This accounting approach for biotic CCS could be carried out as it is, or, preferably, within a future accounting approach for harvested wood products called the stock change approach. An examination of
different HWP approaches and their compatibility with biotic CCS is given in Paper VI, but a brief explanation of the different considerations is given here too.

Carbon is constantly stored in products with a biomass origin and the carbon is thereby restrained from reaching the atmosphere. The assumption used for the UNFCCC reporting and the Kyoto accounting has, however, this far been that all carbon in harvested biomass should be seen as oxidised the removal year (IPCC, 1997, p. 5.17, Box 5). This assumption, which is called the IPCC default assumption, is based on the perception that the total stock of forest products does not increase significantly on an annual basis in most countries. The forest product pool will, thus, in accordance with the stock change principle, not give rise to any net emissions to or removals from the atmosphere. Nevertheless, there are no reasons why the use of biomass could not change so that the HWP pool does increase over time and there are also estimates that show that the wood products pool is already increasing in some countries, see, e.g., Skog and Nicholson (1998) for estimates for the USA. Hence, to account for the possible sequestration of carbon in wood products, three methods called the stock change approach, the production approach and the atmospheric flow approach, are frequently discussed (Winjum et al., 1998; Brown et al. 1998; Sikkema et al., 2002; UNFCCC, 2003; Pingoud et al. 2004). In principle, to perform biotic CCS and to sequester carbon in HWP has many similarities, as the biomass carbon is prevented from reaching the atmosphere in both cases. For that reason, and because different HWP approaches are already discussed, it would be rational to integrate the possibility to account for biotic CCS within one of the HWP approaches by including the biotic CCS carbon pool within the HWP carbon pool. For biotic CCS, it is the difference in the treatment of the cross-border trade of wood products in the different HWP approaches that is the major issue. The importing country will naturally be the one that carries out the possible CCS and, thus, it is interesting to see how emission credits for the CO₂ collected in a biotic CCS carbon pool within the HWP carbon pool could be distributed in the different approaches.

In the stock change approach, the HWP carbon pool increases with imports, and the import as such is, in accordance with the stock change principle, considered as a removal activity. Thus, to add carbon to the biotic CCS carbon pool within the HWP pool would still be considered as a removal activity for the importing country. This approach would, therefore, fulfil all the desirable characteristics in the list above. In the production approach, the HWP carbon pool still belongs to the exporting country and carbon added to the biotic CCS carbon pool within the HWP carbon pool will, consequently, not yield any emission credits to the entity that captures and permanently stores the biotic CO₂. This will thus be in conflict with both the criterion that the reward should be given to the entity that carries out the biotic CCS and the criterion that there should be no need to keep track of the origin of the biomass. It would obviously be problematic to keep track of biomass from different origins, when, for example, biotic CCS carried out on domestic wood-derived biomass would generate emission credits, but not when carried out on imported wood-derived biomass, as these emission credits would end up in the exporting country.

Carbon dioxide emissions from fossil fuels and from imported wood-derived biomass are treated equally by the atmospheric flow approach and this means that imports with the subsequent release of the CO₂ would generate emission debits for the importing country. Biotic CCS carried out on imported wood-derived biomass would consequently be rewarding to the importing country, but only by eliminating the emission debits that otherwise would have been received for the emitted CO₂. Hence, this approach would fail to satisfy the criterion not to discourage the use of biofuels for the replacement of fossil fuels, at least for
wood-derived biofuels. The discussion is a brief summary of some the arguments presented in Paper VI to either create a carbon pool for the assignment of RMUs separate from any of the suggested HWP approaches, or, preferably, to create it within the HWP carbon pool in the stock change approach.

To treat CCS from fossil sources as removal activities, as suggested in the article by Bode and Jung (2004), is consistent with the assignment of RMUs for biotic CCS presented in Paper VI. These two climate change mitigation measures would then be treated equally in all steps of the accounting procedures, i.e. even in the accounting for fugitive emissions during processing and transports, and for possible escaped CO$_2$ from non-permanent storage. Since the impact on the earth’s radiative balance caused by the release of a given amount of CO$_2$ is the same, irrespective of the origin of the carbon, it is rational that both the treatment of and the rewards for the CCS leading to avoided CO$_2$ emissions also should be the same, irrespective of the origin of the carbon.

### 5.5 Oxygen efficiency

The purpose of Paper V is in many ways similar to that of Paper VI. Paper V also aims at cost-efficient CCS solutions, but while Paper VI is limited to the comparison of biotic and fossil CCS, Paper V is limited to a single type of CCS technology, namely oxy-fuel combustion, and the comparison of different applications for this CCS technology.

Oxy-fuel combustion is among the most frequently discussed carbon capture technologies. Other carbon capture technologies are the tail end separation technologies, for example, absorption, adsorption, cryogenic separation, and membrane separation, pre-combustion technologies usually featuring gasification, reforming and the CO/water-shift reaction, or in-situ processes such as chemical looping combustion utilising an oxygen carrier (OECD/IEA 2002; Yan, 2003). All of these capture technologies have their advantages and disadvantages, and the most pronounced disadvantages for oxy-fuel combustion are the high capital costs and the high energy consumption (OECD/IEA, 2002). However, even with these major disadvantages, oxy-fuel combustion has been suggested as a competitive carbon separation technology for several different types of power producing processes (Bolland and Sæther, 1992; Shao and Golomb, 1996; Hochenauer et al., 2004). Noteworthy is also the interest for using existing power processes as the basis for studies (Strömberg, 2001; Wilkinson et al., 2001). The basic principle behind this technology is that more or less pure oxygen is used instead of air for the combustion in a process and that the inert component of air, i.e. nitrogen, does not dilute the resulting flue gases. The flue gases will thereby mainly consist of water vapour and CO$_2$, and the water vapour is easily removed by simple condensation to produce a relatively pure stream of CO$_2$, which is ready to be compressed and transported for permanent storage. In power processes, some part of the flue gases has to be recycled to compensate for the cooling effect of the removed nitrogen. The increased combustion temperature would actually open up for higher electrical efficiencies, but this is only theoretically, as the materials in the power processes currently are the limiting factor for the temperature. An elementary illustration of oxy-fuel combustion when used as a CO$_2$ capture method for almost any process is shown in figure 4.
For good reasons, the power-producing sector is in focus when climate change is discussed, due to the enormous amounts of CO\(_2\) released from this sector. However, large point emission sources of CO\(_2\) may be found in the industrial sector as well, and two examples are the cement industry and the pulp and paper industry. If competitive, there are no reasons why GHG abatement measures cannot be applied to these CO\(_2\) emission sources and Paper V describes how carbon capture by oxy-fuel combustion may be far more efficiently utilised together with some processes in these industries than together with power processes. The processes are the kilns used in cement production and the lime kilns used in kraft pulp mills. One of the ideas behind the paper is that the energy penalty that has to be paid to produce a given amount of oxygen is the same, irrespective of the use, and if this amount of oxygen is used to capture more CO\(_2\), the use of oxygen is more efficient. The amount of carbon dioxide that potentially could be captured per unit of oxygen is, hence, in Paper V termed oxygen efficiency, as it gives an indication of preferred and less preferred applications for carbon capture by oxy-fuel combustion.

Estimates of the oxygen efficiencies for different processes are presented in Paper V and they reveal that the oxygen efficiency for utilising oxy-fuel combustion probably is around five times higher for cement kilns than for methane-fired power plants. The principal reason for this is that one of the process steps in cement production called calcination emits CO\(_2\) that adds to the CO\(_2\) produced in the combustion. This potential benefit for carbon capture utilising oxy-fuel combustion in the cement industry was previously pointed out by Hendriks et al. (1999). The release of CO\(_2\) through calcination also occurs in lime kilns used in kraft pulp mills, but the estimated oxygen efficiency is, in this case, not as high as for the cement kilns, as more fuel has to be used for drying in lime kilns than in cement kilns. To use oxy-fuel combustion together with lime kilns still seems to be an attractive solution in comparison with using oxy-fuel combustion together with power processes, but there is a hitch. The major part of the CO\(_2\) from lime kilns in kraft pulp mills is of biological origin, and, thus, the basic problem here is the same as the problem outlined in Paper VI and above; captured and permanently stored CO\(_2\) else released to the atmosphere is equally valuable for the earth’s radiative balance, independent of the origin of the CO\(_2\), but there seems to be no way to receive emission credits for the captured and permanently stored biotic CO\(_2\) within the present accounting framework. This potentially efficient carbon capture method is thereby, in reality, hindered from competing with other carbon capture methods that could be utilised in the efforts to mitigate climate change.
5.6 Different perspectives with regard to biotic CCS and oxygen efficiency

The importance of the possibility to assign emission credits for biotic CCS and the significance of using oxy-fuel combustion efficiently depend on the perspective. For a decision-maker that is part of the shaping of the international accounting framework, the relevance of the ability to assign emission credits for biotic CCS may be a part of making the overall climate change strategies more effective. The efficient use of oxy-fuel combustion together with emission sources that emit biotic CO₂, could, in this perspective, also be an argument for why such possibilities to receive emission credits for biotic CCS should exist. For a national decision-maker such as a politician, the relevance of biotic CCS as an activity eligible for emission credits could be high as a means to reach the climate change mitigation targets at the lowest possible cost while still being acceptable for the country. The relevance of efficient applications for oxy-fuel combustion might in this case be to widen the horizon for where and how possible climate change mitigation measures could be implemented. However, the oxygen efficiency in itself cannot be used as a tool to find the most efficient ways to mitigate climate change, as it is restricted to a single carbon capture method. In this sense, the survey to find the most efficient use of oxy-fuel combustion for carbon capture purposes is no more system-oriented than an examination of the most efficient way to capture carbon from a given type of emission source. Both these approaches are relatively far from asking how climate change should be mitigated in the most efficient way.

A power producer, a cement manufacturer, and a pulp producer ought to have a perspective that is much more related to their businesses and not to the mitigation of climate change as such. For a power producer, climate change mitigation measures with regard to power production are attractive if they can be motivated in terms of profitability. Thus, the possibility to receive emission credits for biotic CCS might be interesting if biofuelled power production is in the picture and if the biotic CCS could be carried out profitably. However, as the share of biofuelled power production currently is extremely low, the question probably does not receive any attention at all. All the more imminent questions and problems related to cost-efficient ways to meet upcoming demands to abate GHG emissions from power production have to be worked out initially, and biotic CCS is currently a very far-fetched option for the power industry. Contrary to this, efficient use of oxy-fuel combustion might be interesting for the power producer, but only to indicate when it is an attractive capture method for different power processes.

For a cement manufacturer, the possibility to receive emission credits for biotic CCS is not interesting, with one possible exception and that is if the fuel used in the cement production is derived from biomass. If the biotic CO₂ may be captured and permanently stored at a cost that makes it competitive in comparison with the price for tradable emission quotas, the possibility to receive emission credits for biotic CCS might render some interest from the pulp producer. The efficient use of oxy-fuel combustion in their respective processes could similarly be an appealing idea for both these process industries, provided that it can be motivated by profitability. Still, the possibility to receive emission credits for biotic CCS must come first for the pulp producer, considering that the whole business idea otherwise would fail. However, as CCS for the power producer, the cement manufacturer, and the pulp producer is far from their respective core businesses, their attention will probably be relatively weak as long as there are no strong business related motives for becoming more interested.
6 Concluding remarks

While the conclusions in this thesis may be found in the previous text and in the Papers, a summary is also given below. In addition to this, some remarks that neither may be found in the text, nor in the Papers, are added to accompany the conclusions.

Paper I describes the empirical findings on why some energy-related co-operations between industries and district heating companies are carried out and others are not. Favourable techno-economic circumstances are the reason why co-operations are carried out at all, but the main conclusion in Paper I is that these conditions are not enough for the co-operations to be realised. A common feature found in the successful co-operations studied is the existence of individuals on both sides of the co-operation with the true aspiration to carry out the co-operation. These individuals commonly share a view that the co-operation not only is good for their respective organisations, but also for matters beyond this, such as the community and the environment. Decision-makers who want to use energy-related co-operations such as waste heat utilisation as a means to abate GHG emissions should, therefore, consider that economic measures to promote co-operations might not be enough for the co-operations to be carried out. There are a number of obstacles pointed out in Paper I and chapter 3, which have to be overcome before co-operations of the kinds described in this thesis may be initiated and carried through; several of these are not techno-economic obstacles.

The main conclusion from Paper II is that there are no all-applicable methods for emissions accounting for use and supply of electricity. Some kind of marginal approach is still considered to be more feasible for reflecting changes in the electrical grid than the other presented approaches to emissions accounting. There are, nevertheless, so many question linked to rebound, price flexibility, bottlenecks, changed market conditions, unexpected events, market power, et cetera, that no method or model will be able to give a correct prediction of changes in overall CO2 emissions resulting from a given action.

The aim of Paper III is to demonstrate how much estimated direct and indirect CO2 emissions resulting from different energy projects differ depending on the choice of method for emissions accounting. The results are that the estimates varied with several hundred percent in some cases, just depending on the choice of method for emissions accounting. The methods all apply some kind of marginal approach to emissions accounting and none of them is totally unrealistic in the sense that it would automatically be questioned if applied and argued for in a scientific paper or in an investigation made for a government. Thus, these results illustrate the importance of not choosing a method and believe in it as the truth when making decisions intended to mitigate climate change. Instead, various methods, that all have arguments for and against them, ought to be used as tools in the decision making process. Even so, the risk with using emissions accounting methods is that it is the quantified results that are remembered and not the list of assumptions and considerations.

Almost no quantifications are given in chapter 4 that discusses issues related to Papers II, III and IV. The reason for this is that quantifications of, for example, the price flexibility effect or the rebound effect, might be interpreted as: ‘the rebound is normally 20 %, or the price flexibility for 100 MW added power could, typically, lead to a 45 MW reduction in marginal power’. Quantifications would, in this sense, generate problems similar to the problem I try to avoid, as examples of the price flexibility, given a number of assumptions and under certain circumstances, should not be used for generalisation purposes. To
generalise estimates of the rebound effect or the price flexibility effect would merely be to create just another all-applicable method for emissions accounting, which is exactly what I argue against. What kind of conclusions may then be drawn from the discussions about rebound and price flexibility given in chapter 4? If these effects are real and thus cannot safely be ignored, which most empirical findings indicate, this knowledge ought to affect decisions intended to mitigate climate change. The believers in a strong rebound effect usually do not believe in measures that promote efficiency improvements as a way of mitigating climate change, at least not if they are not accompanied by some constraints, such as green taxes and or physical limits. Even if the real rebound is relatively small the mere knowledge should highlight the risk of relying too much on efficiency improvements as a single way to mitigate climate change. A corresponding situation might be described when the less debated price flexibility cannot be safely ignored. Given that the price flexibility could be significant, it might not be a good idea to make a carbon-lean power production technology competitive through subsidies without some constraints of the kinds described above. Subsidies not accompanied by constraints will, because of the price flexibility, not take advantage of the whole CO\textsubscript{2} abatement potential for the carbon-lean technology. There may, however, be other benefits with promoted energy efficiency and subsidised carbon-lean power production, for example, economic growth, the spreading of knowledge and awareness, technology spin-off effects, et cetera.

As energy certainly may be a constraint for development in many possible host countries for CDM projects, the economic issues discussed in chapter 4 are even more relevant here than for mature industrialised economies; this is the main topic in Paper IV. The parallel to the two historical examples with the Watt steam engine and the Bessemer process is obvious, as these examples of what certainly was backfire emerged in a context with a large potential for general economic growth. Thus, if, as suggested above, the addition of subsidised carbon-lean power without any accompanying constraints is a questionable idea for mitigating climate change in mature industrialised economies, the idea is even more questionable in potential high-growth economies, which include many possible host countries for CDM projects. Furthermore, if the real emission reductions from the CDM project will be less than the estimated, they will not be captured at a later stage in the GHG accounting. Nevertheless, as both the economic growth in developing countries and the mitigation of climate change are desirable outcomes from different measures, these issues ought to be considered in the accounting framework.

Power production is usually the main focus when climate change mitigation measures are discussed, and carbon capture and permanent storage is no exception from this. To use oxy-fuel combustion for carbon capture together with power processes is a frequently discussed option for carbon capture, but two other applications for this carbon capture technology are presented in Paper V. The aim is to show that oxy-fuel combustion may be far more efficiently utilised together with cement kilns or lime kilns than in power processes. The basic idea is that the energy penalty, and thus the cost, for producing oxygen is about the same no matter where it is produced, and if more CO\textsubscript{2} otherwise released to the atmosphere could be captured in one application than in another, it is more efficient. No comparisons with other carbon capture methods or measures to mitigate climate change are carried out, but as long as oxy-fuel combustion is discussed as a realistic alternative for CCS together with power processes, these options ought to be discussed as well. It being irrelevant which particular CO\textsubscript{2} emissions are kept from reaching the atmosphere, it is sensible to start where the CCS may be accomplished in the most efficient way.
An issue that brings Paper V and Paper VI together is the discussion about the equality of avoiding the release of CO\textsubscript{2} through capture and permanent storage no matter where it is executed. The difference is that while the discussion in Paper V is focused on a specific capture methodology, the discussion in Paper VI is concentrated on the difference in possibilities to account for the CCS as a measure to mitigate climate change, solely depending on the origin of the CO\textsubscript{2}. There seem to be no possibilities to gain anything from biotic CCS within the accounting framework for the Kyoto Protocol as it is today, and, consequently, it cannot compete on a level playing field with CCS from fossil sources. Several examples of when biotic CCS could indeed be competitive are presented in Paper VI; we therefore argue that it would be unwise to exclude GHG abatement by biotic CCS from the possibility to compete with other options for mitigating climate change. In addition, a possible approach for how to solve this is presented in Paper VI.

Paper VI is focused on biotic CCS as one way of preventing CO\textsubscript{2} from reaching the atmosphere. There are many other possible ways to prevent CO\textsubscript{2} from biomass from reaching the atmosphere, for example, permanent storage of cropland residues in deep oceans, long-lasting storage of charcoal as soil fertilizers, or the use of long lasting wood-derived construction materials. In some cases, there are suggestions for how to include these methods within a future reporting and accounting framework, see Paper VI and section 5.4, but what makes biotic CCS special is that all stages in the process from capture to permanent storage are in principle identical to GHG abatement by fossil CCS. To let biotic CCS compete with fossil CCS should consequently not be a very controversial issue.

The overall aim for the research leading to this thesis was presented as “to suggest and assess possibilities for the mitigation of climate change and to put forward tools for how to solve some of the encountered obstacles linked to these possibilities”. Added to this was the point of view that the mitigation of climate change should be performed in the most efficient way, in terms of most climate change mitigation per money spent. Specifically, how has this aim been reflected in the thesis?

Before this is answered, the system perspective ought to be depicted. The most efficient way to mitigate climate change is a goal that, when expressed this way, refers to an overall perspective and thus it has to be divided into smaller more manageable parts. It may be to find out how to mitigate climate change efficiently within the LULUCF sector, in the industrial sector, in the residential sector, in the transport sector, etc., and all these sectors may be divided or summarised in regional, national, international, or global goals as well. For some types of ideas, such as technical innovations within a specific sector, creativity may not suffer at all from a rather restricted view, while other ideas, like the thoughts needed for the creation of international guidelines for how to abate GHG emissions, only will be useful when a broad view is applied. A broader perspective is, nevertheless, always necessary to evaluate different suggestions, smaller or larger, for how to deal with the climate change problem.

The energy-related co-operations and the oxy-fuel combustion in combination with certain industrial processes discussed in Paper I and Paper V, respectively, are examples of GHG abatement measures of a rather technical nature. The main objective is not in any of the cases to try to compare these measures as GHG abatement measures with a universal perspective. Still, the reason these options are presented at all is that they presumably may be efficient and significant technical options in the struggle against climate change, even with a global perspective. For oxy-fuel combustion, the comparison is only with other possible applications of this specific carbon capture method, and for the energy-related co-operations,
the focus is not at all on a comparison between them and other mitigation measures, but rather
on the barriers against potential implementation of co-operations. So, even if both these
options may be efficient ways to mitigate climate change, the extent to which they can assist
in the efforts to mitigate climate change has not been assessed. (Given the difficulties in
executing a fair assessment presented in other parts of this thesis, I also believe it is difficult
to make such an assessment.)

The discussions about emissions accounting, in Papers II and III, and about an equal
opportunity for biomass in greenhouse gas accounting of CCS, in Paper VI, are more wide-
ranging discussions. When decisions about different options for climate change mitigation are
to be taken, it is important to get a picture of the likely outcome that is as comprehensive as
possible. To use over-simplified methods that give erroneous predictions of the outcome is
counter-productive and this is why the evaluation of different methods ought to be construc-
tive, even when it does not give a simple answer concerning which method is the best one to
use. The use of a pragmatic, experience-based method utilising information from various
kinds of sources, including models, of the kind suggested in section 4.9, is probably a much
more adequate approach for finding efficient ways of how to tackle the GHG problem than
the use of an over-simplified model.

The suggestion that biotic CCS should be allowed to compete on a level playing field
with fossil CCS may hardly be seen as anything else than an approach to finding more
efficient possibilities for mitigating climate change with any perspective, as the two methods
are in principle identical. In conclusion, all the main topics in this thesis reflect the overall
aim, but in different ways.

In section 2.2, I presented my belief that the systems approach most importantly will
widen the horizon of the observer. While doing the research that is the basis for this thesis, I
have certainly changed my mind and found new perspectives a number of times. Thus, the
work has widened my horizon considerably and, as the worldwide work to find possibilities
for how to mitigate climate change has just started, the work has been extremely challenging
too. If this thesis has served the purpose of widening the horizon of the reader is up to the
reader to decide, but I hope it has, at least to some extent.
7 Abbreviations

CCS  Carbon dioxide capture and storage  
CDM  Clean development mechanism  
GHG  Greenhouse gas  
JI   Joint implementation  
KP   Kyoto Protocol  
LCA  Life cycle assessment  
LULUCF  Land use, land use change and forestry  
MCM  Marginal coal method  
MNTM  Marginal new technology method  
PFM  Price flexibility method  
RMU  Removal unit
8 References


9 Acknowledgements

The environment normally has a profound impact on human beings and I’m no different in this sense. The years at Programme Energy Systems and EP have really changed my perspective in a - from my part - not so expected direction and since it has broadened my view, I am really grateful to all the people that have been part of that process.

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