1 Introduction

This thesis studies the long-term development of steel companies faced with CO\textsubscript{2} emission reduction policies. This introductory chapter briefly discusses the Kyoto GHG reduction targets for 2010 and the required reductions thereafter, and the problems associated with the transition to lower emissions. It presents the steel industry as an excellent case to study the dynamics of long-term transitions to new processes with lower emissions. After a description of the research objective, it concludes with a content overview of the thesis.

1.1 GHG-emission reductions

In the 1997 Kyoto protocol 165 participating countries agreed on GHG reductions of 6-8\% in 2010, compared with the 1990/1995 reference years. The subsequent negotiations have eventually resulted in a weakened implementation of the agreement, with lower actual emissions reductions.

The measures required to achieve the Kyoto reductions have a relatively minor impact on the technologies applied in the industry as well as in other sectors. In the period 2000-2010, very few major technological changes will contribute to the emissions reductions. Most reductions will be realised by measures such as good housekeeping, modifications of existing processes, increased cogeneration, isolation of buildings, and some increase of renewables. Apart from the case of the renewables, the emission reduction potential of these measures is relatively limited.

Box 1.1 Emission reduction targets of the Kyoto protocol

Growing concern on the possible threats of global warming induced the organisation of several so-called Conferences of the parties (COP) The third COP took place in Kyoto, Japan, in spring 1997. The 165 participating countries agreed on a treaty (December 1997) on GHG emission reductions by 6-8\% in 2008-2012, compared to the 1990/1995 reference years. The EU-countries agree to an 8\% emission reduction compared to 1990 (CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O) or 1995 (PFC’s, HFC’s, SF\textsubscript{6}). The measures required to achieve these relatively moderate reduction targets will have considerable costs.

Therefore, it is not really a surprise that during the following COPs, both the distribution of the reduction burden and the allowed measures were the subject of debates. The COP-6 in The Hague required a follow-up to result in an agreement, but without the world’s largest emitter, the United States. The 2001 Marakech COP-7 agreement, on the juridical implementation, also had a narrow escape.

The current reductions agreed on have been a source of heated debates. Still, the reductions required to reduce the risks of climate change to manageable levels are much larger. The economic growth expectations of industrialised and developing countries alike require still larger reductions by unit of GDP. Costs are likely to be more than proportional to the reductions. For these reasons, it is of the greatest importance to utilise each cost-effective measure. Both identification of cost-effective measures and effective implementation are imperative.

The reductions before 2010 are likely to be only a minor start. A sufficient reduction of the climate change requires much higher emission reductions. In the long term, global emissions should be substantially below the 1990 emissions in order to stabilize GHG concentrations at acceptable levels [25]. Combined with a both likely and desirable gradual rise of the average global welfare level, specific reductions per unit of GDP should be even higher.
Therefore, the much larger reductions necessary after 2010 will require quite different measures than those for meeting the Kyoto targets. Studies such as the Matter-project (box 1.2) offer insight in the technologies required to achieve these large reductions. The Matter-project uses the Markal model to gain insight into the mix of technologies and options to achieve a 2050 target at lowest costs. The results demonstrate the feasibility of very strict reduction targets, but also point at the necessity of major technology shifts in various sectors, large-scale application of renewable energy sources, and CO₂ removal and storage.

The current policies to reduce GHG-emissions, at least in the Netherlands, are mainly concerned with achieving the Kyoto target. Most measures resulting from these policies are relatively minor modifications to current processes, end-user savings such as building isolation, some renewable capacity and cogeneration capacity. The reductions required after 2010 in many cases involve fundamentally different measures. These often do not build further on the measures taken before 2010. Therefore, the latter offer only a small contribution to a better starting position for more profound reductions.

Box 1.2: Determination of the optimal low-emission society
The Matter project aimed at the determination of the optimal, cost-effective constitution of the West European energy and materials system. In order to determine the cost-effective energy and materials system, Matter applied the linear programming system Markal.

The integrated optimisation methodology of Markal offers important insights in the cost-effective mix of options to achieve a certain level of emissions. Markal is a linear programming model that searches for the lowest discounted costs for which the model can meet an exogenously defined level of goods and services. In one single optimisation round, Markal includes the whole period of 2000 to 2050 and some 40 additional years to prevent undesired horizon boundary effects. In Markal carbon taxes provide CO₂ emissions with an economic relevance, resulting in emission reductions. The linear optimisation of Markal and its comprehensive set of data result in the integrated optimisation of the major part of the economic system. Within the model boundaries, there are no further improvement possibilities left.

The Matter project has resulted in the inclusion of an important part of the materials system in the Markal optimisation. The collected data are translated in process definitions that constitute the input of Markal. The participants of Matter (and the subjects they cover) are ECN (building and infrastructure, inorganic materials), NWS, University of Utrecht (natural and synthetic organic materials, packaging), IVEM, University of Groningen, (transport, basic metal industry), and finally AV, Free University of Amsterdam (barriers for technology introduction). ECN also is the co-ordinator of the project. The Matter project has resulted in dissertations [6, 23,36] and several reports [5, 9, 35, 22, 21,38].

1.2 The 2010-2050 transition
Achieving the 2050 emission reduction target is a global, long-term interest. However, individual companies and households are the ones to decide on the processes and goods they purchase and use. Most of their decisions are based on individual short-term costs and benefits. In the case of emission reductions, the costs are short-term and individual, the benefits long-term and collective. In order for a transition to take place, the long-term collective interest requires a translation in short-term, individual incentives. There are very direct and strong incentives such as prohibitions and directives. However, economists generally prefer the translation of long-term benefits in a short-term price incentive. This may happen by taxes on emissions, or by a system of tradeable emission rights. The most
suitable institutions for providing these incentives are national or supranational governments.

With the proper incentives, companies and households will seek for ways to reduce their emissions. According to economic theories, market forces will induce the (near) optimal allocation of resources for achieving the long-term target. The sum of the individual decisions will add up to the long-term target, against the lowest possible costs. The height of the incentives has to reflect the stage of the transition path. The incentives in the final stages of the transitions have to be high, in terms of costs per unit of emission, in order to bring about the desired effect. Yet, as the emissions have already decreased, these high incentives are not likely to present an inbearable burden for the economy. But in the early stages of the transition, such high incentives would present a huge burden, as the actors have no proper short-term possibilities to respond to these incentives. The construction of new production capacity, the realisation of facilitating infrastructure such as CO\textsubscript{2} storage capacity, and the development of technologies require a lot of time. A well-designed transition path with regard to the height of the incentives will reflect these quite different circumstances in the early and late stages of the transition. The main problem here is that sectors and even individual companies may may go through this transition at different speeds.

Companies may take decisions at the start of the transition that turn out to be very unfavourable in the longer term. This may be due to the fact that decision makers often only take a limited foresight period into account, while the influence of their decisions extends to a much longer period. Generally, companies will prefer improvements within the existing technological framework to a shift to entirely new technologies. If the final emission targets require such a shift, these initial improvements may turn out to be counterproductive and may cause unnecessary costs.

In addition, companies do not start from scratch. They enter the transition from a certain starting position. This inheritance of the past influences their possibilities and the costs of the various possibilities. As such, the starting position may have a considerable influence on the course of the transition process. This also implies that decisions taken before 2010 may have unexpected but considerable consequences. Measures taken to meet the Kyoto targets, might turn out to be disadvantageous after 2010.

A common name for this influence of the past on the future is path-dependency (see box 1.3). Path-dependency is an important factor in transition processes. Relatively minor differences between individual companies may profoundly influence their transition course. Especially in strongly competitive markets, companies may considerably suffer or benefit from a starting situation that is essentially coincidental. A company may run the risk of bankruptcy mainly due to an apparently unfavourable starting situation.

In addition, path-dependency could result in a prolonged transition period, with both higher costs and higher overall emissions. Companies may even manoeuvre themselves in locked-in situations. This means that their situation is not optimal in the long term, but within their foresight period there is no economically viable way to escape this situation. Locked-in situations are always unfavourable for the company concerned. In addition, the emissions may be higher than in the economically most attractive situation.

Generally, the consequences of path-dependency will be beneficial to neither the company, nor the realisation of the emission target. It is very difficult to predict a priori how path-dependency will interfere with desired developments. While it is often relatively easy to pinpoint past decisions that were to have great influence on the course of history
In addition, there are other possibilities to reduce steel related CO\textsubscript{2} emissions, such as decreasing the steel consumption by substitution of steel by other materials, or by increasing the efficiency of steel application. However, while steel companies may experience the consequences of such developments by a decrease in demand, these are not options available to the steel producers themselves.

Currently, scrap availability is insufficient to meet the still growing demand for steel, and the global recycling rate is near the maximum. In the future the demand for steel is likely to grow at a slower rate, and may even stabilise in the long term. Then, the insufficient availability of good quality scrap, required for prime quality steel, will become the main constraint for attaining a much higher recycling rate. Therefore, external constraints will often prevent a steel company from reducing its emissions by increasing its scrap use. Primary production will always be required to meet the demand for qualitatively good steel.

**1.3 Iron and steel companies in transition**

The Iron and Steel industry is a major contributor to anthropogenic CO\textsubscript{2} emissions, accounting for about 5% of world emissions. Especially the primary steel production has very high specific emissions, both measured against the physical production and the added value of the product. Conventional production of one tonne of primary steel causes more than two tonnes of CO\textsubscript{2} emissions. It will be clear that CO\textsubscript{2} emission policies will have profound effects on steel companies. They will make considerable effort to reduce their emissions.

An individual primary steel company confronted with CO\textsubscript{2} policies has roughly two ways\textsuperscript{1} to reduce its emissions. Increase of scrap use is an effective and cheap way of reducing the emissions. However, the possibilities for a shift to more scrap are limited\textsuperscript{2}.

The other way, which is always open for steel producers, is to decrease the specific emissions of primary steel production. Options that result in lower emissions of primary production do so by a change of the carbon content of energy carriers, a higher process energy efficiency, or the removal and storage of the produced CO\textsubscript{2}. Only the latter is subject to external constraints. In order to apply CO\textsubscript{2} removal, there has to be sufficient storage capacity for CO\textsubscript{2}.

The processes that result in lower CO\textsubscript{2} emissions generally have higher costs than the existing processes. For each combination of a level of policy incentives, technological possibilities and external constraints, there will be a specific set of processes that present the cost-effective situation. This situation represents a balance between the higher costs of the processes, the avoided costs as a result of the CO\textsubscript{2} emission reductions and the costs of the remaining CO\textsubscript{2} emissions. While it may be easy to identify the cost-effective situation, the path towards it may be more difficult to find.

In addition to its sensitivity to CO\textsubscript{2} reduction policies, the steel industry is relatively prone to path-dependency. Due to the high barriers, both for starting and for closing a steel production plant, it will be the individual companies and at least the individual production sites that have to go through the transition process. The extreme longevity of many installations, the high capital intensity and the extensive possibilities to upgrade existing

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\textsuperscript{2} Currently, scrap availability is insufficient to meet the still growing demand for steel, and the global recycling rate is near the maximum. In the future the demand for steel is likely to grow at a slower rate, and may even stabilise in the long term. Then, the insufficient availability of good quality scrap, required for prime quality steel, will become the main constraint for attaining a much higher recycling rate. Therefore, external constraints will often prevent a steel company from reducing its emissions by increasing its scrap use. Primary production will always be required to meet the demand for qualitatively good steel.
installations against relatively low costs make that the costs of adopting new technologies vary considerably in time. A steel producer, faced with for example CO$_2$ taxes, will prefer to wait with adopting a low emission process until there is a relatively low-cost opportunity.

Box 1.3 Path-dependency

For most people path-dependency will have an associative meaning. Within the context of the current research, its essence is the fact that some features of the present situation and decisions presently taken are the main determinants of the future situation. People make decisions with only limited knowledge of relevant factors, and generally have a very limited foresight period. The influence period of decisions is often much longer than the foresight period. The chain of events following a decision may result in a situation in which the original decision cannot be undone, or only at very high costs.

There are several factors that tend to increase the influence of path-dependency. Examples are standardisation of processes, especially when combined with economies of scale, the often incremental nature of developments, and the combination of long life-times and high investment costs of processes and infrastructure.

Path-dependency due to benefits of standardisation especially exists when the actual convention is less important than the fact that everybody uses the same convention. An example is the screwdriver. The value of a certain screwdriver design increases when there are more of the same design, with the fitting screws. The initial choice of a standard may be made rather arbitrarily. Yet, once established, a standard is very difficult to replace, even if there are technically or otherwise superior alternatives. Examples in which path-dependency due to standardisation plays a role include utensils, computer software and hardware, the qwerty keyboard design, the Systeme International for physical units. Closely related is the effect of economies of scale. Standardisation and economies of scale often reinforce each other’s effect. The wide circulation of a software package results in lower production costs, and more funds for further improvements. As a consequence, its dominant position will become stronger.

If only incremental changes are possible, this will favour the occurrence of path-dependency. The most evident example is biological evolution. In this case, any modification has to fit within the existing building plan, in order to result in a viable creature. In traditional cultures and conservative institutes that tolerate only small changes, this kind of path-dependency also exists. For technology development, companies and most modern societies, this cultural cause of path-dependency is of less importance.

Another possible cause of path-dependency is the combination of long life-times and high investment costs, especially when upgrades of existing equipment are less expensive than the choice of a new technology, as is often the case. This kind of path-dependency may play an important role in capital intensive sectors such as iron and steel, refineries, base-chemistry and power generation, and in traffic infrastructure. It may also be very helpful in explaining apparently illogical elements in the spatial outlay of cities. The main text further explains the role of this factor for the steel industry.

During the transition, the policy incentives to reduce emissions are likely to become stronger. Other circumstances, such as resource prices, the possibilities for CO$_2$ storage and the availability of technologies also change. Therefore, the most attractive available process may vary during the transition. Due to differences in the starting situation and other incidental factors different for each company, the most favourable moments to adopt new technologies differ between individual companies. Steel producers that have a relatively low-cost opportunity in the early stages of the transitions, may take decisions that prove to
be a cost barrier to further emission reductions later. Path-dependency may be an important factor for the choice eventually made in these companies. At the least, it is very likely to play a role in the timing of the entire transition process.

The combination of a strong sensitivity to CO$_2$ policies and path-dependency with the relatively simple underlying mechanisms makes the iron and steel industry excellent material for a case-study on transitions in individual companies. It is possible to speculate on the way in which path-dependency may influence the transition of iron and steel companies. However, it is very difficult to estimate the extent to which it will influence the result and duration of a transition, and to identify the circumstances that favour the occurrence of path-dependency related phenomenons. This thesis determines the role and quantifies the implications of path-dependency for steel companies passing a CO$_2$ policy induced technological transition.

1.4 Research objective and methodology

The main objectives of this thesis are to analyse the potential to reduce CO$_2$ emissions in a specific sector, the iron and steel industry, by a policy-induced transition to new technologies and to determine the role of path-dependency in this transition. The main focus is on the consequences of path-dependency for the costs, outcome and duration of the transition, and on the emissions during and after the transition. Such effects determine whether path-dependency is likely to harm individual companies to such an extent that their survival is at stake, and to which extent path-dependency threatens the realisation of a certain emission reduction potential.

Box 1.4 backgrounds on the research

Understanding the choice for the research objective requires some information on the backgrounds of this thesis. The research has been part of the Matter project. Within the Matter project activities included the collection of data on iron and steel production processes. During the data collection it became clear that there are important discrepancies between the Markal methodology and the dynamics of change in the steel industry. An article [40] and the contacts with Corus played an important role in revealing these discrepancies. The article studied the net present value of a shift to new iron reduction processes at various stages in the life-cycle of the existing primary steel production capacity.

The article, a reflection of the real-world decision making, included many case-specific details as essential ingredients in their evaluation of new processes, while the integrated decision making of Markal included none. Important differences include the applied fore-sight period, system boundaries, the role of transition costs and the perspective of the decision maker. In Markal, path-dependency is virtually absent, while this phenomenon is very important to understand many developments in the steel industry.

As a result of the juxtaposed positions of Markal on the one hand and the article and the perspective of Hoogovens on the other, the idea arose to simulate the developments in steel companies between 2000 and 2050 by a successive application of the case-specific approach derived from the article. In this way it would be possible to achieve insight in the transition dynamics of the iron and steel industry, and the implications of these for technology choices, costs, and emissions.

Meeting the objectives requires a thorough study of the steel industry. Technological possibilities and policy incentives determine the ideal (i.e. cost-effective) level of emissions. The transition dynamics may play a role both for the extent to which a company achieves this level and for the time it requires. Isolation of the influence of transition-
The objective has important consequences for the geographical scope of the research. The study of the transition to a low emissions situation basically limits the scope to situations in which an established steel industry has to reduce its emissions. This means that from the current perspective, especially the West European and to a lesser extent the Japanese steel industries are relevant. In emerging economies, new technologies are likely to enter in greenfield situations, while the US withdrawal from the Kyoto treaty has made it very doubtful that the US will launch substantial GHG emission reduction policies within the next decades. The European scope of the Matter project, the EU data availability and the EU commitment to Kyoto have made the West European steel industry the obvious choice. However, the focus on especially the West European situation does not mean that the results have no implications at all for the steel industry outside Europe.

1. Inventory of the steel production processes and their characteristics available in the near future
2. Determination of the starting point for the transition in West Europe\(^1\), as a representative starting situation for a transition of an established and stationary industrial sector.
3. Analysis of the influence of individual factors on the attractiveness of shifts to various production routes
4. Identification of the most attractive production routes for various circumstances.
5. Development of SimCo, a model for simulation of the long-term development of steel companies as a result of successive optimisation based on shorter foresight periods
6. Integrated simulation of the long-term development of steel companies in 72 scenarios and 15 single technology scenarios for reference
7. Comparative analysis of the 72 SimCo scenarios with the 15 single technology scenarios and the identified influence of individual factors. Determination of the role of path-dependency for costs, emissions and company survival.

Figure 1.1 gives an overview of the logical framework of the research, with the chapters that deal with the various parts. In order to create a reference for the company simulations, the research has included an analysis (at the left in the figure) on the role of separate factors in the shift to new processes. This analysis includes a calculation of the technical and economic potential for CO\(_2\) emission reductions, and the identification of economically attractive production routes. It investigates all kinds of factors that may be important for the choices made in the steel industry. However, as this approach focuses on the influence of single factors, it fails to integrate all factors into a complete picture.

The simulation of the steel company transition, at the centre in the figure, uses the same data as this single factor analysis, but it integrates all factors identified. The results reflect the roles both of the various individual factors and of the dynamics of the transition process. However, the results of the simulation do not always allow to separate the influences of individual factors from each other and from the influence of path-dependency.

For these reasons, “reference companies” are required. Simulation of SimCo with only

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one technology available provides references additional to those of the factor analysis. Comparison of the results among the single-technology scenarios indicates which production route is the preferred one for a particular scenario.

Figure 1.1 Logical framework of the research

It is in identifying the influence of the transition dynamics, that the three approaches are complementary. As the main difference between the approaches is the inclusion of the transition process and path-dependency, differences in the results should mainly originate in the transition dynamics. A comparison may give insight into the effects on costs and emissions of path-dependency.

Box 1.5 gives an overview of the scope of this thesis with subjects, important aspects of these subjects, the timescale and the methodology. The thesis does not pay attention to add-on options on existing processes, which are likely to play only a major role before 2010.

1.5 Thesis overview
The basis of the research has been the collection of data on individual processes, and the configuration of production routes. Chapter 2 presents the results of the data collection, and gives an overview of the characteristics of the processes. The chapter describes the construction of the evaluated production routes out of the individual processes.

Chapter 3 gives insight in the present and near past of the European steel industry. It describes its development after World War two, through the expansion of the 1960s and the crisis of the 1970s and 1980s. It concludes with an analysis on the current typical primary steel company, the basis of the analyses in the next chapters.
Box 1.5 Scope of thesis

Subjects:  
- path dependence in transitions of iron and steel companies  
- primary steel production processes

Aspects:  
- outcome and duration of transition processes  
- realised emission reductions  
- company survival  
- viability of technologies

Timescale:  
- future long-term, (- 2050)  
- extension to 2090 aimed at achieving a stable situation

Area:  
- Areas with stable, stationary or declining steel sectors. Western Europe is the chosen archetype.

Activities:  
- literature study of the steel industry  
- data acquisition and process definition  
- broad analysis of the influence of a wide range of factors on process viability  
- simulation of company developments by successive short-term optimisations

Chapter 4 gives a broad analysis on the various factors that play a role for the attractiveness of options for steel producers. After a rough investigation of the technical and economic potential, it describes the methodology and the results of a spreadsheet model designed for static analysis of the attractiveness of production routes in relation to exogenous circumstances. It explores the attractiveness of production routes in dependence of varying circumstances, with regard to carbon taxes, the emission factor of the power generation sector, the prices of resources and the life-cycles of the existing processes. In addition, it demonstrates the influence of existing plant configuration on the costs of a shift to new production routes. The results of this chapter allow the identification of attractive options and give insight in the influence of varying circumstances thereon.

Chapter 5 presents the SimCo model, designed for simulating the development of individual steel companies by successive investment and production optimisation rounds. The model integrates the various elements presented separately in chapter 4, and includes the path-dependency phenomenon.

Chapter 6 presents the SimCo results for various scenarios. The chapter starts with a presentation of results of scenarios in which only a single new technology is available, to study performance and effects of these processes. The chapter proceeds with scenarios in which the various processes compete with one another. The chapter concludes with a discussion on the validity of the results and possible flaws.

Chapter 7 aims at identifying the role of transition dynamics in the SimCo scenarios. The analysis compares the scenarios with reference situations derived from chapter 4 and with the single-technology scenarios of chapter 6. On basis of this analysis, the chapter presents six selected scenarios in detail. The chapter concludes with a discussion on the implications of the results.

Finally, chapter 8 discusses the overall research results, with an integration of the preceding chapters. The chapter presents an overview of the viability of the various processes, and focuses on the risk of unrealised emission reductions and on the implications for CO₂ reduction policies. Further, it elaborates on possible implications of the results for other economic sectors.