8 Discussion and Conclusions

8.1 Chapter overview
The chapter starts with the main research objective and continues with some other insights, the byproducts of the research. Further, the chapter briefly comments on possible implications of the results for GHG reduction policies, to conclude with implications for other sectors and recommendations for further research.

8.2 Emission reduction potentials and the role of path-dependency
Chapter 1 has introduced the objectives of the research presented in this thesis. The main objectives of this thesis are to analyse the potential to reduce CO2 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 focus lies on the consequences of path-dependency for the costs, outcome and duration of the transition, and the emissions during and after the transition. In this way it may be possible to 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.

Emission reduction potentials
As chapter 4 has demonstrated, the technical reduction potential heavily depends on external circumstances such as the availability of CO2 storage capacity and the emission factor of the power generation sector. The combined factors determine both the maximum reduction potential and the specific technologies that realise this potential. In the absence of CO2 storage capacity, natural gas based production technologies such as Midrex and Circored allow the maximum potential of roughly 30% reduction for high power generation emission factors and 60% for low emission factors. In the presence of CO2 storage capacity, low power generation emission factors allow reductions between 85 and 90% by all included new production routes. At high power generation emission factors, only the two pig iron based new production routes (Corex and CCF) realise reductions of about 80%. Generally, CO2 storage allows specific emissions of primary production that are in the same range as those of scrap based production.

For a certain combination of the emission factor of power generation and the availability of CO2 storage capacity, the level of the carbon tax is the main determinant for the economic reduction potential. The chapter 4 results indicate that at or even below 100 Euro per tonne CO2 taxes most identified technical reduction potentials are also economically achievable.

As the costs of a transition to the low emission situation also determine the economic reduction potential of a particular company, the starting situation of a company is important. Chapter 4 shows that both the production route present before the change and the stage in the life-cycles of the included processes play a role indeed. It is here that the analyses of chapter 4 point at a role of path-dependency, without being able to determine the importance and consequences of its role for the outcome and duration of a transition to a low emission situation.

Occurrence of path-dependency
The results of chapter 6 and 7 offer a clear confirmation that there are circumstances in
which path-dependency has an influence on the outcome and duration of the transition. In many cases, the transition takes much longer than possible, and in a smaller number of cases, the outcome of the transition is an apparent locked-in situation.

The results further indicate that the influence of path-dependency is likely to be larger in the absence of strong options. When the circumstances do not single out a specific option as very attractive, there is a major chance that companies get stuck in a certain situation that is not the most attractive. Yet, there may be no economically viable escape.

A prudent but important observation is that companies that make fast progress at the start are often the ones that do not achieve an optimal configuration in the end. In many cases, the companies that initially reduce their emissions faster, are the ones that later get stuck in a locked-in situation. This indicates that apparent shortcuts often prove deceptive. It implies that a pressure to change in the early stages of a transition may have counterproductive effects in the later stages of the transition.

However, in order to result in a major influence on emissions or costs, the mere occurrence of a path-dependency related phenomenon is not sufficient.

**Emission reductions**
Path-dependency will only have a major effect on emissions if there are important emission differences among the options. An example are the tax-scenarios with CCF and Circored, without the possibility for CO\(_2\) storage. In this case, Circored is the preferred option, but CCF, especially if it has settled before Circored, is very difficult to expel. Further emission reduction by Circored has costs advantages. However, these are often not sufficient to compensate for the cost advantages of CCF combined with the costs of a shift to Circored.

The results show that in these cases there is a considerable chance that not the entire economic reduction potential is utilised. First, some companies do not reach their optimal configuration. Second, many companies will arrive later at the optimal low-emission situation. The former effect has stronger effects on the emissions than the latter, but has a lower incidence. Box 8.2 highlights some examples from the results.

Although the current results show no cases in which the locked-in situation has significantly lower emissions, such a situation is imaginable. A hypothetical example would be the introduction of CCF after Circored in a situation with taxes around 50 Euro per tonne CO\(_2\) and without storage. In this case, CCF would probably not be able to expel the established Circored process, even if it would have lower costs in the long term. However, it is easy to perceive why path-dependency will generally result in higher emissions. The basis for locked-in situations by definition lies in the earlier stages of the transition. In these stages CO\(_2\) reduction policies are likely to be less strict than later on. Therefore, a locked-in situation is likely to results in higher emissions.

Another important observation is that the effect of path-dependency on the emissions is generally much smaller when CO\(_2\) storage is possible. The specific emissions of the various post-transition companies are very close to each other in case of CO\(_2\) removal. In these cases, CO\(_2\) removal is much more important for the emissions than the production technology choice.

**Company survival chances and the consequences for emissions reductions**
A relevant aspect of path-dependency is the survival chance of companies in relation to differences in their starting-position. In some cases, the production costs differences during the transition period are sufficiently large to threaten the survival of individual companies.
The results show that this may especially concern the companies that turn out to have made the better choices in the longer term. If companies not reaching the optimal situation are often the ones that survive the transition period, the average emission reductions could be worse than would appear from the average performance of all companies.

Survival chances also influence the willingness and ability of companies to take long-term consequences into account. A small chance of short-term survival decreases the importance of long-term aspects of decisions. The long-term is not important for a company if it is not likely to survive the next 5 years. Such a situation results in higher effective discount-rates and shorter foresight-periods. If GHG-reduction threatens the survival chances of a company, it is unlikely to make investments that pay-off only after a longer period. Most emission reduction investments are of this kind. Therefore, companies badly affected by GHG-policies are in danger of entering a vicious circle from which they may not escape.

### Box 8.2 Reduction potential utilisation

#### Reduction potential utilisation after transition

In two cases of parallel companies with Circored, the effects of not reaching the optimal final configuration are 275 and 152 Mt over 90 years, or 3.1 and 1.7 Mt CO$_2$ annually per company. Within smaller time-frames, the annual effects would even be larger. Compared with the current Kyoto objectives, these numbers are considerable even on national scales. Compared with the 2000 emissions of 13.8 Mt CO$_2$ per company or with the identified reduction potential of 7.8 Mt the implications become even more clear.

##### Reduction potential utilisation during transition

The delay-effect of path-dependency for CO$_2$ emissions generally is smaller, but it appears more frequently. Assuming an annual production of 6Mt steel products, the effect of the delay in the current results reaches up to 95 Mt CO$_2$ over the 90 simulated years in one case, or 1.1 Mt CO$_2$ annually per company.

In case of large differences in production costs, the survival chances of companies depend on the possibilities to pass on the costs to their customers. A strongly competitive market, the ideal of many economists, does not allow companies to do so. Excess capacity is another factor preventing companies to pass on the costs. Of course companies going bankrupt would reduce the excess capacity, thereby solving the problem.

The principal question remains whether GHG policies should affect the survival chance of individual companies. It is not desirable that the same policies have very different effects on essentially similar companies. The analyses show that companies which only differ with regard to the life-cycle of one process, could have profoundly different survival chances. There is no objective reason why the companies most affected should be the companies that do not survive.

### 8.3 Other insights from the research

The activities dedicated to achieving the main objective have also resulted in various by-products. These include comprehensive insights in the role of various variables for the choices of steel producers, en the chances for the included production routes. Most striking has been the appearance of optimal hybrid configurations.
Optimal hybrid configurations

Somewhat surprising has been the result that optimal hybrid configuration of CCF and Circofer occur in the tax-scenarios with storage. In these scenarios, the NPVs of CCF and Circofer-based routes are very close to each other. However, the hybrid configuration has an evident advantage above the two pure routes. The occurrence of these configuration is not the result of path-dependency. Instead it results from the capability of SimCo to construct a production route from the individual processes. In a way, the occurrence of these optimal hybrids is a confirmation of the validity of the SimCo approach.

Sensitivity of the production routes' performances to several factors

The research has also resulted in a broad overview of the interactions of various factors with both the economic attractiveness and the emissions of the production routes. Electricity emission factors have proven to be the most important for the attributed emissions of production routes, both with and without CO$_2$ removal. Taxes are the most important factor for the economic attractiveness, and via the taxes the electricity emission factors influence the economic attractiveness. This influence is smallest for production routes with well-balanced on site energy flows, such as CCF. The DRI routes, with high net electricity consumptions, strongly benefit from low emission factors, while COREX with its high excess energy production strongly benefits from high emission factors.

Other important factors are the prices of scrap, the efficiency of the post-processing stages, and the presence of a market for energy by-products. The latter is especially important for COREX.

Technology viability

The results of chapters 4 and 6 give considerable insight in the viability of the included production routes and the factors that influence their viability. Table 8.1 gives an overview of the chances for each production route. Many conclusions on the technology viability do not require the extensive transition analysis of this thesis. However, the spontaneous occurrence of hybrid configurations with Circofer as the best solution for iron production in some scenarios is a result not readily identified in other ways. This is in accordance with publications on hybrid plants with COREX and DRI[4].

8.4 Range of the results

Even though the research has aimed primarily at the European situation, many of the results have also implications for the steel industry in other regions. This section briefly discusses the range of some important results.

The characteristics of the included production routes, as identified in the research, apply equally to Europe and to other regions. Therefore, in comparable situations with regard to CO$_2$ emission factors, power generation emissions and GHG policies, a production route will have about the same emission level and economic attractiveness. This means that the identified reduction potentials for European companies are roughly the same for Japanese and USA companies, which apply comparable processes. Due to the greater occurrence of other processes in many emerging economies, here the potentials may be different. Results with regard to technology viability, sensitivity of production routes to various factors, and the occurrence of optimal hybrid configurations will be essentially the same in all regions.

It is especially with regard to the quantitative aspects of the SimCo scenario results that the scope of the results is limited to Europe. The scenarios have been tailored to the
European situation with regard to the starting situation and the stagnating development of demand. This means that the company developments as they occur in the SimCo scenarios are much more likely to occur in Europe and perhaps Japan than in other regions.

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<tr>
<th>Table 8.1 Overview of technology chances</th>
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<td><strong>Blast furnace.</strong> In absence of strong GHG policies, CCF and restrictive legislation on the coke oven, the blast furnace based production will probably remain the most important primary production routes for a long time to come. CCF is the only new process that is capable of displacing the blast furnace without GHG-policies. Moderate GHG policies do not immediately threaten the position of the blast furnace.</td>
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<td><strong>COREX</strong> is a likely successor of the blast furnace when restrictive legislation on coke oven rebuilding proves to big a burden for the blast furnace. Its current implementation in some countries, as a possibility to exploit indigenous non-coking coals for the steel industry confirms this position. However, even moderate GHG policies give a decisive advantage to other processes. Because of the huge throughput, even CO₂ removal cannot help COREX maintain its position. Perhaps, ongoing improvements and learning effects will give COREX a stronger position.</td>
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<td><strong>CCF.</strong> The Cyclone Converter Furnace is a very promising candidate for the main iron reduction process in the future steel industry, if its characteristics prove indeed as favourable as those assumed in this study. However, its developer, CORUS (the former Hoogovens) has halted the further development of CCF, and it does not seem likely that CCF or a similar process will be available in the near future. When available, CCF is a favourite in varying circumstances. Only in case of stringent GHG policies in the absence of CO₂ storage, CCF loses terrain; it disappears or forms hybrid production routes with Circorex. Yet even then its low investment and operation costs almost balance the costs of its emissions. In case of stringent GHG policies with CO₂ storage, CCF frequently appears in hybrids with Circorex.</td>
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<td><strong>Midrex</strong> would seem a likely candidate in case of stringent GHG policies and the absence of CO₂ storage possibilities. However, the same circumstances favour Circorex, which has just the edge over Midrex because of its use of cheaper fine ore and because of the lower investment costs. However, Circorex is much the newer process, and its characteristics may be less favourable than currently seems.</td>
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<td><strong>Circored</strong> is a likely candidate in case of stringent GHG policies and the absence of CO₂ storage possibilities, more favourable than CCF. However, if CCF or other pig iron technologies have already established themselves, Circorex hardly or not succeeds in replacing CCF. Currently, high natural gas prices are an obstruction for wider appliance. If GHG cause a relative price rise of fuels with a low carbon content, due to fuel substitutions, this may slow down the introduction of Circorex.</td>
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<td><strong>Circofer.</strong> In absence of CCF, Circofer is an attractive candidate in case of stringent GHG policies combined with the possibility of CO₂ removal. Another factor favouring Circofer is the availability of sufficient scrap. Circofer’s most striking feature is its very frequent appearance in hybrid configurations with pig iron processes. Probably, the excess energy balance of the combined processes proves advantageous in case of GHG policies.</td>
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In many emerging economies, an established steel industry is likely to have developed within the next 20 years, largely prior to the introduction of strong CO₂ emission reduction policies. This means that their steel companies may enter a transition that is in many ways similar to that of their European counterparts, but with different starting situations and perhaps other developments of steel demand. Probable starting situations may include Corex or DR-based plants.

As long as there are are no CO₂ emission reduction policies in the USA, the SimCo scenarios without taxes may apply. If the USA finally decide to join the rest of the world in the reduction of CO₂ policies, USA companies will enter the transition from a starting situation that may be different from that of their European counterparts. For the USA situation, starting situations with partly DR-based plants may occur.
So, while steel companies in the emerging economies and in the USA may pass through quite different transitions, they will be subject to the same dynamics. Depending on the specific circumstances, there may be an influence of path-dependency and an occurrence of locked-in situations which is comparable to that in the European steel companies.

8.5 Implications for other sectors
The path-dependency related phenomena shown for the steel industry are likely to be also present in other sectors. These other sectors may not always allow the model simulations this research describes, but the influence of path-dependency will play a role in all sectors that face decision-making with consequences far beyond the foresight period of the decision maker.

Sectors with long-lived installations and infrastructure, or with strong standardisation, are likely to be prone to the pitfalls of path-dependency. Only a few of these sectors might allow the same kind of simulation as the steel industry, examples including refineries, and large chemical industry complexes. Here, both the process life-cycles and the relations between the processes are likely to be more complex. In most other sectors the causes of path-dependency are much more complicated than in the steel industry, and do not allow a SimCo-like approach at all.

However, it does not necessarily require extensive modelling to prevent the kind of pitfalls that SimCo has shown in the steel sector. The next section discusses some implications for policy makers, which hold for the steel industry as well as for many other sectors.

8.6 Implications for GHG reduction policies
Several aspects of the current results may have important implications for GHG-policies. Especially important is the observation that companies which make fast progress at the start of the transition are often the ones that do not achieve an optimal configuration in the end. The gradual rise of the CO$_2$ tax might well have to do with this.

Companies that make a choice that is the best with the low initial taxes, thereby decrease the gain to be made by a further shift to higher reductions. A tax regime that rises much faster or starts at a much higher level might be the obvious solution. However, this is likely to increase the differences in the extent that the taxes harm individual companies. It is also likely to diminish the public support for GHG-policies. Moreover, a sudden introduction of high CO$_2$ taxes might disrupt societies, especially those in the less developed economies.

Probably, the best solution is an intensive co-operation of companies and government, in which both parties explore future possibilities. The parties should agree about the long-term target and the trajectory towards it. In that case, revenues from CO$_2$ taxes could be made available to companies. These should be available for the investments that lead most directly towards the target. They should favour the best choices that might not have been made without additional funding. In this way, CO$_2$ policies are likely to be more effective in the long term against lower costs.

There is another implication of the results. The current policies aimed at meeting the Kyoto targets might have the same effect as the initial low taxes. Adaptation of the existing technology to meet the Kyoto targets may result in higher barriers for a major technological shift required to meet the long-term reduction targets. In order to prevent this, policy makers should acquire themselves a longer foresight period. If the required technological
shift does not build further on the measures taken to meet the Kyoto targets, policy makers might better leave that sector at rest for the moment. They could better concentrate on sectors in which the measures required to meet the Kyoto target also provide the sector with a better starting position for a further transition. Analyses such as the current, and such as the Matter project, may help with the identification of these sectors and the options available.

Table 8.2 Further research possibilities with SimCo

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<th>Uncertainty</th>
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<td>An essential element largely absent in the current analyses is the effect of uncertainty on the decision-making. The current approach is generally sufficient to describe the behaviour of companies striving to the maximum profit. However, most companies take the uncertainty in the circumstances into account. They explore the probable ranges of various important factors, such as demand, policies and prices of resources and products. In doing so, they not only try to identify the decisions that are likely to bring the maximum profit, but they also try to avoid the decisions that might bring the most unfavourable consequences. The current simulation is confined to the production costs, thereby considerably reducing the role of uncertainty. Inclusion of the demand side would increase the role of uncertainty. Uncertainty generally increases the barriers for new technologies, and therefore, the inclusion of uncertainty in the decision making is unlikely to result in a smaller influence of path-dependency. A possibility for the inclusion of uncertainty in the decision making is the optimisation for a range of circumstances, with additional bounds indicating unacceptable risks. A major obstacle for the inclusion of uncertainty in optimisation models is the increase in calculation times.</td>
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<th>Decision support for companies</th>
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<td>Inclusion of more company details, both in the modelling and in the data, would produce a tool for decision support in the steel industry. A SimCo version tailored to individual companies would help to fathom the implications of various decision possibilities. The current computer capacities and improved solving algorithms would easily allow more detailed models. Moreover, analysis of an individual company would also allow better ex ante elimination of specific options. Essentially, this application of SimCo would increase the overview of decision makers in Iron and Steel companies. They would be capable of a better understanding of the implication of particular decisions.</td>
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<th>Varying policy measures</th>
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<td>Varying policy measures would produce better insights in the effectiveness, costs and locked-in danger of policy measures. Investigation of (combinations of) policy measures will give insight in the best policy approach to the steel industry. In case of emission trade systems, interactions with the rest of the economy would be imperative.</td>
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<th>Interaction with macro-economic models</th>
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<td>Interaction with the rest of the economy would produce more realistic results, as the emission factors, resource and (by-) product prices would be results of the model. In this way such factors would be consistent with the tax assumptions, instead of the result of separate assumptions. An additional advantage is the possibility to model emission trading systems. A possibility for interaction with a macro-economic model, such as Markal, would be subsequent calculation rounds. The results of the steel model would serve as an input for the macro-economic model, and vice-versa.</td>
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<th>Other sectors</th>
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<td>The transition simulation might be useful for a limited number of other sectors. These sector should share some characteristics with the steel industry. Long-lifetimes of capital intensive processes, and a small role for other path-dependency related factors, are important provisions. Possible candidates include the refinery sector, and parts of the bulk chemicals industry.</td>
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8.7 Possibilities for further research

The current research has revealed many insights related to the effects of path-dependency in the steel industry. However, there are several directions to extend the research, both within and outside the steel industry. Some of the possible research is a continuation within
the SimCo model, but there are also important fields of research that do not necessarily require the kind of calculations carried out for the steel industry. The application of SimCo in this research is but one of possible applications. SimCo is fit for much more specific analyses, such as the decision support for individual companies. On the other hand, there are some sectors outside the steel industry for which SimCo could provide promising possibilities. Table 8.2 briefly discusses some further applications of SimCo. Important research extensions include decision making under uncertainty, the inclusion of more company details, the effect of various policy measures, the interaction with macro-economic models, and the simulation of companies in other sectors.

For many sectors, it may not be possible to determine quantitatively to which extent path-dependency is important. Yet, this does not preclude the identification of mechanisms that make a sector prone to path-dependency. In many cases, it will be possible to predict whether path-dependency is likely to have consequences for emission reductions. A broad inventory of path-dependency could help to determine the best trajectory towards a long-term target for many sectors. The results could also play a role in determining which sectors have to contribute most to the Kyoto target, and for which it is better to focus on the long-term emission reductions instead.