

Optimization of a steel plant utilizing converted biomass

Carl-Mikael Wiklund

Doctor of Technology Thesis



Thermal and Flow Engineering Laboratory

Faculty of Science and Engineering

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Preface

This work has been done at the laboratory of Thermal and Flow Engineering at Åbo Akademi University mainly under the SYMBIOSIS research program financed by the Academy of Finland and under the SIMP program of the Finnish and Engineering Competence Cluster (FIMECC oy) financed by Tekes. The author would also like to express his gratitude towards all the industrial partners under and outside SIMP that have taken the time to display their facilities and production processes, such as Bioendev, Boliden Harjavalta, Econova, Kemi Mine, LKAB, Mid Sweden University, Norilsk Nickel, SSAB, Swerea Mefos, Outokumpu and VTT. In addition, the collaboration with Oulu and Aalto Universities is gratefully recognized. Special thanks go to professor Timo Fabritius and associate professor Ko-ichiro Ohno for reviewing this dissertation and for giving good and constructive comments.

Besides the author, there are three persons, without whom this project would not have seen the daylight. My good friend and previous colleague Johan Fagerlund, who helped me earlier during my Master's thesis and showed that academic work can be fun too, especially when you are surrounded by good friends. A big thanks goes to Professor Ron Zevenhoven who was the first one to believe I could undertake PhD studies, even when I did not believe so myself. However, the timing was not right in 2008 and the thought had to mature for a while. Unless Professor Henrik Saxén had called me over the phone a few years later I would not be writing this now. He has supported my work and been a very considerate supervisor and a good friend.

Over the years many people have shared the same office with me, such as Johan, Lee Jeongho from POSCO, Ozer Arnas from West Point and Carl Haikarainen, not to forget Lei Shao, a very good friend of mine who has thought me a lot about the Chinese culture. Colleagues who have helped me with my work and with whom I have had good discussions are, among others, Mikko Helle and Frank Pettersson. Thanks goes also to Mikko's brother Hannu for good discussions and whose work this thesis is partly based on. A good friend of mine, who has from time to time helped me with some mathematical problems is Anders Skjäl. Additionally, the lab would not be the same without the pleasant company of Viveca Sundberg and Alf Hermanson. Furthermore, all good prefaces from PhD-theses written at the old Heat engineering laboratory should have the coffee room mentioned, because it is here where the best discussions are held. Thank you Alice, Evelina, Daniel, Debanga, Hamid, H-P, Inês, Inga, Martin, the other Martin, Markéta, Mitra and many, many others.

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Svensk sammanfattning

Det senaste årtiondets heta ämne, kanske även detta århundrades, är den globala uppvärmningen. Den största orsaken bakom den misstänkta uppvärmningen antas vara utsläppen av koldioxid (CO_2). Även andra gaser, såsom metan, tros påverka uppvärmningen. Deras förmåga att bidra till den s.k. växthuseffekten kan vara mångfaldigt större än hos CO_2 , men kvantiteten av dessa gaser är mycket mindre och därmed är det CO_2 som är av största intresse. Det råder en allmän konsensus att dessa utsläpp bör minskas, men metoderna för detta är en öppen fråga. Faktum är att om vi vill upprätthålla dagens höga levnadsstandard och med beaktande av den globala befolkningstillväxten, så kan vi inte helt och hållet bli av med våra CO_2 -utsläpp, åtminstone inte så länge vi använder oss av fossila bränslen. Användningen av dessa bränslen är oundvikligt, men det vi kan göra är att förnuftigare förbruka våra resurser samt på innovativa sätt använda den nuvarande teknologin ur ett miljöekonomiskt perspektiv. Det räcker dock inte enbart med den teknologiska utvecklingen och innovationer för att minska på utsläppen, utan det krävs också starka politiska beslut som befrämjar den ekologiska utvecklingen.

Den globala stålindustrin är ansvarig för ungefär en femtedel av de årliga industriella CO_2 -utsläppen; därmed är den ett lämpligt objekt att fokusera analysen på. Ett sätt att minska stålindustrins bidrag till den globala uppvärmningen är att ta ett steg tillbaka, nämligen genom att använda biomassa som ett hjälpbränsle och reduceringsmedel i framställningsprocessen av råstål. Detta kräver dock att återplantering av biomassakällan görs för att fånga den frigjorda koldioxiden samt för att undvika erosion. Den verkliga nettoeffekten från biomassa-användningen fås då man tar i beaktande utsläppen från skördande, transport av råvaror samt alla andra processsteg. Förutom användning av biomassa skall hänsyn också tas till en möjlig systemintegration för att utnyttja de existerande resurserna förnuftigare.

Ett antal tekno-ekonomiska undersökningar gällande användning av biomassa inom stålindustrin har utförts. Däremot, enligt författarens bästa kännedom, så finns det inte studier som beaktar de till biomassan relaterade investeringskostnaderna med processintegration som utförs på ett stålverk. I denna doktorsavhandling har användningen av biomassa vid framställning av råstål undersökts med hjälp av matematiska modeller, som utvecklats vid Laboratoriet för värme- och strömningsteknik vid Åbo Akademi. Samarbete har också gjorts med andra enheter, universitet och företag som har tagit del i forskningsprogrammet System Integrated Metals Processing (SIMP) som koordinerats av FIMECC (Finnish Metals and Engineering Competence Cluster). Modellerna som utvecklats beskriver en stålfabrik, där en målfunktion som uttrycker produktionskostnaderna för råstål minimeras genom att optimera råmaterialströmmar samt andra processvariabler inom fabriken. De CO_2 -utsläpp som härstammar från fossila bränslen är belagda med en miljöskatt medan CO_2 -utsläpp från biomassa inte beaktas som någon kostnadspost. Modellen sammanfattar olika enheter vid det fiktiva stålverket. Dessa enheter är masugnen, konvertern, koksverket, kraftvärmeverket, cowprar, syrgasverket och anläggningar för förbehandling av biomassa. En del av enheterna beskrivs med enkla linjära funktioner,

medan andra modeller är mer komplexa. Genom att utnyttja modeller för helhetsstudier av fabriken kan effekten av processintegration analyseras, där råmaterialen samt procesströmmarna utnyttjas möjligast väl under de rådande betingelserna.

Huvudvikten av avhandlingen ligger vid analys av konverteringen och utnyttjningen av biomassa och hur biomassans användning påverkar masugnens drift samt den totala processekonomi. I arbetets två första delar gjordes en övergripande optimering av resurser och tillståndet hos enheterna inom ett stålverk där biomassa används som hjälpreduktionsmedel i masugnarna. Biomassans konversion beskrevs av synnerligen enkla temperaturberoende uttryck. Ett stålverk med två eller tre masugnar studerades och fördelningen av produktion mellan dessa undersöktes och jämfördes med det optimala resultatet för ett stålverk med bara en masugn. Skillnader i drifttillstånd introducerades indirekt genom att anta att masugnarna förses med bläster vid olika temperatur (pga. Olika tillstånd hos cowprarna) och systemet optimerades. Denna analys gav intressanta resultat beträffande optimal biomassa-användning och drifttillstånd för ett större fabrikskomplex.

I de två senare delarna av avhandlingen beaktades processerna för biomassans förbehandling, dvs. tork-, konversions- samt malningsenheterna i större detalj. Den simulerade torkenheten består av en eller flera bandtorkar, som utnyttjar varm rökgas som torkmedium. Vid behov används en del av masugnens toppgas som kompletterande värmekälla. Efter torken kommer konversionsenheten som antingen är en torrefierings- eller en pyrolyseringsenhet. Torrefiering och pyrolysering är former av milkolning där biomassan hettas upp i syrefattig atmosfär. Skillnaden mellan processerna ligger i temperaturen och drifttiden, vilket ger upphov till olika slutprodukter. Produkterna består av tjäror (bio-oljor), gaser samt fast material ("träkol"). Efter malning injekteras träkolet i masugnen där det ersätter injekterat kolpulver och chargerad koks. Ersättningsgraden beror på vilken konversionsprocess som har använts. Bättre ersättningsgrad fås vid långsam pyrolysering, som normalt varar en halv timme eller längre. Gaserna som uppstår antas användas för att driva själva konversionen medan bio-oljorna kan utnyttjas i övriga delar av fabriken vid mån av möjlighet. Malningsenheten är placerad efter konversionsenheten om inte det är fråga om snabb pyrolysering (uppehållstid på några sekunder), i vilket fall är enheterna finns i omvänd ordning. Energikravet för biomassans processering beaktas i objektfunktionen.

Simuleringar visade att produktgaserna härstamande från konversionen inte alltid var tillräckliga för att göra processen självförsörjande sett från ett värme-ekonomiskt perspektiv. Värmekravet uppfylldes då en del av bio-oljorna användes som kompletterande bränsle där en viss förlustmarginal har tagits i beaktande. Torkmodellen visade att torkenheten kunde drivas med avgaserna härstamande från de regenerativa värmeväxlarna, men att kompletterande toppgas behövdes ifall användningen av biomassan blev stor. Tröskelvärdet uppfyllades då massaströmmen biomassa närmade sig 10 t h^{-1} (torrsustans) och fukthalten på det fasta materialet minskades från 50 till 10 vikt-% (våt biomassa). Den inkommande rökgasens temperatur uppskattades vara kring 200°C , vilket

är en försiktig uppskattning. De inkommande gaserna utspäds till 80°C med luft förrän de kommer till torken för att undvika utsläpp av flyktiga organiska komponenter. Under dessa betingelser uppskattades att det skulle räcka till med en 30 m lång bandtork, vilket var hälften av den tillåtna maximala längden i denna studie. Kostnaderna hos bandtorken uppskattades att bestå av en fast andel och av en rörlig del som var beroende av torkens längd. Likaså var för konversionsenheterna de rörliga kostnaderna kapacitetsberoende.

Nuvärdesmetoden visade att det är lönsamt att använda torrefiering enbart då CO₂-skatten är mycket hög och priset på biomassan är under nuvarande prisnivå. Däremot gav simuleringar med pyrolyseringsenheterna mera lovande resultat. Nuvärdesmetoden för långsam pyrolysering gav nära positiva värden under uppskattade rådande omständigheter och kunde mycket väl ge vinst ifall CO₂-skatten ökade. Simulering av processen baserad på snabb pyrolyseringen gav sämre resultat än för långsam pyrolysering och utgör nödvändigtvis inte ett realistiskt alternativ inom nära framtid. Orsakerna till detta är delvis de stora förlusterna av fast material vid konversionen. Däremot ger den snabba pyrolyseringen upphov till högre mängder bio-oljor och av hög kvalitet och därför är nyttan med processen starkt beroende på hur oljorna värderas ekonomiskt. En annan faktor som påverkar resultaten är anläggningarnas investeringskostnader, som i litteraturen varierar med tiotals procent eller mera, beroende på källan.

Sammanfattningsvis har utvecklingen under de senaste åren i Europa och globalt visat att det finns ett ökat intresse inom industrin för användning av biomassa i olika former. Inom nära framtid kommer sannolikt mera och mer noggrann information att finnas till förfogande om kostnader vid konversion av biomassa. Denna studie visar att det föreligger en potential att utnyttja biomassa inom stålindustrin.

Abstract

A hot topic of the past decade, perhaps the topic of the century, is global warming. One of the causes is presumed to be the release of carbon dioxide (CO_2). Also other gases, such as methane, are suspected to contribute. Their global warming potential can be far greater than that of CO_2 , but they are not released to the same extent and thus the CO_2 is of greatest interest. There is a general consensus that the emissions should be reduced, but how this should be done is an open question. If we want to keep our present day commodities and standard of living, we cannot reduce these emissions down to zero, at least not as long as we are using fossil fuels, which are a necessity for the time being. However, we can make better use of our existing resources and the technology at hand. For a greater impact, strong political decisions that promote ecologically sustainable development are also needed.

The worldwide steel industry is responsible for around one fifth of all industrial CO_2 emissions. Hence, it has a significant impact on the environment and thus is a good place to look for alternative solutions. One of these alternatives, without loss of productivity or reduced quality, is to take a step back, namely the use of biomass as a secondary fuel and reductant in the production process of steel. If proper measures are taken, such as replantation in order to avoid erosion, then part of the CO_2 released in the combustion process of biomass is rebound to the new plants. Net CO_2 savings depend on transportation and the efficiency of all other process steps. Emissions can be reduced also by making better use of present resources through process integration.

Although some techno-economic studies of biomass use in the steel industry have been presented, there are not, to the best of the author's knowledge, any studies which consider the investment costs related to biomass pre-treatment (drying and conversion) together with options of process integration of the steel production process to make the entity energy and resource efficient. In this doctoral thesis, the use of biomass as a secondary reductant in the production process of steel has been studied by means of mathematical modeling and optimization, including the effect of investment and operation costs of biomass processing. A model describing a steel plant, developed at the Laboratory of Thermal and Flow Engineering at Åbo Akademi University was used as the basis for the work. Collaboration has also been done with other universities and companies that have taken part in the SIMP (System Integrated Metals Processing) program organized under FIMECC (Finnish Metals and Engineering Competence Cluster). In solving the optimization problems, an economic objective function, the production costs of liquid or rolled steel, is minimized with the raw material streams and process parameters as unknowns under a set of constraints. A penalty fee is imposed on the CO_2 emission derived from fossil fuels. The mathematical model includes sub models of the Blast Furnace (BF), Basic Oxygen Furnace, Coke Plant, Combined Heat and Power Plant, Hot Stoves, Oxygen Plant and the different biomass processing units. Some of these units are expressed by simple linear relations while

others are more complex. By this process integration, a more profound utilization of raw materials and process streams can be realized and thus the net emissions are reduced.

Special emphasis in this thesis is given to the biomass processing units and how the products that derive from them affect the operation of the BF and the total economy of the steel plant. In the first two parts of the thesis, an overall optimization of a plant with biomass as auxiliary reductant in the BF(s) is studied. The conversion of biomass is expressed in a very simplified way through a temperature dependence, and the conversion temperature is included among the unknowns to be optimized. A steel plant with two or three BFs was studied and the optimal distribution of resources to these and the optimal production rate of the furnaces were found by using an evolutionary search method or mathematical programming (MILP). Differences in the states of the furnaces were implicitly introduced by assuming the blast temperature to be different (due to the states of the hot stoves) and the system was optimized, yielding interesting findings about the optimal resource allocation and biomass used in the larger plant.

In the later parts of the work, the biomass pre-treatment units were considered in more detail. The biomass processing units considered are a drying unit and a biomass conversion unit as well as a grinding unit. The simulated drying unit consists of one or more bed dryers that utilize hot stove flue gas as a drying medium. If necessary, BF top gas is used as a complementary heat source. The dryer is followed by a conversion unit, i.e., a torrefaction or a pyrolysis unit, where the biomass is heated under non-oxidizing atmosphere. The difference between these two conversion units lies in the temperature and residence time. Resulting products from the fuel conversion are tars (bio-oils), gases and solids (char). After grinding, the char is injected into the BF through the tuyeres, replacing some of the pulverized coal that otherwise would be used. The product gases are used to provide heat for the conversion process while the bio-oils are used, when possible, in other parts of the plant. The grinding unit is placed after the conversion unit, unless a fast pyrolysis unit (residence time of a few seconds) is simulated, in which case the units are in a reversed order.

Simulations showed that there was not always an adequate amount of product gas produced during the biomass conversion in order for the process to become thermally self-sufficient. Therefore, the heat demand was fulfilled by using part of the bio-oils for this purpose. As for the drying unit, calculations showed that the hot stove flue gases fulfilled the heat requirement as long as the biomass conversion rate was not large. The threshold was reached when the mass flow of biomass was near 10 t h^{-1} (dry basis) and the moisture content of the solids was reduced from 50 to 10 weight-percent (wet biomass). The temperature of the hot stove off gases was set to 200°C , which is a conservative estimate. Before entering the dryer, the gas is assumed to be diluted with air down to 80°C in order to avoid the release of volatile organic carbons during the drying. Under the conditions stated above, an approximately 30 m long dryer would be needed, which is half of the maximum allowable dryer length in this study. The investment costs for the dryer was estimated according to a base cost that was one

third of the total costs and a floating cost that was length dependent. For the conversion units, the investment costs was calculated in a similar fashion but the floating costs were capacity dependent.

The net present value showed that torrefaction is profitable only when the CO₂ tax is very high and the biomass cost is well below present market prices. However, simulation results for slow pyrolysis showed that the net present value is almost positive under estimated current circumstances and becomes profitable if the CO₂ tax would slightly increase. Fast pyrolysis did not give as good results as slow pyrolysis and may not be a realistic investment in near future. A reason for this is the low solid yield that results from the conversion. On the other hand, the quantity and quality of bio-oils deriving from fast pyrolysis are higher than from slow pyrolysis and thus the way in which the bio-oils are valued has a direct effect on the profitability. Another factor is the unit investment costs, which was found to vary considerably depending on the literature source. As for coke replacement ratio of the biomass char, it was found to strongly depend on the conversion method. The best replacement ratio was achieved with slow pyrolysis, while the lowest ratio was, as expected, obtained for torrefied biomass.

In conclusion, recent developments in and outside Europe show that there is a growing interest in biomass use in its different product forms. This will probably give rise to more industrial activities in biomass conversion and new information about price levels related to biomass processing in near future. This study shows that there is a clear potential of utilizing biomass in the steel industry, but that the concepts may not yet be feasible under the present CO₂ emission penalties.

Objectivities of the thesis

The large CO₂ emissions from the steel industry and the concern for global warming are the main motivations for carrying out the work reported in this thesis. The main objectivities of the thesis, which comprises of four journal publications, is to study options to reduce fossil derived CO₂ emissions in a steel plant by using biomass, still keeping the production costs of steel reasonable. This is done by studying the system computationally, posing the problem as an optimization task. More specific objectives are to find the best strategy for biomass conversion when the process is integrated in a steel plant and to maximize utilization of different product fractions deriving from such conversion.

Contribution of the author and list of publications

The thesis consists of the following four publications, which are found in the same order in the appendices, and are referred to as Part I-IV in the text:

1. Wiklund C-M, Pettersson F, Saxén H, 2012. Optimal resource allocation in integrated steelmaking with biomass as auxiliary reductant in a blast furnace. *ISIJ International*. 52, 35-44.
2. Wiklund C-M, Pettersson F, Saxén H, 2013. Optimization of a steel plant with multiple blast furnaces under biomass injection. *Metallurgical and Materials Transactions B*. 44:2, 447-458.
3. Wiklund C-M, Helle M, Saxén H, 2016. Economic assessment of options for biomass pretreatment and use in the blast furnace. Revised manuscript
4. Wiklund C-M, Helle M, Kohl T, Järvinen M, Saxén H, 2016. Feasibility study of woody-biomass use in a steel plant through process integration. *Journal of Cleaner Production*, Revised manuscript

The author is the main contributor to these publications. He has continued developing a mathematical model of a steel plant developed in earlier research efforts at the Laboratory of Thermal and Flow Engineering at Åbo Akademi University. He has included different variations of the model, such as an evolutionary algorithm and an MILP formulation for optimizing the model, a model of a steel plant with multiple blast furnaces, as well as models of drying and conversion of biomass. The author has also participated in the work of incorporating the fast and slow pyrolysis units in the steel plant model.

List of related contributions

Presentations of other work by the author related to the topic of the thesis are found in:

1. Wiklund C-M, Saxén H, Helle M, 2014. Optimal Resource Allocation in Steel Making Using Torrefied Biomass as Auxiliary Reductant. Springer Proceedings in Physics (ENEFM2013). 155, 33-41.
2. Wiklund C-M, Helle M, Kohl T, Järvinen M, Saxén H. Numerical Study of Biomass Use in a Steel Plant. Submitted to Scanmet V, Luleå, Sweden, June 2016.

List of abbreviations

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CC	Combustion Chamber
CU	Conversion Unit
DE	Differential Evolution
DRI	Direct Reduced Iron
DU	Drying Unit
EA	Evolutionary Algorithms
EAF	Electric Arc Furnace
HHV	Higher Heating Value
hm	Hot Metal
HS	Hot Stoves
ISP	Integrated Steel Plant
LP	Linear Programming
OP	Oxygen Plant
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MSP	Mini Steel Plant
NLP	Non-Linear Programming
PC	Pine Chips
PP	Power Plant
VOC	Volatile Organic Carbon

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1. Background –fossil CO₂-emissions and renewable energy

One of the main motivations behind this thesis is the desire to reduce the environmental impact caused by the steel industry. Given that it takes around 20 GJ to produce one tonne of crude steel cast [1] and that the annual production of steel ranges up to 1.6 Gt (in 2013), with an expected growth rate of 50% by the year 2050 [2], it is evident¹ that this is a huge and energy intense industry. The steel industry relies heavily on fossil fuels (around 12% of global hard coal production is used in steel making and related processes [3]) and for each tonne of crude steel produced, around 1.7 tonne of carbon dioxide (CO₂) is released. Since CO₂ emissions are one of the major components of the greenhouse-gases (GHG), which are believed to cause global warming, a reduction of these would be an attempt to retard the ongoing climate change. Presently 6-7% (2010) of all global CO₂ emissions derive from the steel industry, comprising about a fifth of all industrial CO₂ emissions [4, 5]. Thus a reduction of these emissions in the steel industry could have a significant impact on a global scale.

A combination of two alternatives has been considered in this thesis in order to reduce the CO₂ emissions deriving from fossil fuels, without reducing productivity of steel. The first option is to improve the production process efficiency, i.e., to reduce the raw material consumption. Fuel usage in the main unit of the steel plant, the blast furnace (BF), has already been reduced quite well (heat utilization of a BF is around 85-90% [6]). However, the overall distribution of raw materials and process streams of the entire steel plant is not yet fully optimized. Through such process integration, raw materials can be used to their full extent. The second option, or a complementary option to process integration, is to replace some of the fossil reductants with renewable ones, such as biomass. Basically, the CO₂ emissions from the combusted biomass can be neglected since CO₂ is recaptured when replantation is done. In practice, however, the net CO₂-savings depend on emissions from transportation and processing (fuel upgrading) of the biomass, what fertilizers have been used and the level of deforestation [3, 7]. The investments required by the biomass processing units have also been considered in this study. A good techno-economic assessment of biomass availability for use in the steel industry has been done by Suopajärvi and Fabritius [8], but to the best of the author's knowledge techno-economic studies of biomass use in a steel plant considering also investments costs have not been presented before.

Different types of biomass can be considered for use in the steel industry. In the Nordic countries, for instance, where the forests cover 75% of the total land area in Finland [9] and 58% in Sweden [10], the use of forest residues would be a profound option. These residues could consist of logging residues, stumps and small diameter wood as well as stem wood with quality problems. Suopajärvi and Fabritius

¹ For reference the heating value of wood is approximately 20 MJ kg⁻¹ and thus from an energy point of view it takes roughly one tonne of wood to produce one tonne of crude steel cast. With a wood density of 500 kg m⁻³ (birch) and assuming that the volume of one tree is approximately 2 m³ then 1.6 billion trees would be needed to cover the energy demand. Much more is needed in reality due to losses; here for instance drying and a low yield fuel conversion should be done before use.

[8] estimated that in 2006 the theoretical logging residual potential in Finland was around 16.2 TWh, while in 2020 it would be in the range of 23.7-31.5 TWh during which the installed capacity in Finnish heat and power plants would be around 27 TWh. However, the authors concluded that there would be an excess of forest chips available near the steel plants in Finland.

As such, the biomass is not a very attractive fuel due to its high moisture content, disadvantageous chemical composition (low carbon and high oxygen contents) and low heating value. Through drying, followed by thermal conversion in a non-oxidizing environment, the moisture and oxygen contents can be reduced while the carbon content and heating value are increased. This conversion step is known as either torrefaction or pyrolysis, where the definition depends on what temperature is used. Furthermore, the residence time distinguishes slow- and fast pyrolysis from each other. The products that derive from biomass conversion can be categorized into condensable and non-condensable volatiles as well as solid charcoal. With increasing temperature and residence time, the latter will approach the properties (composition, heating value) of graphite but at the same time its mechanical strength is reduced. The strength is lower than that of graphite, which limits its use as a bed material to small BFs only [7]. It has been suggested that charcoal can be injected, either separately or co-injected with pulverized coal, into the BF through the tuyeres [5, 7, 11, 12]. A reasonable replacement of pulverized coal by charcoal could be around $50\text{-}100 \text{ kg t}_{\text{hm}}^{-1}$. Flame temperature and furnace productivity become critical issues when converted biomass is injected into the BF. A reduction of the former two can be compensated by increased oxygen enrichment of the blast air (cf. Chapter 2) [13, 14]. Alternative uses of charcoal could be to mix it with the iron ore for burden feed or to mix it with metallurgical coal in coke production [5]. For the latter, a ratio of up to 5% has been suggested [8]. Other benefits of charcoal use, besides reduction of fossil derived CO₂ emissions, is the reduced ash-, sulphur- and phosphor contents that follow from fuel replacement. This, in turn, can lead to reduced slag ratios, which have been reported to be 50% less for charcoal operated furnaces compared to those operated by coke and coal [5]. The thermal conversion of biomass is more thoroughly addressed in Chapter 3.

Reported biomass market prices, especially charcoal costs, vary strongly from one study to another. For instance, charcoal costs ranging from $213\text{-}400 \text{ € t}^{-1}$ have been reported [5, 8]. For torrefied pellets, delivered to Europe from North America, the cost has been estimated to be 139 € t^{-1} . In terms of energy this would be 7 € GJ^{-1} , while for regular pellets it would be 7.7 € GJ^{-1} [15]. As for biomass, prices in the range of $8.5\text{-}22 \text{ € MWh}^{-1}$ have been given [16, 17].

2. Introduction to steelmaking

Steel, presently a widely used construction material that is both durable and strong, is one of the most important metals in our modern society. It is a metal alloy with its main component being iron, but which is much stronger than the latter due to its carbon content that generally ranges between 0.15-1.5 weight percent [18]. The roots of ironmaking date far back in our known history. The Egyptians and Sumerians made iron spears already around 4000 BC where the iron was acquired from fallen meteors. Later, around 3000-2000 BC iron was extracted from iron ore both in Mesopotamia and Egypt, but it would take centuries before it replaced bronze [19]. In India, steel was produced in crucibles already in 300 BC; this steel was later used in the production of the infamous Damascus swords. Similar crucibles were used also by the Vikings when they were producing steel for their swords. In their process wrought iron was put together with charcoal, sand and glass into the crucible. The purpose of the latter two ingredients was to bind the slag. The crucible was heated in a smelting furnace up to around 1500°C [20]. Since the melting point for pure iron is 1536°C [21], it is likely that iron in most processes of that time remained as a solid while the slag material melted. By repeatedly forging and reheating the *sponge iron* most of the slag materials could be removed forming *wrought iron* as a final product. First evidence of iron melting, which led to the production of *cast iron*, comes from China from around 1000 AD. This process was made possible due to more efficient furnaces and also because the iron bearing raw materials contained more phosphorous, which together with carbon and iron (ternary system) have lower melting points than corresponding iron-carbon (binary system) composition. The lowest achievable melting point of iron burden (eutectic) is at 1153°C, with a carbon content of 4.26% [21].

The forerunner to the modern BF, where presently over 90% of global iron is produced, is considered to be the Stukofen furnace that was developed in Germany. It had a height of 3-4.5 meters, water driven bellows and the furnace lining consisted of stone and clay. It was followed by the Flussofen in the 14th century, also developed in Germany. From there the next great development took place in 1709 in England, where Abraham Darby was the first to replace charcoal with coke in iron production. He noticed that by using coke instead of charcoal in the BF a higher temperature could be reached and thus also the carbon content in iron increased making it more durable. By his method the production rate increased three fold and at lower cost with increased iron quality compared to production with charcoal [21, 22]. However, it was not until 1856, when Henry Bessemer introduced at the British Association meeting in Cheltenham the so called Bessemer process, when mass production of steel became possible [23]. In the Bessemer process air is blown into a steel converter from below, causing an increase in crude iron melt temperature due to the combustion of impurities. The first to utilize this process in the US was Andrew Carnegie, an eager business man and an innovative steel producer. Partly thanks to his pioneering work the construction industry started using steel more widely in the late 19th century [24].

As mentioned above, most of world's iron is produced using BF technology and only around 8% is produced using alternative methods that are not dependent on coke as their primary reductant [21]. Therefore the main focus is given to the BF route, which is described in section 2.1 and includes units that are essential for the BF operation and steel production. In section 2.2 the alternative methods are briefly discussed.

2.1. From ore to steel - the Blast Furnace route

An overall schematic of a possible BF-operated steel plant layout (used in this study) is shown in **Figure 1**, where some of the units, such as the biomass units, are addressed later on in the text (Chapters 3-4). The following paragraphs deal with the development and function of the most important units in an integrated steel plant.

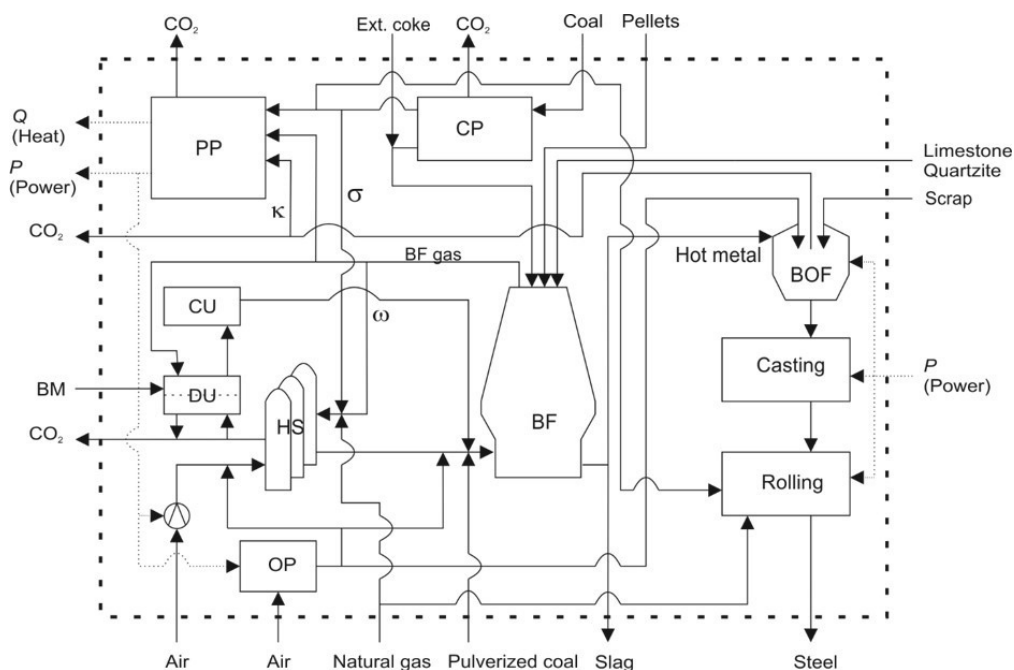


Figure 1 Schematic of the steel plant model. BF – blast furnace, BM – biomass, BOF – basic oxygen furnace, CP – coke plant, CU – conversion unit (grinding unit included), DU – drying unit, OP – oxygen plant, PP – power plant and HS – hot stoves.

2.1.1. Blast Furnace

The BF can be seen as a vertical furnace that is charged from above with its two main components that form the bed material in the furnace: a source of coal that acts both as a reducing agent and a fuel, and an iron ore, from which iron is to be extracted. The former, which is usually coke, consists of coal or a coal blend that has undergone carbonization (coke plant – Figure 1), i.e., a destructive distillation of coal at high temperature and in the absence of air. Coke is the only material that descends down the entire furnace height as a solid. Good coke should be mechanically resistant in order to withstand the harsh conditions in the furnace and to be able to support the weight of the bed. Furthermore, its reactivity should be chosen so that favourable furnace conditions are obtained. By choosing, e.g., less porous and thus less reactive coke the start of endothermic gasification, where CO_2 is reduced, can be shifted to higher temperature regions [6, 21]. Charcoal can be used as an alternative to coke. However, in order to make high quality charcoal the biomass must undergo a similar kind of carbonization process (addressed in Chapter 3), which results in good fuel quality but poorer mechanical strength in comparison to coke [7, 11, 15]. This limits the use of charcoal as a burden material to BFs no larger than 600 m^3 [5]. In comparison, the world's largest coke-operated BF has an inner volume of about 6000 m^3 [25]. In a recent study by Noumi et al. [26] an attempt was made to increase the crushing strength and reduce reactivity of charcoal by applying pressure during thermal conversion of biomass. It was found that the temperature had a greater effect on the CO_2 -reactivity than pressure and that the process resulted in only a slight increase in crushing strength, which nevertheless, was better than that of traditionally produced charcoal.

The second bed component, i.e., iron ore, is quite an abundant material and it is estimated that around 5% of earth's crust consist of iron, mainly in the form of hematite (Fe_2O_3) and magnetite (Fe_3O_4). However, for economic extraction of iron an iron deposit of 55-60% is preferred, where rich ores contain 50-65% of iron and lean ones around 30-50%. The rest of the ore usually comprises of silica and alumina [6, 21]. Two alternatives are commonly used for furnace feed: iron ore in the form of pellets or sinter. Both consist of agglomerated mineral ore fines that can contain flux material, such as lime and magnesia. These flux materials are used to lower the fusion temperature and to decrease the viscosity of the arising slag [6]. Since the sinter is of various lump shapes and the pellets are more homogenous due to their spherical nature, it can be reasoned that the latter results in a more uniform gas distribution in the furnace, which is beneficial for the furnace operation. An approximate schematic of the BF is given in **Figure 2**, where the different parts of the furnace are listed in the left panel and where the volume in the right panel it is divided into different thermodynamic zones.

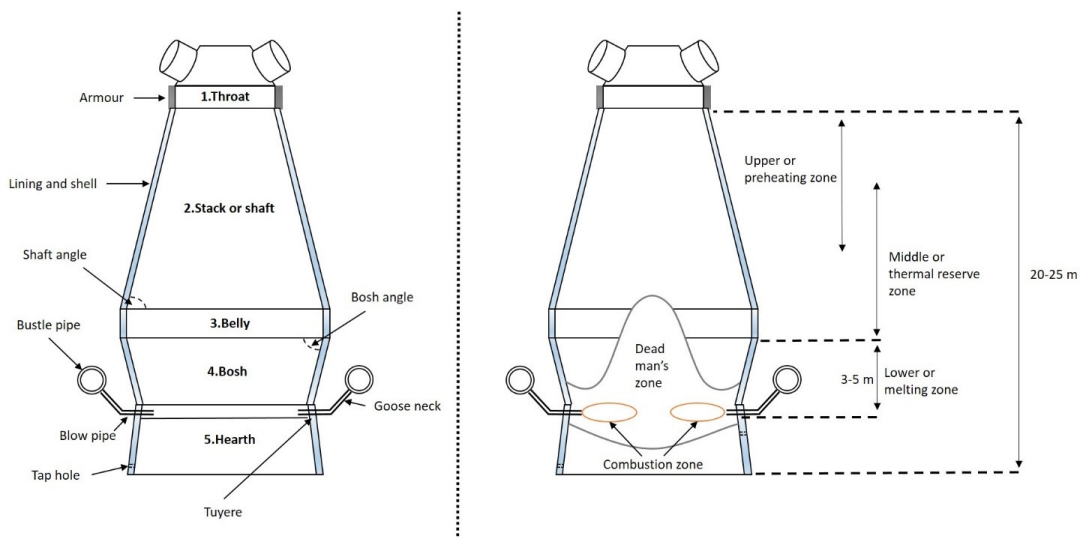


Figure 2 Approximate illustration of the BF. The left panel illustrates the different parts of the BF, while the right panel shows the different thermodynamic zones.

Starting from the top, the bed material is charged in certain sequences (e.g. coke-ore-coke) and in different patterns. For instance, the top of the bed can form a V-shaped slope with more material on the outer periphery of the furnace or alternatively, it can have an M-shaped form. By adjusting the charging sequence and pattern the gas permeability and location of the thermal reserve zone can be controlled. Burden charging was given attention for the first time in 1845 and in 1850 the cup-and-bell charging system was introduced. Later it was followed by the double-bell charging device that was used until 1970-80s. The double-bell charging system consists of a small and a large bell, where the material is charged through the small bell into the large bell after which it is released into the furnace. During charging one of the bells is always closed in order to avoid furnace top gas from escaping. A desired burden distribution is acquired by applying movable armours in the throat of the furnace. Segregation occurs due to different particle sizes and densities, where coke is around 3.5-4 times lighter than iron ore [21]. Fines are unwanted due to the resistance they cause to gas flow and are therefore removed by screening before charging. Modern BFs use a bell-less top and a top gas gauge pressure of 1.5-2 atm. The bell-less top was developed by Paul Wurth in 1972 and consist of a rotating chute operating at different angles. The benefit with it is a superior charging control. A new furnace charging technique has also been recently introduced called SIMETAL and has been developed by Siemens VAI that allows for generating any burden profiled desired.

Followed by the charging at furnace throat comes the shaft, also known as the stack, which extends 3/5 of the total height with expanding diameter downwards [6]. In the beginning of the shaft the **preheating zone** exists, where the temperature of the solids rise to 800°C, while the gas temperature is reduced down to 100-250°C. In the preheating zone moisture and hydrated water is vaporized and the non-calcium carbonates are decomposed. Furthermore, carbon monoxide (CO) may react into CO₂

and carbon through the reverse Boudouard reaction, called the carbon deposit reaction, which is exothermic. The reaction is very slow at temperatures below 400°C, but the reaction rate is increased in the presence of a catalyst such as freshly reduced iron oxide or metallic iron, where the latter is more efficient. Maximum reaction rate is reached at temperatures in the range 500-550°C. At a temperature above 700 °C the CO becomes more stable. For temperatures above 1000°C the highly endothermic Boudouard reaction takes place



With increasing temperatures the oxygen dissociation pressure increases for oxides of interest, i.e., the oxides of silicon, iron, chromium, manganese, titanium, aluminium, magnesium and calcium become more unstable. At the preheating zone a partial or a complete reduction of hematite and magnetite occurs at the surface of the iron ore particle, either by CO or by hydrogen (H₂), where hematite is reduced to magnetite



and magnetite is reduced to wustite



In practice, wustite does not exist in the form of FeO with stoichiometric ratios of Fe and O but has an average formula of FeO_{1.05} or Fe_{0.95}O in the temperature region of 600-1371°C. At temperatures below 570°C wustite is unstable and slow cooling results in spontaneous decomposition



At temperatures of 700-750°C oxygen diffusion becomes more difficult due to recrystallization of iron resulting in reduced permeability of the iron particle and therefore the rate controlling mechanism shifts from phase-boundary- to solid state diffusion [6]. This means that other reduction methods occur inside the particle due to the formation of a dense iron layer (R2-R4). The iron, formed at the surface, diffuses into the particle reacting with both hematite and magnetite



The reduction of inner iron oxides by metallic iron causes pores to form and again makes the particle more permeable and hastens the reduction process. The structure of the partially reduced particle consists of a hematite nucleus that is surrounded by a magnetite and wustite layer. In general the reduction of hematite results in a more porous particle structure compared to reduction of magnetite. The rate of reaction that is both chemical and diffusion controlled is proportional to the partial

pressure of CO or H₂ and can also be accelerated when foreign cations such as soluble impurities of alkali oxides and alkaline earth metals are present. For a mixture of H₂ and vapour the diffusion constant is about 3-5 times greater than for CO. However, Biswas [6] states that the resulting pore size for both hematite and magnetite reduction is larger when reduced with CO than with H₂ and that reduction with hydrogen results in a more dense iron layer. On the other hand, a higher diffusion rate of iron into wustite is obtained from the reduction of hematite in comparison to magnetite, resulting in a more porous product. Biswas [6] further states that a less porous iron layer is apt to form when the reaction rate is high.

The **thermal reserve zone** begins lower down in the shaft after the preheating zone. In this zone the temperature of both solid and gas is 800-1000°C and it occupies in a well-run furnace around 50-60% of the total volume. Two very important reactions that take place in this zone are the indirect reduction of wustite (reduction by CO) and the water-gas shift reaction (R7). Most of the indirect reduction occurs in the thermal reserve zone and it is desired that this zone extends as far as possible.



Below the shaft is the belly, which has the largest diameter in the BF in order to account for the volume expansion of the gases. Here the fusion and contraction of the slag and metal start. Followed by belly comes the bosh that is situated just above the tuyeres and has a decreasing diameter downwards. The **melting zone** is in these regions, approximately 3-5 m above the tuyeres. Here two immiscible phases are formed that consists of carburized iron and FeO-SiO₂-Al₂O₃-MnO primary slag where the latter contains also some lime (CaO). These two phases are formed at temperature above 1200°C and separate further down. In the melting zone an endothermic reaction called direct reduction takes place where wustite is directly reduced by elemental carbon.



Oxygen enriched air, called blast, which contains some moisture and is preheated to a temperature of 1000-1200°C, is injected at a gauge pressure of 1.5-2.5 atm into the furnace through water-cooled nozzles, tuyeres, 0.4-0.6 m below the upper rim of the hearth [6]. In front of each tuyere, a combustion zone forming a cavity in the coke bed, a raceway, is formed, where coke and injected reductants react at high temperatures. The blast air combusts the carbon to CO₂, but this is reduced to CO at the edges of the raceway, resulting in a flame temperature usually above 2000°C [6, 21]. The combustion zones extends approximately 1-2 m into the furnace. Inside and below the raceways is an area called the dead man's zone (see Figure 2) and it is occupied by a closely-packed central column of coke that either floats on top of the liquid iron or stretches all the way down to the furnace floor. Through this column the iron melt and primary slag trickle downwards towards the furnace hearth. As the bosh slag passes the tuyeres it will pick up coke and coal ash, assuming its final form, the hearth slag. The basicity of

slag, often expressed as the ratio $\frac{CaO+MgO}{SiO_2+Al_2O_3}$, should be around 0.9-1.2 so that the slag will remain in liquid form in the temperature range of 1450-1500°C. For free running slag the temperature of the slag should be kept in the range of 1500-1550°C. The final temperature of the molten iron will be in the range of 1350-1450°C [6]. Since the slag is less dense than molten iron, it will float on the latter, but the two liquids are still extracted through the same tap hole(s). Tapping is done by mechanically drilling a hole in the clay from the tap hole and after extraction the hole is resealed with new clay. Further processing of both liquids and gases continue once they exit from the furnace. For the burden material a residence time in the furnace is 6-8 hours, while it for the gas is only a few seconds [6]. Up to 25-40% of the top gas, which usually comprises of 20-25% CO and 20-25% CO₂, is combusted in the hot stoves (HS) in order to heat the incoming blast. The rest of the top gas can be utilized elsewhere in the plant, e.g. for power production. The liquid iron is transported in torpedo cars or ladles to its next processing step in the Basic Oxygen Furnace (BOF) where it is converted into steel. The HS and BOF are presented in the following paragraphs.

Due to the harsh conditions in the furnace the wall material must be chemically resistant to alkali and other vapor attacks including CO, and it should withstand both the high temperatures and mechanical stress caused by the descending bed material and high gas velocities. The BF lining commonly consist of refractory materials made of aluminosilicates and carbon. The purpose of the latter is to act as a good thermal conductor between the inner lining and the water cooling units. The outer shell of the furnace is made of steel. By advancements made in furnace wall construction the campaign life in between relining has increased from 4-6 years in 1980 to 15-20 years at present. As for furnace construction the maximum height of 25 m has been reached and further increase is prohibited by lack in mechanical strength of the coke, which is the supporting bed material. Another limiting factor is the pressure loss of the gas over the bed. Productivity has instead been increased by increasing the furnace diameter up to 13 m and by burden preparation [21]. From a thermodynamic perspective the BF can be looked upon as a counter-current heat exchanger. The theoretical minimum fuel consumption is approximately 250 kg coke and 250 kg of coal per ton hot metal (t_{hm}), which has almost been reached by Hoogovens in the Netherlands where coke rates of 268 kg t_{hm}^{-1} and pulverized coal rates of 233 kg t_{hm}^{-1} have been reported [21]. The historical development of production rates and reduction in fuel consumption are given in **Figure 3**.

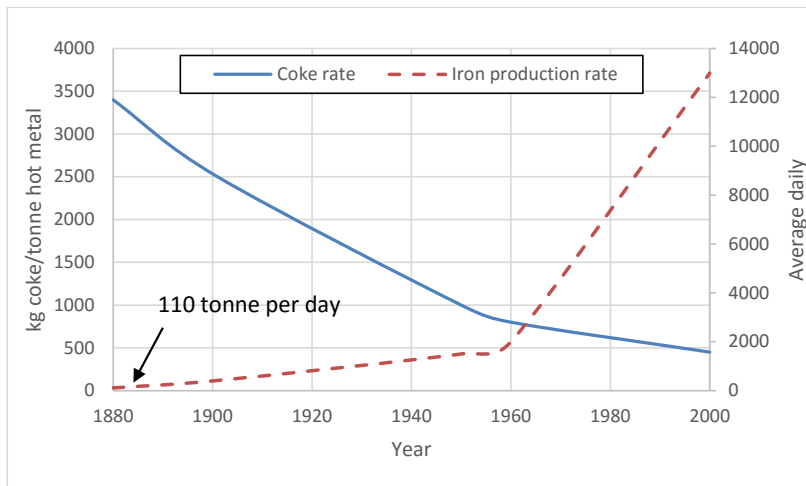


Figure 3 BF coke rate evolution and average daily production [21]

2.1.2. Hot stoves

In 1829 the coal consumption for producing one tonne of iron was reduced from 8 to 5 tonnes by Neilson, whom started pre-heating the blast air. The following advancement was done in 1857 when fire-brick lined stoves were introduced. These regenerative stoves where operated in a cyclic manner and allowed the blast air to be heated to higher temperatures. Today stoves work in a similar manner and are first heated by combusting top gas in them after which blast air is blown in reverse direction for a shorter period. Because of the cyclic nature, and the requirement of a steady blast flow, a minimum of three stoves is needed. Stove height varies from 20-36 m and the diameter is 6-8 m with a brick lining and outer shell of steel [21].

2.1.3. Basic Oxygen Furnace

The first industrial converter was the one presented by Henry Bessemer in 1856. It was a cylindrical vessel that could be turned from horizontal to vertical position into which air was blown through tuyeres connected to a wind box. The oxygen in the air reacted with Si and Mn forming oxides that together with some wustite formed acidic slag, while excess carbon was removed in the form of CO and CO₂. A major shortage of the process was that sulphur and phosphorous could not be removed, which caused fractures or so called hot shortness during forging. This problem was tackled by Mushet in 1864 by adding ferromanganese in the ladle where steel was tapped. By doing so the oxygen content of the steel was reduced and this in turn increased the Mn content that prevented hot shortness caused by high levels of sulphur. The problem with phosphorous was avoided by using iron ore with low phosphorous content. The process is known also as the acid Bessemer process. Use of iron ore with medium or high phosphorous content was made possible by the Thomas- or the basic Bessemer process, introduced in 1879, when fluxing agents in the form of basic oxides such as CaO were blown into the converter together with the air. This allowed phosphorous to be removed in the form of

calcium phosphate. High nitrogen content in steel was still a problem and was resolved when the open hearth furnace, the predecessor to BOF, was introduced. The open hearth furnace introduced in the 1860s was a shallow refractory-lined rectangular tray with a roof on top. Steel scrap, hot metal, lime and iron ore were used as feed material. Heat was provided by combustion of gaseous and liquid fuels in burners positioned at the furnace walls using pre-heated air as oxygen source, which made it possible to reach flame temperatures above 1600°C. A benefit with the process was that almost all steel grades could be reached but a downside was the long processing time of 6-8 hours caused by the slow process kinetics. The LD process, later known as the BOF, was developed in 1952-53 and improved in late 70s and early 80s. In this process pure oxygen is injected from the top in combination with small gas injection from below, known as mixed blowing, into the hot metal resulting in oxidation of carbon and other elements. Benefits with this process is that no external fuels are needed and the processing time is less than 60 minutes. Scrap iron and sometimes iron ore are introduced into the BOF in order to counteract the rapid temperature increase caused by the highly exothermic oxidation reactions. Today the BOF together with the electric arc furnace (EAF –addressed below) cover over 98% of world's steel production. The steel that is produced in these are classed as primary steel making processes followed by secondary steelmaking processes that take place in the ladle after tapping or extraction. These secondary steps compose of degassing, desulphurisation, reheating, deoxidation etc. Similarly a pre-treatment is made in the ladle or torpedo after the BF, where sulphur, silicon and phosphorous contents can be reduced [21]. For further information about the BOF and the pre-treatment processes please refer to [6, 21].

2.1.4. Steel grades, production routes and resource consumption

Up to 90% of all world's steel is classed as plain carbon steels that are categorized as low- (0-0.2%), medium- (0.2-0.6%) and high carbon (0.6-1.5%) steels. The remaining 10% consists of alloy steels with alloying elements ranging to 5% in low-, 5-10% in medium- and above 10% in high alloying steels, where alloys such as nickel, chromium, molybdenum, cobalt are used. The alloy steels are almost always produced in mini steel plants (MSP) to which the EAF – DRI (Direct Reduced Iron) production route belongs. The BF – BOF route on the other hand belongs to the integrated steel plant (ISP) category. Resource wise, for producing one tonne of crude steel the following may be needed (even though the setup varies depending of the availability and price of the raw materials): 1.5 t iron ore, 610 kg coking coal, 60 kg mineral coal, 150 kg lump ore, 200 kg flux, 175 kg scrap and 5 m³ water. Emissions that derive are approximately 28 kg of CO, 2.3 tonne of CO₂ and 455 kg slag but varies naturally depending on the plant in question [21]. The amount of recycled steel used in the world is about 350 Mt annually, which equals roughly to 20-30% of yearly steel production depending on the values used for the comparison [2, 21].

2.2. Alternative production routes

The EAF had its first commercial application in 1899 and they are still used today. Approximately 29% of world's steel is produced through the EAF route, while 70% is produced with the BOF route and the remaining 1% comes from the open hearth furnaces [27]. Heat is provided in the EAF by electric arcing and recycled steel is used as raw material. DRI, or in other words sponge iron, is used as a supplemental raw material since there is an inadequate amount of recycled steel in comparison to present day production capacity. An alternative for the EAF is the Electric Induction Furnace that can be used for producing high-quality steels. The Coreless induction furnace was patented by Ferranti in 1877 with capacities ranging up to 20-25 tonnes. Alternatives to the BF technologies are among others (listed from largest to smallest in respect to global production rates): Midrex, HYL, Rotary kiln processes, fluidized bed processes and rotary hearth processes. A novel process with great potential is the use of composite pellets that consists of a blend made of coal, coke and char fines. Both the Inmetco and Fastmet processes are based on composite pellets [21]. Furthermore, POSCO has invested large sums in research, development and realization of the FINEX technology, which allows direct use of cheap iron ore fines and non-coking coal as feedstock in the iron making process. This eliminates the need for coke and sinter plants and the process is claimed to have, besides reduced production costs, lower emissions from the production process [28, 29].

3. Biomass pre-treatment and conversion

If ironmaking existed already 6000 years ago the pre-treatment of biomass must be far older, probably dating back to the days of inventing fire, since with sticks and stones it is mighty difficult if not impossible to set fire to any biomass of a high moisture content. Therefore, one can assume that drying and some sort of grinding were the first forms of pre-treatment. Drying could be categorized in naturally occurring- and forced drying. In the former the biomass is allowed to dry by itself in nature and the success of it depends on the surrounding conditions, such as air humidity and temperature. This form of drying can be accelerated by sheltering the biomass from rainfall, increase its contact surface exposed to air and easing air exchange so humid air is transported away as much as possible. Methods for this can be for instance debarking, stacking, stacking by overlapping (air gaps between trunks) and chipping. In nature fresh wood has usually a moisture content of 50-60% $\left(\frac{\text{kg H}_2\text{O}}{\text{kg wet biomass}}\right)$ [30], which can decrease down to 20-30% by natural drying if allowed to dry during the summer months [31]. The latter option, forced drying, requires somewhat more understanding of the drying phenomena but in its simplest form can be done by placing wet firewood next to the fireplace, which hastens the drying procedure due to a higher temperature and an increased water absorption ability of air. By doing this in a confined container with a forced air flow, achieved for instance by a fan or by natural draft through a chimney, a basic form of a dryer results. Different types of dryers are briefly discussed in section 3.1.

More advanced wood treatment or fuel improvement technologies have also existed for quite a while. For instances in Middle Eastern Sweden during the Roman Iron Age (240-540 AD) destructive wood distillation of pinewood was done in small funnel-shaped pits in order to procure tars, which were used, e.g., for taring wood parts in ship building [32]. Additionally, the charcoal acquired from the distillation could be used for several purposes, among others in iron making (cf. Chapter 2). The distillation was done by making a funnel shaped pit in the ground, above which wood material was assembled and then covered with peat and soil. Once combusted from the top the wood tars, formed due to decomposition of wood in an environment with low oxygen content, started trickling down the bed and were collected at the bottom. The best pine tar woods consist of old stumps and roots, since these contain high amounts of resinous acids. In the 17th and 18th centuries the Swedish-Finnish pine tar production used resin-soaked stems from young pine trees that had been debarked during a period of 3-4 years, which is known to accelerate lightwood formation of the trees [32].



Figure 4 A debarking iron used for debarking tree trunks. The still very sharp iron was forged by a blacksmith who happens to be the great-grandfather of the author.

A similar kind of process, but for charcoal production and in a more recent time, was described by Bergström [33] in 1955. It describes the production of charcoal in an earth kiln or charcoal stack where a heap of air-dried wood is placed on top of slats forming a so called roast under which there is an excavation; a pit where the ground has been compressed in order to hinder air leakage. The wood heap is of uniform shape and is first covered with small shrubs, then by bark or moss followed by a mixture of sand, soil and dirt that should be at least 20 cm thick, which should make the kiln air tight. On the side of the construction there is an approximately 3 m tall chimney, where a fire is lit and kept burning for 30 minutes during start-up of the kiln in order to create a sufficient draft through the wood bed. The bed itself is lit with kindling² through an air duct that runs 1.5 m past the centre of the stack. In the lower central parts of the kiln a combustion zone is formed from where the flue gases travel to the upper parts of the kiln and then through the wood bed, first through the carburization zone followed by the drying zone and finally out through the chimney. Temperatures of 550 °C can be reached in the combustion zone. Air ducts at the foot of the kiln are adjusted to control smooth carburization of the wood material. Additionally, uneven burning can be reduced by placing dryer wood at the periphery and moist wood closer to the middle of the kiln. The whole carburization process is completed after 7-9 days (for dry wood) and if successful no major collapses have occurred. Thereafter, the bed is either allowed to cool from one to two days after which a hot tear down is done or it is quenched, which takes up to 10 days. The benefit of quenching is a higher solid yield and that the charcoal can be left as is and no additional shelter needs to be constructed.

To the best of the author's knowledge the process described above (Sw. milkolning) is no longer in use, apart for illustrative purposes in the regions of Ostrobothnia and Kainuu in Finland [34, 35]. It constitutes a shift between two eras, which in a way was indicated by Bergström when he mentioned the option of carburization in a container through indirect heat transfer. Earth kilns (sv. mila) could have a fairly large capacity, usually between 100-250 m³ with radius of 5-7 m, but required many man-hours and were terribly slow. Furthermore, the gases were not utilized in any way, which resulted in poor yields since the solid mass was used instead as a heat source, not to mention the constant death

² For a roast of 130 m³ about 5 m³ of kindling is needed.

hazard when uneven burning could result in men falling in the earth kiln while they were compacting the heap during carburization [33]. Although the carburization process is old it has several similarities to present day torrefaction- and slow pyrolysis processes, which are presented in sections 3.2 and 3.3.

3.1. Dryer types

Holmberg [31] classified biofuel dryers according to the drying medium used, heat supply and biomass transport mechanism. As a drying medium either air, flue gas or superheated steam can be used. Heat can be supplied through convection, conduction and by radiation. The transport mechanisms can be either rotary-, conveyor-, screw-, fluidized bed-, cascade- or pneumatic dryers. Some most common direct dryers for biofuels are listed together with their pros and cons in **Table 1**.

Table 1 Some common direct dryers of biofuels [31]. (* For steam $T > 150^{\circ}\text{C}$, ** Steam)

	Drum	Conveyor	Cascade	Pneumatic
<i>Drying medium</i>	Flue gas	Air	Flue gas	Flue gas/Steam
<i>Temperature ($^{\circ}\text{C}$)</i>	200 - 600	30 - 150	160 - 280	150 - 700*
<i>Evaporation rates ($t_{\text{H}_2\text{O}}\text{ h}^{-1}$)</i>	3.6 - 20	0.5 - 40	0.8 - 7	10 - 26 (6 - 30)**
<i>Pros</i>	Low maintenance	Good controllability	Reasonable dimensions	Small dimensions
<i>Cons</i>	Dust and smell problems	Large dryer dimensions	Corrosion and erosion	High maintenance

Risk of combustion exists when using air or flue gas of too high temperatures. Another is the possible release of VOC (Volatile Organic Carbon), which are greatly affected at temperatures above 100°C [31, 36].

3.2. Torrefaction

Torrefaction of biomass takes place under a non-oxidizing environment at modest temperatures $\leq 300^{\circ}\text{C}$ and can be divided into three different temperature zones: light (220°C), mild (250°C) and severe torrefaction (280°C) where the residence time can vary from minutes to hours [37, 38, 39]. However, the effect of residence time is considered to be of less importance than that of temperature [37, 40, 39]. A benefit with biomass conversion is hydrophobicity and an increase in both carbon content and heating value of the solid product while a downside is reduced mechanical strength and yield loss of solid mass [38, 41]. Resulting changes in biomass composition and characteristics are explained by removal of volatiles and decomposition of hemicellulose that take place at temperatures below 250°C [40, 39, 41, 42]. Cellulose and lignin are less reactive during torrefaction but slight decomposition occurs already at $250\text{-}260^{\circ}\text{C}$ [40]. Both endo- and exothermic reactions take place but the overall balance is only slightly endo- or exothermic [37, 40]. However, more exothermic behaviour is seen with increasing torrefaction temperature [37]. The effect of temperature on solid biomass yield and char composition as well as higher heating value is illustrated in **Figure 5** where the data is taken

from [43]. The horizontal black line is for comparison and shows the carbon content of amorphous graphite, which ranges between 70-75%, while that of flake graphite contains 80-98% carbon [44]. The illustrated temperature effects are quite positive in regards to fuel quality for the given biomass and more restrained development of the heating value during torrefaction are seen for biomasses presented e.g. in [45].

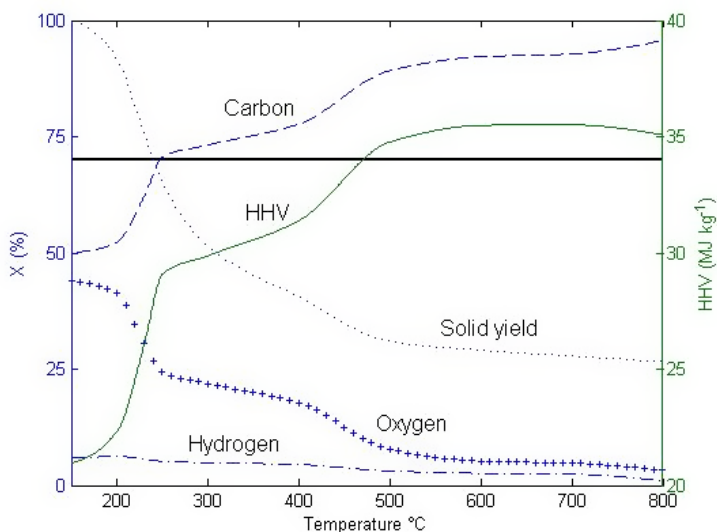


Figure 5 Biomass composition and solid yield (left ordinate) as well as higher heating value (right ordinate) as a function of the conversion temperature (abscissa) [14]. Carbon content of amorphous graphite is illustrated by the thicker horizontal line.

As for the gaseous components, the non-condensable volatiles consist mainly of CO and CO₂ where the CO content increases at elevated temperatures [46]. According to results presented by Prins et al. [47] the mass yield of CO, for willow torrefied at 270°C for 15 minutes, is about 0.5% and that of CO₂ is just under 4%. With increased torrefaction temperature (300°C, 10 minutes) the CO and CO₂ contents increase to about 1.3% and 4%, respectively. The condensable volatiles on the other hand constitute a larger share, as shown in **Figure 6** (for willow). Please refer to the fourth part of this thesis for further information about volatile fractions and their compositions deriving from wood pyrolysis.

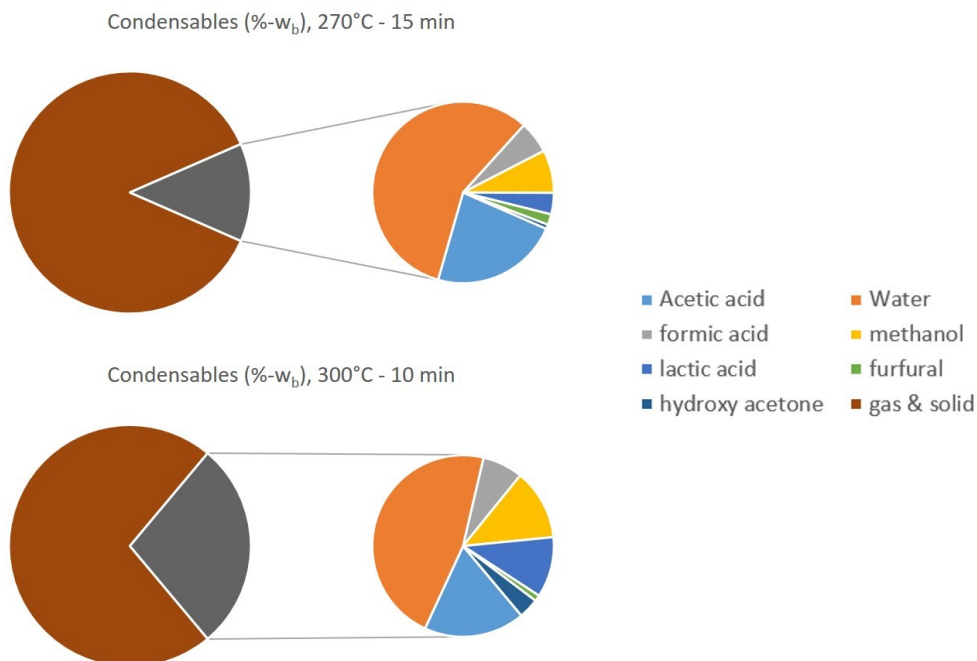


Figure 6 Share of condensable volatiles versus solid and non-condensable fractions (left side pie chart) for willow torrefied at two different temperatures. The right side pie chart displays the ratio of the various components of the condensable volatiles [47].

3.3. Slow and Fast Pyrolysis

Above torrefaction temperatures the thermal decomposition of organic compounds starts, which takes place at 350-550°C and continues up to 700-800°C [48]. Operating temperatures for slow pyrolysis is usually around 400-500°C with residence times from 30 minutes up to several hours [49], although shorter residence times have been reported [48]. For fast pyrolysis the temperatures can range from 400-1000°C, depending on the product fractions desired, with residence times of 2-10 seconds [49, 48, 50]. For instance, a large bio-oil quantity is gained with a pyrolysis temperature of 500°C and a residence time below 2 seconds [50, 51] while the biomass particles should be of a very small size (< 2mm) and have a low moisture content (< 10%) [50]. Slow pyrolysis produces also bio-oils but not in the same quantity and the quality is lower [48, 51]. The bio-oils from slow pyrolysis consist mainly of water, acetic acid, methanol, acetole (hydroxypropanone), acetone and furfural [52]. Chemical groups deriving from fast pyrolysis are carboxylic acid-, aldehyde-, phenol- and sugar-species along with char, pyrolytic lignin and water [53]. Chemical composition of the volatile fractions are presented later in Chapter 6.

3.4. Investment costs for pre-treatment and conversion units

A biomass pre-treatment plant consisting of a hammer mill and a drum dryer with a daily maximum capacity of 200 tonne of dry biomass was estimated by Rogers and Brammer [50] to have a capital cost of 3000 k£ (around 4.1 M€). Kung et al. [49] reported an investment cost of 7.3 M\$ for a biomass pre-treatment plant with a yearly capacity of 70 000 tonnes. If the operation time is approximated to be 8000 hours on annual basis then the capacity of these two plants are similar but the cost are roughly 60% higher for the latter.

A torrefaction plant consisting of a conversion reactor, a burner, a heat exchanger, turbo blowers, a precipitator and a biomass cooler with an hourly production capacity of 15.7 tonnes was estimated by Mobini et al. [15] to cost around 19.6 million Canadian dollars, equalling about 12.9 M€. The costs of a similar sized torrefaction plant (112 kt a^{-1} , which equals 14 t h^{-1} with an operation time of 8000 hours) was reported by van der Stelt et al. [40] to be around 7.3 M€.

Rogers and Brammer [50] provided a formula for estimating the capital investment costs for a fast pyrolysis plant with a daily processing capacity of 50-250 dry tonnes of biomass

$$\frac{k_{\text{plant}}}{\text{k£}} = 2853.8 \ln\left(\frac{\dot{m}_{\text{bio}}}{\text{t/d}}\right) - 6958.8 \quad (1)$$

where \dot{m}_{bio} is the mass flow rate of dry biomass and k_{plant} is the capital cost. Salman [48] reported that for a fast pyrolysis plant with a daily capacity of 620 tonnes the capital cost would be 46 M\$, which is over 30% more than the cost of three separate pyrolysis plants calculated with Eq. 1 with equal capacity.

Fortum built an industrial-scale fast-pyrolysis plant for bio-oil production with an annual production rate³ of 50 thousand tonnes. The plant was integrated with their existing power plant that is located in Joensuu and the total budget of the expansion was some 30 M€ [54]. In Vaasa a 140 MW biomass gasification plant was built to complement the existing power plant of Vaskiluodon Voima. The reported budget for the project was 40 M€ [55, 56].

As seen from the values reported above the costs vary greatly depending on the source. Reasons for this might be that not all of the sources have included the same units in their estimations, regional differences, hidden costs and other uncertainties.

³ With a bio-oil yield of 70% and an annual operation time of 8000 h the production rate of biomass would be about 9 t h^{-1} .

4. What is optimization, linearization and genetic algorithms

This chapter is to give a glimpse to some of fundamental concepts used in solving the mathematical problems presented in Chapter 5. The Latin word “optimus” means “the best”, and to optimize is to find the best solution to a given problem. Simple problems usually have simple solutions. For instance if you brew coffee for yourself and want to minimize the power consumption then when is the right time to turn off the brewer? If you intend to take only one cup of coffee, the best solution is to turn the brewer off as soon as you’ve filled your cup. However, if one cup is not enough then the time span between two cups determine whether it is better to have the brewer in standby or to turn it off and brew new coffee when desired. If we now add five new coffee drinkers with different habits (five new variables) and include a time dependent comfort factor that gives penalty (a new constraint) for bad tasting coffee, one can see that a simple problem has quickly become a more complex one. Although the problem has a practical solution of pre-determined coffee times and “don’t like it don’t drink it”-mentality it gives a hint of the complexity of problems that engineers will face when trying to find the “optimus” in large industrial plants. Often it is difficult or even impossible to see the best solution with the naked eye when facing very complex problems and solving them requires usually the use of computational tools. Depending on the problem, there might be several good solutions (local optima) but only one can be the best (global optimum) as illustrated in **Figure 7** for a one-dimensional problem.

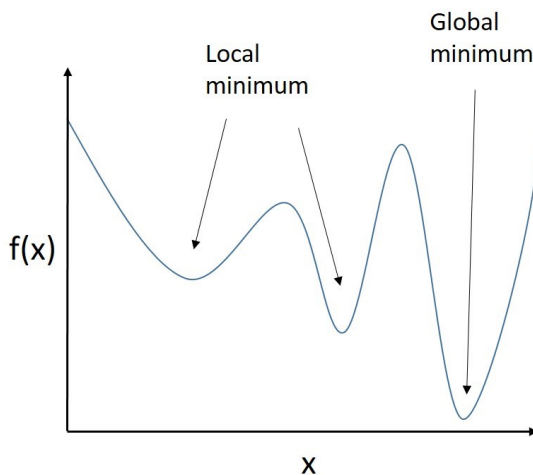


Figure 7 Illustration of local and global minima for a function.

Since multi-dimensional problems cannot be depicted as easily as in Figure 7 another pathway is needed, which depends on the complexity and nature of the problem. Classification of different optimization problems and methods for solving them are briefly discussed in the following sections.

4.1. Linear and non-linear programming problems

A linear function is defined as

$$f(x) = a^T x + b \quad (2)$$

where x is a variable vector while a and b are a vector of constants and a constant, respectively. A Linear Programming (LP) problem consists of a linear objective function and linear constraints expressed in continuous variables [57]. However, if the optimization problem has variables that express options (e.g., “yes” or “no”) or integers (e.g., number of engines) the problem becomes a Mixed Integer Linear Programming (MILP) problem. Global optimum can be guaranteed by using the deterministic (non-stochastic) methods (cf. **Table 2**). Problems with non-linear functions in the objective and/or in the constraints are defined as Non-Linear Programming (NLP) problems and Mixed Integer Non-Linear Programming (MINLP) problems, respectively. These are more difficult to solve than the LP and MILP problems and a global optimum cannot be guaranteed if the NLP or MINLP problem is not convex. Convexity is addressed in paragraph 4.1.1, while problem formulation and methods for solving them are presented in paragraph 4.1.2.

4.1.1. Convexity

A function is convex if a line drawn between two arbitrary selected function values is on or above the function curve (see illustration in **Figure 8**). A linear function is both concave and convex but not strictly convex or concave. In order for the function to be strictly convex or concave the line should only touch the curve at the endpoints.

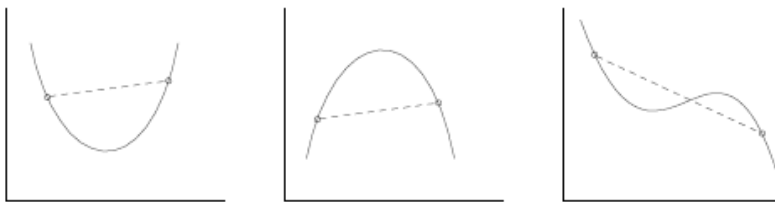


Figure 8 From left to right: a convex, a concave and a non-convex function.

Furthermore, for a function to be convex

- it should have a derivative (slope) that increases with increasing x -value (refer to Eq. 2)
- it has always a non-negative second derivative for any x -value
- any linear approximation at x should be an underestimate of the given function
- the local minimum is always the global optimum

A strictly convex function is always convex, but not the other way around. A function is convex if a combination of arbitrary selected values on x_1 and x_2 fulfil the inequality [58]

$$f[(1 - \lambda) \cdot x_1 + \lambda \cdot x_2] \leq (1 - \lambda) \cdot f(x_1) + \lambda \cdot f(x_2) \quad (3)$$

where $0 \leq \lambda \leq 1$. Similarly, a function is strictly convex if the following inequality, again for arbitrary selected values on x_1 and x_2 , holds true

$$f[(1 - \lambda) \cdot x_1 + \lambda \cdot x_2] < (1 - \lambda) \cdot f(x_1) + \lambda \cdot f(x_2) \quad (4)$$

4.1.2. Problem formulation

A general problem formulation can be written as [58]

$$\min f(x) \quad (5)$$

s.t.

$$h(x) = 0$$

$$g(x) \leq 0$$

$$x \in R^n$$

where $f(x)$ is the objective function that is subject to constraints. A problem can also be unconstrained. Various methods for solving different optimization problems are listed in Table 2.

Table 2 Different numerical methods for solving the linear and non-linear programming problems

	Unconstrained	Constrained			
	NLP	NLP	LP	MILP	MINLP
<i>Branch & Bound</i>				x	x
<i>Cutting Plane</i>				x	
<i>ECP</i>					x
<i>GBD</i>					x
<i>Golden section</i>	x				
<i>GRC</i>		x			
<i>Interior point</i>			x		
<i>Newton</i>	x				
<i>Outer Approximation</i>					x
<i>Penalty Methods</i>		x			
<i>Quadratic Interpolation</i>	x				
<i>Quasi Newton</i>	x				
<i>Random Walk</i>	x				
<i>Simplex</i>			x		
<i>Simplex (NM)</i>	x				
<i>SQP</i>		x			
<i>Steepest descent</i>	x				

Many problems can be tackled by the MINLP, where part of the coverage include both MILP and NLP problems. The problems shared by the latter two are LP problems, as illustrated in **Figure 9**. Basically this means that MINLP problems can only be solved by MINLP methods but LP problems can be solved by using any of the methods. Naturally, the best results and most effective performance comes from using the methods developed for the explicit problem in question. An indicative list of some different software for solving optimization problems is given in **Table 3**.

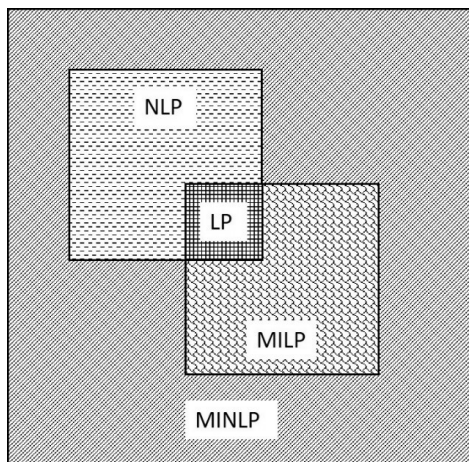


Figure 9 Coverage of different programming problems.

Table 3 Various software for solving different programming problems.

	NLP	LP	MILP	MINLP
<i>CPLEX</i>		x	x	
<i>Excel</i>	x		x	x
<i>GAMS</i>				x
<i>LINDO</i>			x	
<i>Lp_solve</i>		x	x	
<i>Matlab</i>	x			
<i>OSL</i>		x	x	
<i>Quattro Pro</i>	x		x	x

4.2. Piecewise linearization

A MINLP problem can be simplified by piecewise linearization after which it can be solved as an MILP problem. The function value of the discretized problem will always be an approximation of the original one but with suitable discretization steps the deviation to the exact value can be kept reasonable. However, applying small steps also brings about a considerable computational load because the number of binary variables in the problem increases. For a two-variable non-linear function a possible linearization procedure could be as follows.

With reference to **Figure 10**, the fixed discretization steps the product of two variables in the middle of the discretization block is

$$f_{i,j} = \left(x_i + \frac{\Delta x}{2}\right) \left(z_j + \frac{\Delta z}{2}\right) \quad (6)$$

where Δ expresses difference and subscript i and j denotes discretization points along the x and z variables, respectively. The slope in x direction can be calculated as

$$p_{i,j} = \frac{x_{i+1} \left(z_j + \frac{\Delta z}{2}\right) - x_i \left(z_j + \frac{\Delta z}{2}\right)}{\Delta x} \quad (7)$$

which simplifies into

$$p_{i,j} = z_j + \frac{\Delta z}{2} \quad (8)$$

Similarly, the slope in z direction becomes

$$q_{i,j} = x_i + \frac{\Delta x}{2} \quad (9)$$

The intercept of the linearized model is given by

$$k_{i,j} = \left(x_i + \frac{\Delta x}{2}\right) \left(z_j + \frac{\Delta z}{2}\right) - p_{i,j} \left(x_i + \frac{\Delta x}{2}\right) - q_{i,j} \left(z_j + \frac{\Delta z}{2}\right) \quad (10)$$

which simplifies into

$$k_{i,j} = - \left(x_i + \frac{\Delta x}{2}\right) \left(z_j + \frac{\Delta z}{2}\right) \quad (11)$$

The linearized function value can now be expressed as

$$f = k + v_x + v_z \quad (12)$$

where the variables k , v_x and v_z are determined by the following conditions

$$k \leq k_{i,j} + M(2 - y_i - \hat{y}_j) \quad (13)$$

$$k \geq k_{i,j} - M(2 - y_i - \hat{y}_j) \quad (14)$$

$$v_x \leq p_{i,j}x + M(1 - y_i) \quad (15)$$

$$v_x \geq p_{i,j}x - M(1 - y_i) \quad (16)$$

$$v_z \leq q_{i,j}z + M(1 - \hat{y}_j) \quad (17)$$

$$v_z \geq q_{i,j}x - M(1 - \hat{y}_j) \quad (18)$$

where M is a large value ("big M ") to disconnect inactive regions. When the region or block of interest is reached then the product xz of that block is given. The binary variables y_i and \hat{y}_j have to satisfy the following conditions

$$\sum_i y_i = 1 \quad (19)$$

$$\sum_j \hat{y}_j = 1 \quad (20)$$

$$x \leq x_{i+1} + M(1 - y_i) \quad (21)$$

$$x \geq x_i - M(1 - y_i) \quad (22)$$

$$z \leq z_{j+1} + M(1 - \hat{y}_j) \quad (23)$$

$$z \geq z_j - M(1 - \hat{y}_j) \quad (24)$$

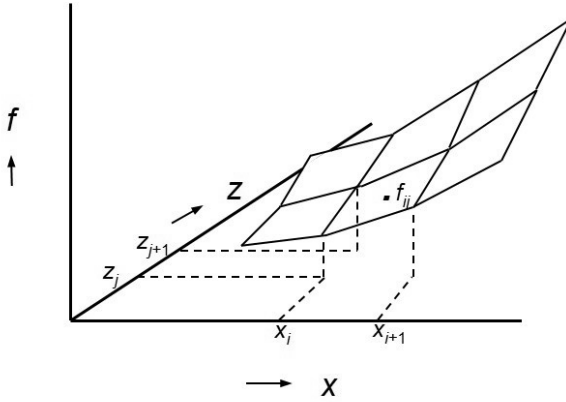


Figure 10 Graphical illustration of the linearization procedure between two variables [59].

4.3. Evolutionary Algorithms

An alternative to the deterministic methods presented in section 4.1 is stochastic methods to which the evolutionary algorithms (EA) belong. The EA uses concepts borrowed from nature, such as mutation, recombination and selection. The former two concepts derive from biological cell division and have to do with DNA reproduction, while the latter concept can be looked upon as 'survival of the

fittest' ideology. The solution procedure of the problem goes as follows; with an example where a surface area is to be maximized with respect to a length and a width.

- 1) Initialization – a set (a population) of vectors (individuals) are created at random.

Example:

	Length (m)	Width (m)	
Individual 1	5.0	2.0	<div style="border: 1px solid black; padding: 10px; display: inline-block;"> where: $n \in \mathbb{R}$ $Length + Width \leq 10$ $0 \leq Length, Width \leq 10$ </div>
Individual 2	6.1	2.4	
⋮			
Individual n	2.1	7.8	

The population number (n) should be at least ten fold compared to the number of variables.

- 2) Evaluation – function value (fitness value) of each individual (candidate solution that exists in phenotype space) is evaluated.

Example:

	Fitness value: Surface (m ²)
Individual 1	10.0
⋮	
Individual n	16.4

- 3) Selection – Individuals (parents) are selected according to fitness value or by other criteria.

Example:

	Length (m)	Width (m)	Fitness value
Individual 2	6.1	2.4	14.6
Individual 8	4.3	4.0	17.2

- 4) Recombination – Parents (encoded as binaries in genotype space) are recombined into new individuals (offspring).

Example:

Individual 2	110010	010100
Individual 8	101011	101000
<hr/>		
Individual 2r	110011	010000
Individual 8r	101010	101100

Parents are above the horizontal line and offspring below it.

- 5) Mutation – Random positions (genes) in the offspring binary string (chromosome) change values.

Example:

Individual 2r	110011	010000
Individual 8r	101010	101100
Individual 2m	110001	010000
Individual 8m	101010	100110

Bolded font indicate where values are flipped, i.e. from zero to one or vice versa.

- 6) Survival selection – The parents/offspring that proceed to the next generation (next iteration) are selected.

Example:

	Fitness value
Individual 2	14.6
Individual 8	<u>17.2</u>
Individual 2m	7.8
Individual 8m	16.0

Here both offspring have lower fitness values than the parents. It might be profound to allow some offspring to pass on to the next generation in order to create diversity.

Steps 3-6 are repeated until no better fitness value is found for a number of generations or the generation number reaches a maximum allowed value.

The procedure presented above is only one variant of an EA and many others exist. For instance a fast converging and reasonably robust method is the Differential Evolution (DE). It distinguishes itself from other EA techniques because of its differential mutation. As described above a population of size n is randomly generated consisting of individuals ($j = [1, 2, \dots, n]$). For each j a mutant vector is created:

$$P_{m,j} = P_j + F_m(P_{r1} - P_{r2}) \quad (25)$$

where r_1 and r_2 denote randomly selected individuals that are distinct from j . F_m is a mutation constant that can be used to expand or decrease the search space. A recombination (here: crossover) is done between the mutation vector ($P_{m,j}$) and another randomly selected individual j with a certain probability. The crossover is done with real numbers, where randomly selected variables between the two row vectors switch place. A greedy scheme is used to consider whether or not to keep the offspring in the next generation. The following rules of thumbs can be used:

- Crossover probability ≤ 0.3
- $0.5 \leq F_m \leq 1$, although no upper or lower bounds needs to be imposed
- A population size that is at least ten-fold in comparison to the number of variables
- The mutation constant should be decreased with increasing population size

5. Mathematical model of the optimization problem

The steel plant model used in this study is based on the model presented by Helle et al. [14, 60]. It consists of both linear and non-linear functions that describe the different units at the plant. The base of the model is the same in all publications behind the present thesis [45, 59, 61, 62, 63] and consists of models of a BF, HS, coke plant, sinter plant, biomass conversion unit, BOF as well as a combined heat and power plant. The base model is treated here and the changes made to the model in the different publications are briefly described in sections 5.1-5.4 in chronological order of submission of the papers (Parts I-IV). Some basic concepts behind the methods used for solving the mathematical problems were already described in Chapter 4.

In the BF model the furnace is divided into three zones, an upper preparation zone, a lower elaboration zone and a middle zone known as the thermal reserve zone. In the latter the gas and solid temperatures are known and practically equal, and the gas composition can be calculated on the basis of an approach to chemical equilibrium. Using this thermodynamic model [60], a semi-linearized BF model was created by using eight input variables, expressing 13 outputs, which are allowed to vary freely within their admissible regions for a large number of simulations. Infeasible solutions from the simulations are excluded [14, 60]. Input and output variables are presented in **Table 4** and a graphical illustration of the steel plant is given in Figure 1, where the biomass dryer- and grinding unit models have been developed in the present work [62, 63].

Table 4 Input and output variables for the BF model used in [61]. Units m^3n and t_{hm} refer to normal cubic meters and tonne of hot metal, respectively.

<i>Input variable</i>	<i>Range</i>	<i>Output variable</i>	<i>Range</i>
X_1 :Blast volume	$0-140 \cdot 10^3 \text{ m}^3\text{n h}^{-1}$	Y_1 :Production rate	$120-160 \text{ t}_{\text{hm h}^{-1}}$
X_2 :Oxygen volume	$0-40 \cdot 10^3 \text{ m}^3\text{n h}^{-1}$	Y_2 :Coke rate	$\geq 0 \text{ kg t}_{\text{hm}}^{-1}$
X_3 :Oil rate	$0-120 \text{ kg t}_{\text{hm}}^{-1}$	Y_3 :Flame temperature	$2000-2300^\circ\text{C}$
X_4 :Blast temperature	$850-1100^\circ\text{C}$	Y_4 :Top gas temperature	$100-250^\circ\text{C}$
X_5 :Pellet rate	$0-1200 \text{ kg t}_{\text{hm}}^{-1}$	Y_5 :Bosh gas volume	$170-200 \cdot 10^3 \text{ m}^3\text{n h}^{-1}$
X_6 :Limestone rate	$0-100 \text{ kg t}_{\text{hm}}^{-1}$	Y_6 :Residence time of solids	$6.0-9.0 \text{ h}$
X_7 :Oxygen flow with biomass	$\geq 0 \text{ kg t}_{\text{hm}}^{-1}$	Y_7 :Slag basicity CaO SiO_2^{-1}	$1.00-1.20$
X_8 :Energy flow with biomass	$\geq 0 \text{ MJ t}_{\text{hm}}^{-1}$	Y_8 :Slag rate	$\geq 0 \text{ t}_{\text{hm h}^{-1}}$
		Y_9 :Top gas volume	$\geq 0 \text{ m}^3\text{n h}^{-1}$
		Y_{10} :Top gas CO content	$\geq 0 \%$
		Y_{11} :Top gas CO ₂ content	$\geq 0 \%$
		Y_{12} :Top gas H ₂ content	$\geq 0 \%$
		Y_{13} :Heating value of top gas	$\geq 0 \text{ MJ m}^{-3} \text{ n}$

In the steel plant model the raw material streams and process parameters are optimized in order to minimize production costs of liquid or rolled steel. CO₂ emissions that derive from fossil fuels are subjected to a penalty fee. The extent of biomass conversion dictates how much of the biomass is lost (loss of char yield) and how the injected char(coal) affects the thermal state of the furnace. The production cost of steel is defined by the objective function

$$F = \left(\sum \dot{m}_i c_i + \psi \dot{m}_{CO_2} c_{CO_2} - P c_{el} - \dot{Q}_{dh} c_{dh} \right) / \dot{m}_{steel} \quad (26)$$

which is expressed in € per tonne of steel (subscript steel). Subscripts *el* and *dh* denote electricity and district heating, *P* is the power produced and \dot{Q} is the heat flow used for district heating. The variable \dot{m} denotes mass flow rate, *c* is either a cost or a price variable (defined in **Table 5**) and ψ expresses the mass ratio between fossil- and total CO₂ emissions.

Table 5 Cost/price variables used in [62].

	Cost/Price
<i>Biomass</i>	0...100 € t _{dry} ⁻¹
<i>Pellets</i>	120 € t ⁻¹
<i>Coal</i>	145 € t ⁻¹
<i>Coke</i>	300 € t ⁻¹
<i>Pulverized Coal</i>	100 € t ⁻¹
<i>Limestone</i>	30 € t ⁻¹
<i>Quartzite</i>	30 € t ⁻¹
<i>Oxygen</i>	0.05 € (m ³ n) ⁻¹
<i>Electricity</i>	50 € MWh ⁻¹
<i>District heat</i>	10 € MWh ⁻¹
<i>CO₂ emission penalty</i>	0...100 € t ⁻¹
<i>Scrap</i>	100 € t ⁻¹

The HS set is approximated as one counter-current heat exchanger, which is heated by burning cleaned BF top gas. The coke plant, sinter plant and BOF models are based on simple linear equations that mimic the overall behaviour of these units in the SSAB Raahe steel plant, which has been used as a reference. Both the BF and the BOF use oxygen from the oxygen plant. Coke oven gas, part of the BOF gas and remaining BF top gas are used for generating high pressure steam that is used for electricity production in the power plant, where the resulting low pressure steam is used for district heating. Due to intermittent operations of the converters half of the BOF gas is considered unrecoverable and thus is accounted as losses.

5.1. Steel plant model with dual BFs optimized by an Evolutionary Algorithm

In Part I of this study [59] a limited amount of resources including biomass was distributed between two identical BFs (BF1 and BF2) in a steel plant. Prior to injection in the BFs, the biomass was converted into a product with higher heating value and lower oxygen content by torrefaction or pyrolysis, where

the conversion was taken to depend on a conversion temperature only. A difference in furnace behaviour was established by allowing the blast temperature of BF1 to be $\leq 1100^{\circ}\text{C}$, while for BF2 the blast temperature was restricted to $\leq 1000^{\circ}\text{C}$. The resulting nonlinear steel plant model was applied in a NLP formulation of the optimization problem for solving the optimal resource allocation and state of an individual furnace, while the raw material distribution between the two furnaces was optimized by using a stochastic model, a differential evolution algorithm (section 4.3). Five unknown variables (specific rates of biomass, coke and oil, blast oxygen as well as target production of steel) were optimized within constraints, which are given in **Table 6** together with the availability of the raw materials at the plant. Based on the number of variables an adequate population size ($M = 60$) for the evolutionary algorithm was selected. Five cases (**Table 7**) were analysed with different available resources of biomass, oxygen and oil, where specific oil injection rates in the range of $60\text{--}120\text{ kg t}_{\text{hm}}^{-1}$ were used. The pyrolysis temperature for biomass was allowed to vary between 150°C and 800°C . In addition, the effect on resource allocation for different steel target production (TP) rates ($280\text{--}340\text{ t h}^{-1}$) were looked upon. The NLP model was solved in Excel [64] while the DE algorithm was implemented in Matlab [65].

Table 6 Lower and upper bounds per BF and plant resource availability. TP – target production

	TP (t h^{-1})	Coke (t h^{-1})	Sinter (t h^{-1})	Biomass (t h^{-1})	Oxygen ($10^3\text{m}^3\text{n h}^{-1}$)
<i>Lower bound / BF</i>	140	0	110	0	0
<i>Upper bound / BF</i>	183	100	210	30	20
<i>In total</i>	320	110	320	20-60	20-40

5.2. Multiple BFs optimized by MILP

In Part II [61] a similar resource allocation problem as addressed in Part I was tackled, but the non-linear parts of the model, i.e. inputs X_7 and X_8 in Table 4, were made linear by piecewise linearization (section 4.2). The optimization problem could then be formulated as a MILP problem and was solved with IBM's CPLEX software [66] (cf. Table 3) where the encoding of the problem was done in Matlab. CPLEX was chosen because it is efficient and well suited for solving MILP problems with a great number of variables and the same software was therefore also used in the work of Part III.

The cases studied here, presented in Table 7, were similar to those studied in Part I and included different variations in biomass- and oxygen flows as well as different oil rates. The TP was set to 320 t h^{-1} , while both furnaces could utilize blast air with a temperature of 1100°C . Same cases were studied with a degraded set of HS for the second BF, resulting in a blast temperature of 900°C . Additionally, the effect of different steel production rates on dual BF operation was studied with TP ranging in $280\text{--}340\text{ t h}^{-1}$ with blast temperatures of 1100°C and 1000°C for the respective furnaces. Finally, the raw material distribution was studied for three simultaneously run BFs where the raw

material availability and total TP had been increased to account for the additional BF. The corresponding blast temperatures were selected to be 1100°C, 1000°C and 900°C, respectively. As for the biomass conversion, the same torrefaction/pyrolysis temperature range was used here as in Part I.

Table 7 Cases studied in parts I-II with two simultaneously operated BFs.

	Case 1	Case 2	Case 3	Case 4	Case 5
<i>Biomass feed flow ($t\ h^{-1}$)</i>	60	30	30	30	20
<i>Oxygen feed flow ($10^3 m^3 n\ h^{-1}$)</i>	40	40	20	40	40
<i>Specific oil rate ($kg\ t_{hm}^{-1}$)</i>	120	120	120	60	120

5.3. Biomass drying using process flue gases

The work in Parts I-II demonstrated the general feasibility of using biomass in the BF(s) in a steel plant with one or several BFs, and shed light on the optimal resource allocation between the furnaces. However, the model of the biomass conversion was extremely simple, and no attention was paid to the energy need and investments required for integrating biomass drying and conversion units in the steel plant. In Part III [63] a grate/conveyor drying unit as well as a grinding unit were included in the base model. The energy demand of the drying unit, estimated by the energy balance equation

$$\dot{n}_{CC,fg}H_{CC,fg} + \dot{n}_{HS,CC}H_{HS,CC} + \dot{m}_{BM,wet}h_{BM,wet} = \dot{n}_{DU,fg}H_{DU,fg} + \dot{m}_{DU,BM}h_{DU,BM} \quad (27)$$

was satisfied by flue gas from the steel plant. In Eq. (27) subscript CC denotes combustion chamber, fg flue gas, BM biomass and DU drying unit. Flue gases deriving from the HS are directly used for drying the incoming wet biomass from a humidity content of 60% down to 10%, where the latter level was chosen in order to avoid remoistening of the biomass after the dryer. The gas temperature was assumed to be 200°C, which is a somewhat conservative estimate and allows for some heat losses after the stoves. If there was an inadequate amount of flue gases from the stoves then supplemental BF top gas was used to cover for the heat deficiency. The top gas was taken to be combusted and diluted with air to yield a temperature of 300°C to avoid too large temperature gradients in the dryer and for keeping the material costs of the equipment at bay. As for the biomass composition, pine wood was studied here because it had a more moderate heating value development as a function of conversion temperature compared to the biomass studied in Parts I-II. However, the biomass from Parts I-II was kept for reference. A schematic of the drying procedure is given in **Figure 11**. Here it was assumed that the combustion of the volatiles, deriving from the conversion unit, was adequate to make the conversion process self-sustaining from a thermal point of view; the same assumption was made in the work of Parts I-II. The outgoing gas temperature from the dryer was set to 80°C.

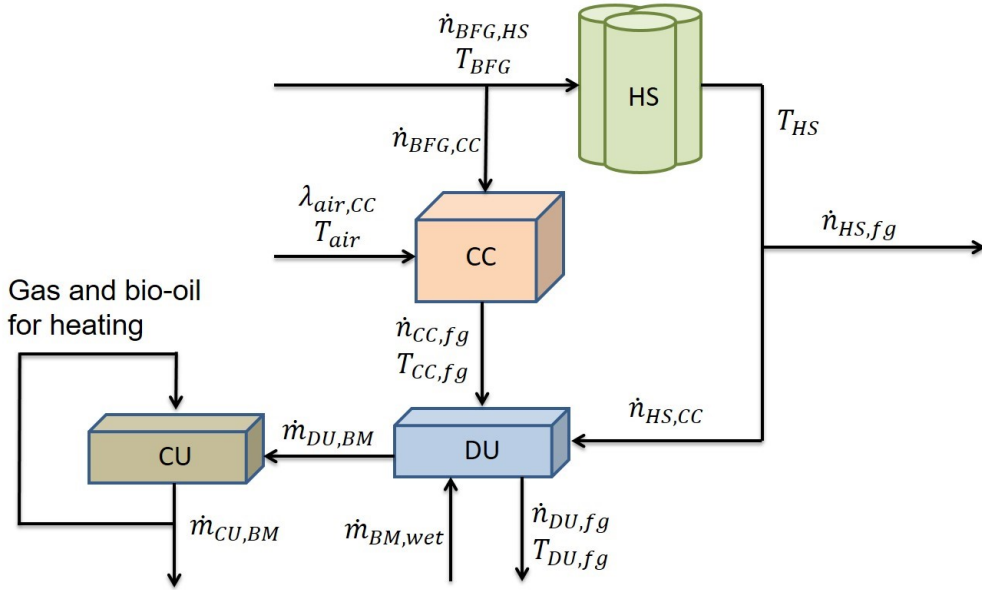


Figure 11 Schematic of the drying procedure, where the hot stove (HS) off gas and top gas (subscript BFG) is used as a drying medium. The latter is combusted in the combustion chamber (CC). The biomass (BM) is dried in the drying unit (DU) and further processed in the conversion unit (CU). Subscript *fg* denotes flue gas, while λ expresses the ratio of incoming air versus air needed for stoichiometric combustion [63].

A variety of cases were solved using the model, where flow rates of biomass, oxygen and oil were constrained and blast temperatures varied. The power requirement of a fan (supplying the air for BF top gas combustion) was included in the objective function.

Table 8 Cases studied in Part III.

Case	Biomass (t h^{-1})	Oil rate ($\text{kg t}_{\text{hm}}^{-1}$)	Blast temperature ($^{\circ}\text{C}$)	Oxygen ($10^3 \text{ m}^3 \text{ n h}^{-1}$)
1	30	120	1100	20
2	15	120	1100	20
3	15	120	900	20
4	15	60	1100	20

5.4. Biomass conversion units and detailed economic analysis

In the fourth and final part of the thesis, more detailed models of the biomass conversion step, i.e., torrefaction, slow- and fast pyrolysis conversion units, were applied [62] to the base model together with the grinding and drying unit models. The main analysis of the paper was focused on an optimal dimensioning of the biomass drying and conversion steps. Both HS flue gas and combusted BF top gas was used for drying (cf. Figure 11). The gas demand of the dryer was calculated according to an approach-to-saturation relation, expressing the difference between outgoing gas temperature and its dew point. Furthermore, in order to avoid the risk of release of harmful volatile organic carbons in the dryer, the incoming gas was assumed to be diluted with air to a temperature of 80°C . The maximum

length of the drying unit was set to 60 m and if a longer unit was needed then multiple units were used.

Mass balances of the product fractions and their compositions from biomass conversion were solved using conversion models developed in GAMS [67] at Aalto University. The results from the GAMS models were used in Aspen+ [68] in order to solve the energy balance of the conversion processes. The conversion temperature of torrefaction was selected to 280°C, while for slow pyrolysis it was 480°C and for fast pyrolysis 500°C. **Table 9** show the char composition during the different states as well as the starting composition of the biomass. These conversion units and their impact on the steel plant operation and economy were studied separately. Here each task was solved as an NLP problem using Matlab's SQP solver.

Table 9 Composition of char (% – w_b) and moisture content for the different conversion processes as well as starting composition of biomass.

	Biomass	Torrefaction (280°C)	Slow pyr. (480°C)	Fast pyr. (500°C)
<i>C</i>	47.2	55.0	84.8	72.8
<i>H</i>	6.6	6.2	3.7	2.9
<i>O</i>	45.8	38.3	10.5	22.3
<i>Ash</i>	0.4	0.5	1.0	2.0
<i>Moisture</i>	10.0	2.5	2.5	2.5

Investment costs of the biomass processing units were included in the objective function

$$k_i = k_{0,i} \left(a_i + b_i \left(\frac{z}{z_{0,i}} \right)^{0.72} \right) \quad (28)$$

where $k_{0,i}$ is the cost of the reference unit i . The share of solid costs is defined by constant a while the share of movable costs is defined as the product of constant b and a size (length of dryer) or capacity (production rate of biomass conversion unit) dependent ratio (where z_0 is the base size or capacity) raised into a power yielding an appropriate size-dependent investment cost. The constants and base costs are given in **Table 10**.

Table 10 Parameters used in Eq. 28.

	k_0 (M€)	a	b	z_0
<i>Drying</i>	15	1/3	2/3	60 m
<i>Torrefaction</i>	15	1/3	2/3	25 t h ⁻¹
<i>Slow pyrolysis</i>	20	1/3	2/3	25 t h ⁻¹
<i>Fast pyrolysis</i>	25	1/3	2/3	25 t h ⁻¹

The different process alternatives were evaluated by maximizing the calculated Net Present Value defined as

$$NPV = NP \left(\frac{1 - (1 + r)^{-n}}{r} \right) TCI \quad (29)$$

where TCI expresses the total investment while n and r are the estimated unit lifespan and interest rate, respectively. NP is the yearly Net Profit gained given by

$$NP = A_{sp}(c_0 - c)m_{steel} - \beta TCI \quad (30)$$

where A_{sp} is the annual availability of the steel plant in hours, m_{steel} is the hourly steel production rate and β is the annual equipment maintenance costs. Steel production costs with and without biomass use are expressed by c and c_0 , respectively. The coefficients of Eq. 30 are $A_{sp} = 8000 \text{ h a}^{-1}$, $\beta = 0.08$, $r = 0.1$ and $n = 40 \text{ a}$.

In the base case the steel plant was optimized for a production rate of 150 t h^{-1} , a coke plant capacity of 55 t h^{-1} , a maximum biomass feed rate of 25 t h^{-1} (dry basis) and a maximum specific injection of $150.0 \text{ kg t}_{hm}^{-1}$ for pulverized coal. The minimum and maximum injection rates of biomass char were set to $20.0 \text{ kg t}_{hm}^{-1}$ and $50.0 \text{ kg t}_{hm}^{-1}$, respectively, and the energy input with the injected reductants was kept constant. Additionally, the flame temperature was kept constant by adjusting the oxygen enrichment of the blast.

6. Key Findings and Discussion

Here the key findings from the different publications (Parts I-IV) are listed. Each section presents the most important results from one publication and these are presented in a chronological order.

6.1. Part I – Differential evolution: a steel plant with dual BFs

The optimization study in Part I, which was based on the DE algorithm, found somewhat surprising results concerning the use of resources between two BFs in a steel plant. Slightly lower production costs were found when the two identical BFs with the same blast temperatures were operated with different target productions (cf. **Figure 12** – top panel).

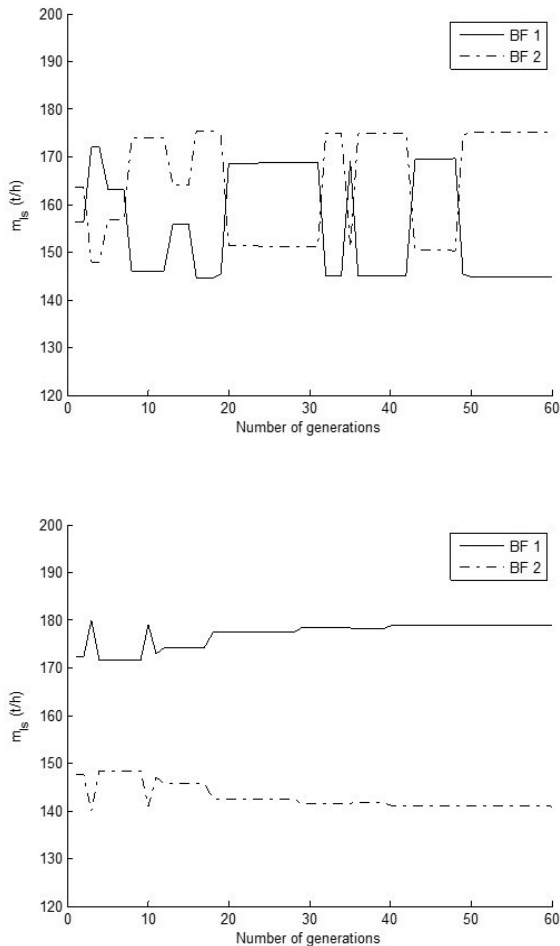


Figure 12 Top - Steel production using iron from the identical BFs operated with the same blast temperatures. Bottom – Steel production using iron from the BFs with lower blast temperature for BF 2 (cf. Case 4 – Table 7). The abscissa shows the number of generations (cf. section 4.3)

This illustrates the complexity of the problem and that it is difficult to foresee such optimal states. The fact that the larger TP varies between furnaces from one generation to the other reflects that the BFs

are identical. After about 50 generations the furnace operation seems to be unchanged, which is due to convergence of the algorithm and no better solutions are found. The economic benefit with this non-uniform operation was, however, marginal compared with the identical operation of the BFs, but nevertheless it showed that a better solution could be found by using the DE-algorithm.

When the blast temperature of the second BF was restricted the results became more apparent and the steel production rate of the BF operating with deteriorated HS capacity was lower than for the other BF (cf. Figure 12 – lower panel). As a result the BF with higher production rate utilized less biomass in comparison to the other furnace. In terms of optimal biomass conversion temperature, modest temperatures around 250°C were found to be optimal by the NLP model, which was in accordance to the results presented by Helle et al. [14, 69]. By using biomass the specific CO₂ emissions were reduced by 4-15% for the different cases compared with conventional BF operation without biomass injection.

As for convergence of the DE-algorithm, no big improvement in fitness value was noticed after approximately 10 generations and the mean fitness value of the entire population seemed to converge after 20 generations (cf. **Figure 13**). The production cost of liquid steel was about 241.5 € t_{LS}⁻¹ when solving the NLP model with the same parameters as in Case 1 but without biomass. This shows that corresponding furnace run including biomass injection (Case 1 – Figure 13) results in a significantly lower production costs. The method of solving the sub-problems, BF optimization with NLP, and the main problem of raw material distribution between the BFs, by the DE algorithm, which is a stochastic method, was found robust. However, the computational time for solving the problem was quite long and more efficient approaches for larger systems are required.

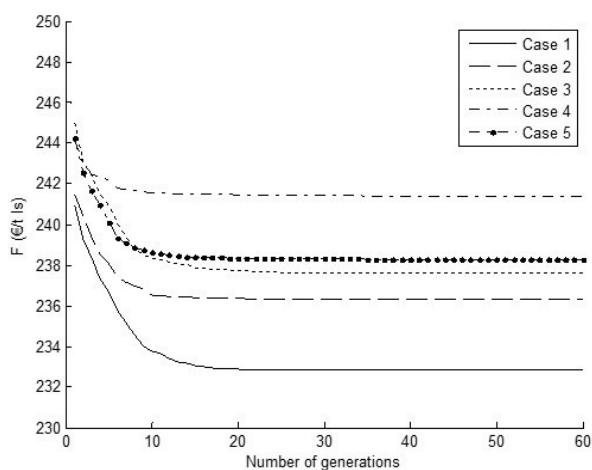


Figure 13 Evolution of mean fitness value for the DE-algorithm solving an objective function with two BFs operating at different blast temperatures

6.2. Part II – MILP problem: a steel plant with multiple BF_s

By piecewise linearization of the non-linear model the calculation time of the resulting MILP model was successfully reduced to about 30 seconds for two simultaneously run BF_s. It was found that with increasing number of furnaces the computational time increased exponentially, so the maximum complexity studied was a steel plant with three BF_s (calculation time of approximately 2.5 hours). The production costs and specific emissions estimated by the MILP solver were practically equal with those obtained by the DE algorithm when the same cases (plot with two BF_s) were studied. However, the resource allocation for the same cases could deviate, which indicated that there were different furnace states that could give rise to the same or nearly same results. The optimal steel production rates of two furnaces, which operate under different blast temperatures, are presented in **Figure 14** together with production cost and specific emissions as functions of the total production rate.

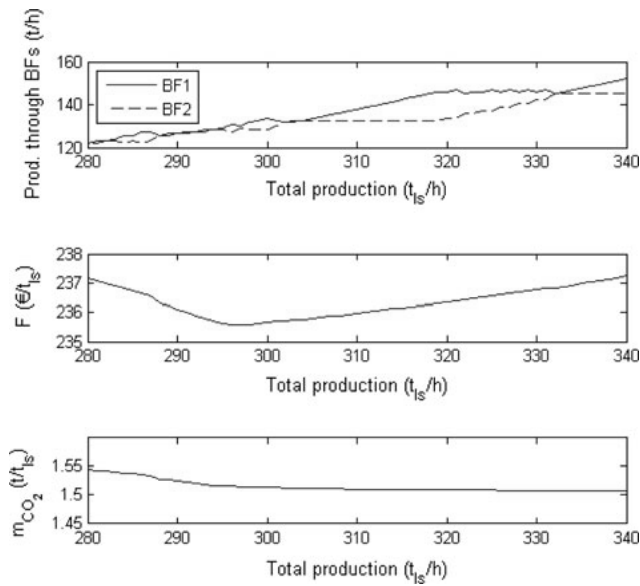


Figure 14 Production rate of steel per BF (top), production cost (middle) and fossil CO₂ emissions (bottom) for two simultaneously run BF_s with blast temperatures of 1100°C and 1000°C for respective furnace.

From Figure 14 it can be seen that it is not necessarily always best to have a greater production rate in the “better” furnace (BF1). This is further emphasized when optimizing a plant with three different BF_s with blast temperatures of 1100°C, 1000°C and 900°C, where the most efficient BF does not contribute by the largest share. Some of the results from optimizing this system are summarized in **Table 11**, where the feed rate of sinter and biomass have reached their maximum values of 160 $t h^{-1}$ and 120 $kg t_{hm}^{-1}$, respectively. Furthermore, the oxygen content of the blast is at its upper limit (32%). The maximum values reached, either limited by resource availability or allowable injection rates, are indicated in bold font, while the values at the lower boundaries are underlined. The unexpected result regarding the production rate distribution can be concluded to reflect the complexity of the systems

studied and it stresses the importance of developing mathematical tools by which the production can be planned.

Benefits of the linearization compared to the stochastic solution method is the reduced calculation time and the fact that finding a global optimum can be guaranteed. A downside is the unavoidable loss of accuracy that result from the linearization, which however, can be reduced by a selection of suitable linearization intervals. The stochastic method, on the other hand, can give reasonably good results with very little knowledge of the model itself.

Table 11 Optimal results for plant with three BF's with different maximum blast temperatures (BF1: 1100°C, BF2: 1000°C, BF3: 900°C). Maximum and minimum limits are indicated by bold- or underlined fonts, respectively.

	BF1	BF2	BF3
<i>Hot metal production rate</i>	144	148	127
<i>Steel production rate ($t\ h^{-1}$)</i>	165	170	145
<i>Oxygen ($10^3 m^3 n\ h^{-1}$)</i>	16.2	17.3	15.3
<i>Spec. sinter rate ($kg\ t_{hm}^{-1}$)</i>	1111	1078	1264
<i>Spec. pellet rate ($kg\ t_{hm}^{-1}$)</i>	436	467	295
<i>Spec. coke rate ($kg\ t_{hm}^{-1}$)</i>	255	277	318
<i>Oil rate ($kg\ t_{hm}^{-1}$)</i>	120	109	79.0
<i>Limestone rate ($kg\ t_{hm}^{-1}$)</i>	<u>0.0</u>	2.2	<u>0.0</u>
<i>Biomass feed rate ($t\ h^{-1}$)</i>	26.2	27.0	23.0
<i>Pyrolysis temperature ($^{\circ}C$)</i>	248	248	248
<i>Flame temperature ($^{\circ}C$)</i>	2011	<u>2000</u>	<u>2000</u>
<i>Slag basicity (-)</i>	<u>1.0</u>	<u>1.0</u>	1.2
<i>Blast temperature ($^{\circ}C$)</i>	1100	1000	900
<i>Spec. production costs ($\text{€}\ t_{ls}^{-1}$)</i>	234.2		
<i>Specific emissions ($t_{CO_2}\ t_{ls}^{-1}$)</i>	1.43		

6.3. Part III – MILP problem: drying and grinding of biomass

The pre-treatment of the biomass used in the computational studies of Parts I and II was very simplified, and attention was not paid to the energy and process unit requirements. In the work of Part III some improvements of the mathematical model were made in regards to the linearization procedure, which improved model accuracy. Furthermore, the addition of the drying unit model required the linearization of six new variables, which handled the heat demand of the dryer and top gas consumption. The results showed that a torrefaction temperature near or at the upper bound (300°C) was preferred for both types of biomass studied. In some cases not all available biomass was injected, although more than two thirds was used in all cases. The use of biomass is associated with an increased oxygen enrichment of the blast for keeping the flame temperature at reasonable levels and thus maintaining the target production rate. The coke replacement ratio of the torrefied biomass was estimated to be about $0.5\text{--}0.7\ kg_{\text{coke}}^{-1}\ kg_{\text{coke}}$. Energy flows with incoming reductants are shown in

Figure 15 for the four cases solved (cf. **Table 8**). Complementary top gas is required for drying in all of the cases studied and 0.3-3.3% of the total top gas is used for this purpose. If only top gas is used for drying, excluding flue gas from the HS, the steel production costs are increased by 0.3-0.4 € t_{ls}⁻¹. If the annual steel production at the plant is 1.4 Mt, the net savings in operational costs, when biomass is used, would be approximately 0.5 M€.

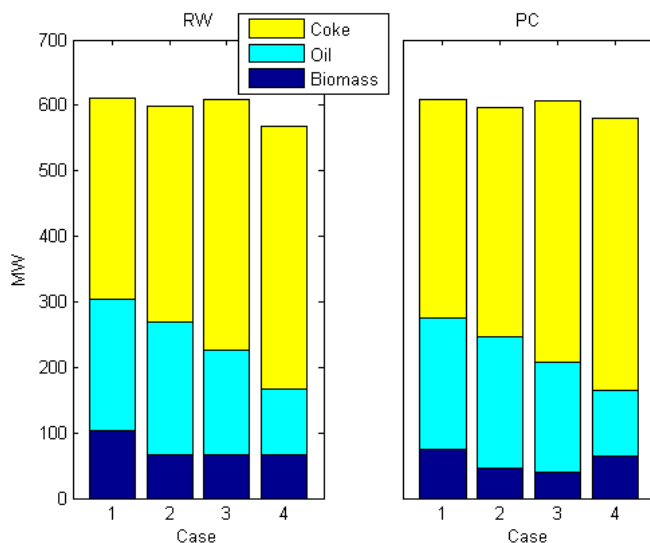


Figure 15 Incoming energy flows into the BF with the reductants coke, oil and biomass. The energy flow quantities (in MW) for the different reductants are stacked on top of each other in the graph. The left panel shows the flows for Cases 1-4 (Table 8) using RW biomass (reference wood – used in Parts I, II and III) and the right panel shows the flows for Cases 1-4 using PC biomass (pine wood chips – used in Parts III and IV).

The results gave reason to consider higher conversion temperatures and therefore a slow and fast pyrolysis unit were also included in the model in the work reported in Part IV of this thesis. Additionally, since investment costs and volatile product fractions, deriving from the conversion unit, were not taken into account in earlier work, it was decided that these should be included in the analysis to make a more realistic economic assessment of the alternatives.

6.4. Part IV – NLP problem: evaluation of various biomass conversion units

The mass yield of different product fractions from biomass conversion, for the conversion units studied, are given in the upper left panel of **Figure 16**. From there it can be seen that about 70% of the char remains after torrefaction at 280°C and the corresponding values for slow (480°C) and fast pyrolysis (500°C) are approximately 35% and 20%, respectively. The energy yields (upper right panel of the figure) show that about 90% of the energy is still in the solid char after torrefaction, while after slow pyrolysis the char contains roughly 70% of the total energy. After conversion by fast pyrolysis the major part of the energy (about 55-60%) is in the bio-oils. This correlates quite well with its bio-oil yield of 70%, while for slow pyrolysis the energy content of the bio-oil is quite low (20%), although the bio-

oil yield is about 50%. Studying at the char composition (lower left panel of Figure 16) it becomes evident that the conversion by slow pyrolysis results in superior char compared to the two other methods. The lower heating values for char deriving from torrefaction, slow and fast pyrolysis are 20.0 MJ kg^{-1} , 30.8 MJ kg^{-1} and 24.7 MJ kg^{-1} , respectively.

The energy balance showed that all of the conversion processes were self-sustaining if the gas products are used for heating, but in the case of torrefaction all the volatiles had to be used to provide sufficient heat for the process. To make the treatment of the heat requirement less optimistic, for slow and fast pyrolysis a share of 20% of the bio-oils were assumed to be used together with the product gases for heat provision, while the rest of the bio-oils were used in other part of the steel plant to substitute other fuels (here taken to be natural gas). The bio-oil utilization could have been even greater, but the given amount accounts also for possible losses in the process.

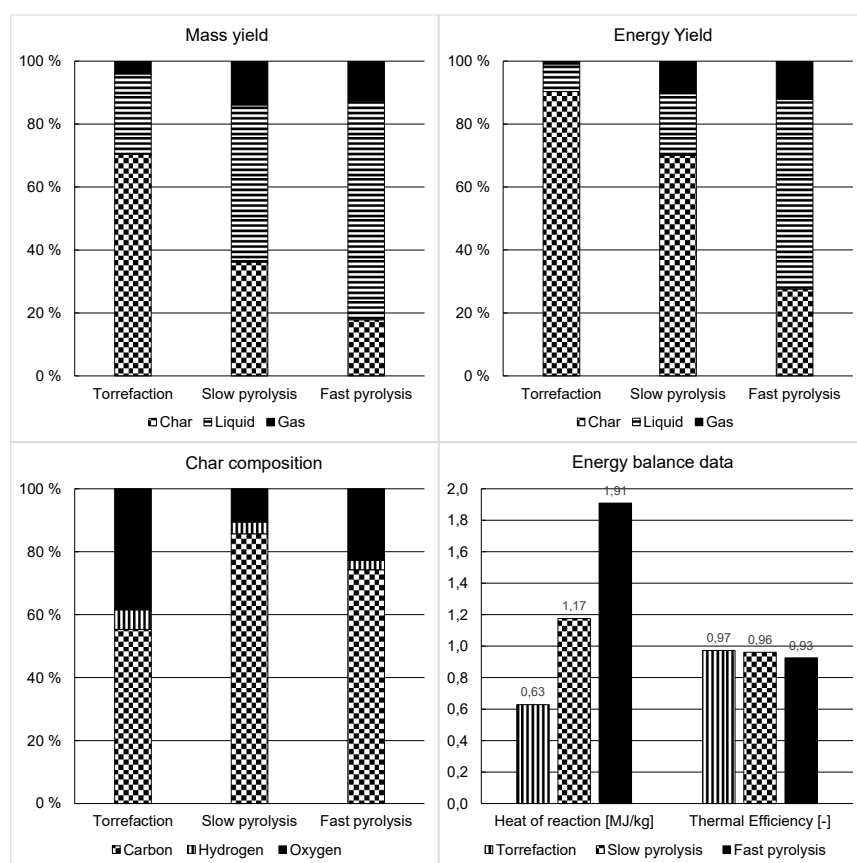


Figure 16 Mass and energy yields as well as char composition and energy balance of biomass conversion with torrefaction, slow and fast pyrolysis units.

A steel plant was studied where 25 t h^{-1} of biomass (dry basis) was available at 50 % moisture content. The NPV for torrefaction in the base case (rf. section 5.4) is positive only at very low biomass prices and at unrealistically high CO_2 penalty fees as illustrated in the left panel of **Figure 17**, which shows the NPV as contours versus the price of biomass (dry basis) and the emission penalty. In the right panel the reduction in production costs are shown when compared to the base case without biomass injection (excluding investment costs). The low NPV values for torrefaction can be explained by the poor replacement ratio of coke, which is here about $0.3 \text{ kg kg}_{\text{coke}}^{-1}$. The replacement ratio for the equivalent biomass was $0.5 \text{ kg kg}_{\text{coke}}^{-1}$ in Part III, as stated above. A possible reason for this deviation, apart from changes made to the mathematical model, is the somewhat lower torrefaction temperature used here (Part IV). Although the temperature is only some 20°C higher in the study of Part III, the heating value is about 13% greater for the torrefied biomass and the oxygen content is decreased by 4% compared to the lower torrefaction temperature. Still, even using the higher torrefaction temperature the replacement ratio is inferior compared to those from both forms of pyrolysis, as seen below.

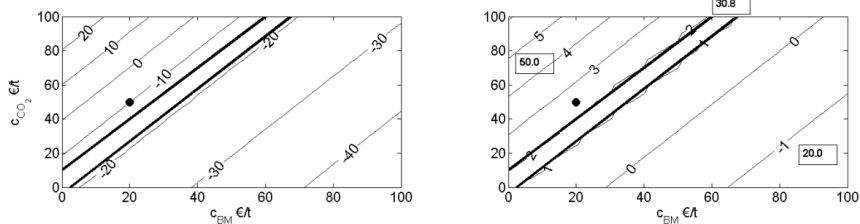


Figure 17 NPV (left panel) of the investment for **torrefaction** expressed in M€ and the specific economic benefit in operation cost of the concept compared to a reference case (right panel). The rate of injection of torrefied biomass (values in boxes in the right panel) increases from the minimum ($20 \text{ kg t}_{\text{hm}}^{-1}$) for the region right of the thick solid line to the maximum ($50 \text{ kg t}_{\text{hm}}^{-1}$) left of the lines and in between ($31 \text{ kg t}_{\text{hm}}^{-1}$) in the middle of the lines.

For fast pyrolysis the coke replacement ratio was over double that of torrefaction and was $0.6 \text{ kg kg}_{\text{coke}}^{-1}$. However, the availability of biomass restricted the char injection rate to a maximum of $30 \text{ kg t}_{\text{hm}}^{-1}$ due to the low solid yield. Therefore, for fast pyrolysis an additional case was studied where the availability of biomass was doubled to $50 \text{ t}_{\text{dry}} \text{ h}^{-1}$. Results from this case are illustrated in **Figure 18**, which show that for a biomass price of $20 \text{ € t}_{\text{dry}}^{-1}$ the penalty fee for specific emissions still needs to be above $40 \text{ € t}_{\text{CO}_2}^{-1}$ for the investment to become feasible.

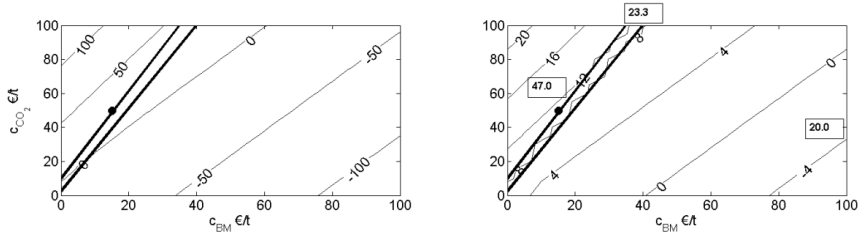


Figure 18 NPV (left panel) of the investment for **fast pyrolysis** expressed in M€ and the specific economic benefit in operation cost of the concept compared to the reference case (right panel) for a case with higher biomass availability (50 t h^{-1} , dry basis).

The results for slow pyrolysis, depicted in **Figure 19**, were the most promising ones. Here the break-even point for the investment comes already at a low emission penalty fee, which is about $10 \text{ € t}_{\text{CO}_2}^{-1}$ for a biomass price of $20 \text{ € t}_{\text{dry}}^{-1}$. At a penalty fee of $20 \text{ € t}_{\text{CO}_2}^{-1}$ the economic benefit is expected to be about 35 M€. Almost full injection rate of char ($47 \text{ kg t}_{\text{hm}}^{-1}$) is applied and the coke replacement ratio is close to $0.9 \text{ kg kg}_{\text{coke}}^{-1}$. Similar replacement ratios for different biomass conversions have been reported in [70].

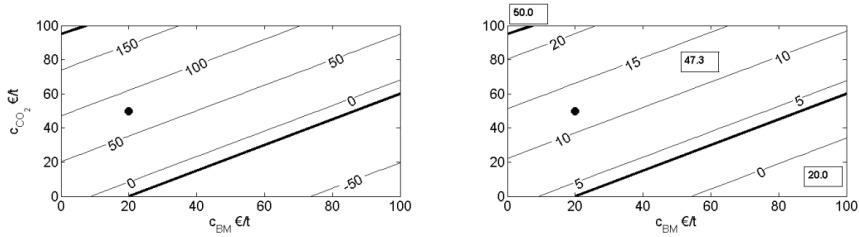


Figure 19 NPV (left panel) of the investment for **slow pyrolysis** expressed in M€ and the specific economic benefit in operation cost of the concept compared to the reference case (right panel).

Table 12 summarizes the states of the BF and reports some key indices of the steel plant for the cases illustrated in Figures 17-19 at the points indicated by bullets in the left panels. For this study a low biomass price and a high emission penalty ($c_{\text{CO}_2} = 50 \text{ € t}^{-1}$) were chosen to guarantee that the optimal solution lies in the region with the higher specific injection rate of biomass char. The first column shows the reference case, where no biomass is injected, which was simulated with a PC injection rate of $150 \text{ kg t}_{\text{hm}}^{-1}$ and a blast oxygen content of 25 %. In all cases with biomass injection the flame temperature was kept constant at the level of the reference case by adjusting the blast oxygen content.

Table 12 Operation states and investment costs at an emission penalty of **50 € t⁻¹** CO₂ and a biomass price of **20 € t⁻¹**. (*biomass price of **15 € t⁻¹**) The steel production rate for all cases is **150 t h⁻¹** (corresponding to a hot metal production rate of **146.7 t_{hm} h⁻¹**), the blast temperature is 1100 °C and the flame temperature 2140 °C.

	Reference	Torrefaction	Fast pyrolysis*	Slow pyrolysis
<i>Figure</i>	-	17	18	19
Blast furnace:				
<i>Blast volume (· 10³ m³ n h⁻¹)</i>	148.9	137.5	147.0	149.8
<i>Blast oxygen (%)</i>	25.0	27.7	25.1	24.4
<i>Biomass feed (t h⁻¹)</i>	-	10.4	38.7	19.2
<i>Pulverized coal (kg t_{hm}⁻¹)</i>	150.0	114.4	110.1	100.0
<i>Biomass char (kg t_{hm}⁻¹)</i>	-	50.0	47.0	47.3
<i>Coke rate (kg t_{hm}⁻¹)</i>	319.8	333.5	320.5	315.8
<i>Limestone (kg t_{hm}⁻¹)</i>	34.0	35.1	33.1	32.2
<i>Bosh gas volume (· 10³ m³ n h⁻¹)</i>	201.9	196.6	200.0	200.8
<i>Top gas volume (· 10³ m³ n h⁻¹)</i>	221.2	213.6	220.0	221.4
<i>Top gas temperature (°C)</i>	172.7	144.3	169.5	176.3
<i>Top gas CO (%)</i>	22.7	24.7	23.2	22.5
<i>Top gas CO₂ (%)</i>	22.9	24.2	23.2	22.8
<i>Top gas H₂ (%)</i>	3.4	4.3	3.3	3.2
<i>Slag rate (kg t_{hm}⁻¹)</i>	223.1	221.7	219.3	216.8
Steel plant:				
<i>Electricity bought (MW)</i>	27.8	26.9	26.3	30.7
<i>Heat sold (MW)</i>	92.3	102.1	112.7	85.1
<i>Top gas to stoves (· 10³ m³ n h⁻¹)</i>	71.8	59.0	69.8	73.9
<i>Coke oven gas (· 10³ m³ n h⁻¹)</i>	22.3	23.2	22.3	22.0
<i>Specific CO₂ emission (t t_{steel}⁻¹)</i>	1.70	1.65	1.56	1.53
<i>Natural gas cons. (m³ n t_{steel}⁻¹)</i>	13.2	13.2	0.0	4.0
<i>Biomass liquid (kg t_{steel}⁻¹)</i>	-	-	143.3	51.1
<i>Extra TG to drying (· 10³ m³ n h⁻¹)</i>	-	4.3	31.1	11.2
Economics:				
<i>Biomass price (€ t⁻¹)</i>	-	20	15	20
<i>Production cost (€ t_{steel}⁻¹)</i>	327.7	325.2	316.4	315.5
<i>Diff. to reference (€ t_{steel}⁻¹)</i>	-	2.5	11.2	12.2
<i>Investment, drying (M€)</i>	-	11.5	30.0	15.0
<i>Investment, conversion (M€)</i>	-	10.3	31.2	17.7
<i>OPEX difference (€ t_{steel}⁻¹)</i>	-	1.1	7.4	10.2
<i>NPV (M€)</i>	-	-9.9	19.2	77.6

In the case of torrefied biomass, pulverized coal injection drops from the base level to 114 kg t_{hm}⁻¹ when 50 kg t_{hm}⁻¹ of torrefied biomass char is injected. However, the coke rate simultaneously increases by nearly 14 kg t_{hm}⁻¹ and a higher blast oxygen content is required to reach the desired flame temperature. For fast pyrolysis, when biomass availability has been doubled and the price of biomass is $c_{bio} = 15 \text{ € t}^{-1}$ (by contrast to $c_{bio} = 20 \text{ € t}^{-1}$ in the other columns), the char injection rate reaches 47 kg t_{hm}⁻¹, which is almost at its upper limit. Here, the pulverized coal injection is reduced down to 110 kg t_{hm}⁻¹. For slow pyrolysis, where also 47 kg t_{hm}⁻¹ of char is used, the pulverized coal injection rate drops by 50 kg t_{hm}⁻¹ and the coke rate decreases by 4 kg t_{hm}⁻¹ compared to the reference case while the flame

temperature is maintained with slightly lower blast oxygen content. As for other BF variables, Table 12 illustrates that the values stay within reasonable limits, indicating that the points of operation could be feasible. The table also reports the specific CO₂ emissions of the plant, showing a decrease in all cases compared to the reference case: the torrefaction case reduces the CO₂ emissions by 50 kg t_{steel}⁻¹, fast pyrolysis by 140 kg t_{steel}⁻¹ and slow pyrolysis by 180 kg t_{steel}⁻¹ for the injected amounts used in the analysis.

The liquid phase of the pyrolysis contributes significantly to the economic objective function since it is taken to replace other fuels in the steel plant. Therefore, a case with a more conservative estimate of the use of bio-oils was investigated. A 50% decrease in bio-oil utilization was found to shift the NPV contours for the optimal solutions down in the diagram by about 10-15 M€ for slow pyrolysis and by about 20 M€ for fast pyrolysis, which stresses the significance of the bio-oil utilization. By contrast, further treatment of the bio-oil could increase its value and make it attractive for re-sales purposes, which, in turn, could make the fast pyrolysis more appealing than what it now seems in these results. Still, without doubt, the slow pyrolysis is the best alternative for biomass conversion according to these results, while torrefaction is the least attractive one.

7. Conclusions and Suggestions for Future Work

In this PhD thesis, the resource allocation within a steel plant with biomass used as auxiliary reductant and fuel has been optimized by minimizing the production cost of steel by mathematical modelling and optimization. The stochastic models evaluated proved to be robust but slow. For larger problems, the different MILP, NLP and MINLP methods were to be preferred. The key finding has been that slow pyrolysis seems to be the preferable option for biomass conversion in the steel plant. This result would not have been so obvious unless the utilization of the volatiles from the biomass conversion process had been accounted for. However, the profitability of the investment is dependent on many assumptions that can shift the break-even point to some extent. Nevertheless, the results indicate directions for future studies. A more detailed study of the different investment costs and utilization degrees of the condensable and non-condensable volatiles should be undertaken as well as a better assessment of the impact of injecting char into the raceways on the combustion conditions and the coke replacement ratios in the blast furnace. As a final remark, there is great potential in biomass utilization in the steel industry and even though the profitability might not yet be clear, future political actions could change the situation. Yet, it is essential that the biomass resources are harvested, transported and converted in a sustainable way so that there is a net saving in regards to carbon dioxide emissions.

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