Forestry meets Steel. A Technoeconomic study of the possible DRI production using biomass

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Summary
The possibility to produce DRI using gasified Biomass is studied in a cooperative project. LTU, MEFOS, ETC and five industries in the areas forestry & pulp, mining, iron and gas are involved. The production chain Biomass production and distribution -Gasification-DRI production-DRI use is investigated in four work packages:
WP1: Biomass supply: A large amount of Biomass has to be delivered into a single site to exchange a large amount of fossil reductant. It is important to use forestry by-products as a major part of round wood is reserved for other uses. Harvesting, logistics and economics have to be considered. Available data were collected and used to make a system model on harvesting treatment and transport. The simulations indicated that the supply of residuals is possible but will need material from a large part of the north Sweden wood area. WP2: Gasification. The aim is to use to produce hot gas that can be used directly. Pilot experiments are carried out using oxygen in an entrained flow gasifier. WP3: Metallurgical processes. Reduction tests are carried out with gas that can be produced in the gasifier. The limitations of the gas content are studied as well as the effect on DRI. Also the suitability of the DRI product is evaluated WP4: Process integration. A system model is built using the results from work packages 1-3 and used for technical economic optimization the whole system harvesting-transport-gasifier-direct reduction-use of DRI.

The process chain is technically possible; however there are problems to be solved, e.g., gas quality vs. demands from DRI process, Biomass supply and logistics. The result is important to evaluate for industrial application, but also to get information of the effect of different governmental control instruments.

Key Words
Green steel, BioDRI, Logistics, System study, Biomass gasification, substitution of fossil coal

Introduction
The CO2 emissions in the world are looked upon as a danger to the climate. The most important CO2 source for the steel industry is the use of fossil coal for reduction. Figure 1 shows the distribution between energy carriers in the Swedish steel industry.

Fossil coal is the dominant fossil source but also oil and gas are important. It has been considered important to study the possibility to substitute the fossil reductants and energy carriers with renewable sources, e.g., biomass. Different approaches have been studied with the Swedish steel industry. A study on the possibility to substitute the oil and gas used in reheating furnace with biomass was carried out in 2012-2013. It was a cooperative project, organized by Jernkontoret (the Swedish Steel Producers’ Association), see e.g., [2] [3] The result indicated that a gasifier to produce fuel gas was the best solution. A study was carried out in 2013 on the possibility to use converted biomass (torrified or char) as "bio coal" for injection or charging in a blast furnace. The result indicated a potential to replace 457 ktonne PC coal (or 4 TWh) if the conditions in furnace remain unchanged. [4].

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Figure 1 Energy use in the Swedish Iron and steel industry [1]
The European ULCOS (Ultra Low CO$_2$ Steelmaking) project tested several approaches to decrease CO$_2$ emissions. One of them was to use natural gas to produce DRI and then melt the DRI in EAF or BF furnaces [5]. Also a case with a coal gasifier was included [6]. Buergler [7] also made a study with rough calculation on an estimated case using gas that was generated from biomass and technical oxygen (95% O$_2$) in a fluid bed gasifier (see).

One problem with the calculations in [7] is that the syngas was assumed to have a CO$_2$ content of 5.4%. This is regrettable not realistic, since the gasification of biomass tends to give a higher CO$_2$ content than syngas from other fuels. This is mainly because of the content of oxygen in biomass. A shifter was assumed before the CO$_2$ separation in the calculations in ref. [5] and [6] but not in those of Figure 2 and [7].

Later, Bergman et al. [8] presented a system study on a case where which the ULCOS BF concept was applied at the Luleå steel plant. This indicated a system problem: the decrease in coke also decreased the availability of the rest gases that are presently used for district heating in Luleå. The extra fuel to compensate for this decreased the effect on CO$_2$ emissions. A conclusion is that system studies involving local conditions are important.

It was considered that it would be of interest to study the applicability of biomass based DRI production for Scandinavian conditions. Initial calculations indicated that replacing 50% of the ore burden (pellets) in a 2.5 Mton BF with biomass based DRI could cause a reduction of around 1 Mton CO$_2$ [9]. A study was then considered interesting and financing was obtained. A project started and has been carried out during 2014-2015. It is a cooperative project with participation of Luleå University of Technology (LTU), the research institutes Swerea MEFOS and ETC, as well as the industrial partners LKAB (mining), Höganäs (iron production), Sveaskog, Billerudkorsnäs (forestry and paper) and AGA Linde (gases). The project is cofinanced by the Swedish Energy Agency and the partners. The project structure is shown in Figure 3.

There are four work packages. WP1 handles the logistic problem of supplying up to 1 Mton biomass to one user. WP2 studies the gasification process in the pilot unit of ETC. In WP3 reduction processes and use of DRI are studied by laboratory experiments at LKAB and Höganäs as well as by theoretical evaluations. In WP4 a system study is made of the whole production chain, from forestry to production and use of DRI.

**Modeling**

Sweden and Finland are to a large extent covered by forests (see Figure 4) so woody biomass should be the major biomass supply in this case.

**Figure 2**: Principal flow sheet for gasifier + DRI production. The original sheet is from Buergler [7], the gasifier and some explanations have been added.

**Figure 3**: Project structure.

**Figure 4**: Forest areas in Europe [10]
been focused on the possible use of forestry by-products. There are usually of the following types: tops & branches (GROT), long tops, thinning, grubbing and stumps. Over the years the Swedish wood industry has made studies on the available wood resources. A relatively new, updated study by Thuresson [11] has been used in this project to get a quantitative estimation of by-product biomass. The study is based on statistics and data for the four balance areas that are commonly used in Swedish wood statistics; BO1-BO4. These are shown in the map on the left in Figure 5.

Then the balance areas were subdivided into smaller areas and the transport costs were calculated from each subarea. The subdivision for the northern balance area (BO1) is shown in Figure 6. The background map is from the transport study by Andersson and Frisk. The intensity of forestry in each subarea was estimated from the density of transport and multiplied by the area to get the distribution of production among the areas. A subarea in Finland close to the Swedish border was also included as suggested by the forestry partners. The forestry production from that area was calculated from the Finnish Statistical Yearbook of Forestry [12].

Figure 5 Biomass availability. Based on data from [11]

The diagram on the right in the figure shows the available amounts of biomass in these areas according to Thuresson’s study. The black bars show the estimated possible increase in the amount of biomass by-products that could be extracted from those areas. Thuresson also estimated the part that would be consumed by planned new users, (e.g. heat and power plants) in the same areas. These are shown as grey bars in the diagram. The white bars show the remaining quantity that is not already claimed by other parties. In principle, an additional user, e.g., a steel plant has two choices:

- Avoid competition by using the material that has not been claimed yet according to the white bars.
- Compete with other users by using the material available according to the black bars (but this will probably increase the price of the biomass by-products)

Figure 6 Subdivision of the northern harvesting areas. The background map is from reference [13]

The transport distances from the terminals in each subarea to the user plant were estimated by measurements taken on the map, as well as the mean distance from the harvesting location to the closest terminal. The transport cost from harvesting locations to terminal was calculated from models in [14] and the transport cost from terminal to user was calculated from models by Johansson-Mortazavi [15]. A model for the marginal harvesting cost of logging residues and stumps was found in [14]. A problem is that this marginal cost is increasing rapidly in a non-linear way with increasing harvesting rate and that the MILP optimization model used for process integration needs linear functions. A stepwise approximation of the harvesting cost was used to get an equation for mixed integer linear model of the costs.

The process integration in WP4 is made using a model of MILP type: reMIND. This model works with linear expressions. Reality is seldom linear, so linear approximations have been made. It is important to test these before use. For this reason an Excel model
of the total process chain has been made where the linearized equations are tested. The Excel model in itself is also a powerful tool and has been used for initial system modelling. The reMIND model is still being built, so the main part of the calculations in this paper are made with the Excel model.

Experimental
Pilot scale gasification experiments are carried out at ETC. The gasification is made with Biomass powder + Oxygen in an entrained flow gasifier. One motivation for choosing that type is that it tends to give a gas which is closer to equilibrium. Theoretical calculations have been made in parallel to estimate up scaling effects.

Reduction experiments have been carried out in the pot furnace at LKAB’s laboratory in Malmberget. The effect of the syngas composition on reduction rate and DRI quality was studied.

Results
The experiments in LKAB’s pot furnace were made both with direct reduction pellets (KPRS) and blast furnace pellets (MPBO and KPBA). This was to cover DRI products for a final use both for arc furnace melting and in blast furnace burden. The effect on reduction rate is illustrated as a function of temperature in Figure 7. Two main types of reduction gas were used: “Stark” = strong gas with low CO2 and “Svag” = weak gas with high CO2 (15%).

Figure 7 Summary of pot furnace experiments. Effect of pellet type, gas composition and temperature on reduction behavior

The result shows that the type of pellets has limited influence on reducibility. On the other hand the gas composition can be crucial: a weak gas gives a slow reduction that can be disastrous for the economy.

The effect of the process parameters on the tumbling strength is shown in Figure 8.

Figure 8 Summary of pot furnace experiments. Effect of pellet type, gas composition and temperature on tumble strength

Here the gas composition has limited effect. Instead the effect of pellet type was high: the blast furnace pellets (KPBA and MPBO) gave a strong DRI. On the other hand the direct reduction pellets (KPRS) gave a DRI with lower strength. However, this is usually acceptable as the strength demand for their normal use is lower than the demand for blast furnace use.

The Excel model that was originally built for model testing was also used for an extensive amount of simulations about the harvesting, transport and use of biomass with different parameters. Figure 9 shows the amount of biomass that had to be delivered from the different sub-areas in northern Sweden and Finland to a steel plant in Luleå. The areas SE1 to SE9 refer to Swedish subareas 1 to 9 in the map in Figure 6, and the area FI1 is the subarea in Finland in the same map.

A simplification has been made by lumping tops & branches, long tops, thinning and grubbing into one big group of GROT (this was considered acceptable at this stage as long tops, thinning, grubbing are small compared to tops & branches). Accordingly, the diagram shows the volumes of GROT and stumps that are taken from each subarea as well as those that are not taken.
Figure 9 Delivery of biomass to a BioDRI plant close to the steel plant site in Luleå. 80% recirculation of DRI top gas, competition on biomass avoided. (Numbering of subareas according to Figure 6)

The diagram shows that the model prefers to use material from the closest area (because of transport cost). On the other hand the model also considers the effect of the harvesting cost. This is increasing progressively with the harvested quantity. When it has increased enough, it is less expensive to take the cheaper initial amount from the next area and pay an increased transport cost. In addition, harvesting is more expensive for stumps, so that it may be profitable to leave an amount of stumps in an area and take more GROT in the next one.

According to the flow sheet previously shown in Figure 2 the off gas from the DRI shaft is partly recirculated and injected again after removal of CO₂ and H₂O. It is possible to choose

- Either a high recirculation rate and use as much return gas as possible for reduction. This results in a lower biomass consumption
- Or a lower recirculation rate and use more of the remaining off gas for other purposes, e.g. heat and power production. This would result in a higher biomass consumption

Figure 10 shows the effect of different recirculation rates on the biomass balance. The calculation was made assuming a shifter before the CO₂-adsorption (like in ref

Figure 10 effect of the degree of recirculation and of the competition policy on the availability of biomass and top gas export

The diagram shows that a recirculation degree of about 70% is needed as a minimum in case competition is avoided with the other users that have already claimed the amounts of biomass according to Figure 5. If competition is chosen, then it is possible to get enough biomass to reduce the recirculation degree down to about 40%. However, if zero recirculation is chosen, the available biomass by-products in BO1 and in the northern Finland area are not enough so extra import would be needed.

The recirculation rate must also be lower than 100% to avoid N₂ accumulation.

A certain amount of recirculation can also be necessary to dilute a syngas with a relatively high CO₂ content. Figure 11 shows the results from a calculation with a syngas input from the gasifier having 11% CO₂. The simulation had to be made using an iterative procedure in Excel, since a change in the input gas composition changes the composition of return gas from carbon capture, and this in turn changes the input gas composition, closing the loop.
Discussion
A problem with Biomass gasification is that the CO2-content of the Syngas is higher than for other fuels. On the other hand a low CO2 in the gas is preferred in the DRI process. This will need a careful balancing of process parameters e.g. recirculation rate. It will also create a need to improve processes to get a good match between produced and needed gas quality. A gasifier method that is relatively close to equilibrium is preferable.

A possible solution if CO2 is not low enough could be to that the syngas also passes through the CO2-separator, e.g., by adding it to the top gas directly after the DRI reactor. This has not been included in the model so far but it could be of interest.

A general problem in the development of renewable technology is that it has to compete with existing fossil energy carriers that are now relatively cheap. Some type of governmental instruments can be of needed to support the introduction. These should be formulated so as not to hamstring regional industry. It is important to continue research and development in this area with the target to have technologies with a relatively short time to application when if conditions change.

It is important that these done without hamstringing the regional industry. Research to help with that is important.

Conclusion
A study is made on the possibility to decrease climate effect of primary iron making. The preliminary results indicate that it is technically possible. However, a careful balancing of gasifier and reduction process is necessary because of the effect of biomass oxygen on the gas quality. The result is important to evaluate for industrial application, but also to get information of the effect of different governmental control instruments

Abbreviations
DRI Directly Reduced Iron
GROT Tops and branches (a forestry by product)
MILP Mixed-integer linear programming
ULCOS EU project “Ultra Low CO2 Steelmaking”
EAF Electric arc Furnace
BF Blast Furnace

All abbreviations used in the paper should be explained in a table.

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