Forestry meets Steel. A system study of the possibility to produce DRI (directly Reduced Iron) using gasified biomass.

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Abstract:

The main production of primary Iron from ore is now made by reduction using fossil reductants, either by producing hot metal in the blast furnace process or as directly reduced iron with natural gas as most common reductant. The climate gas impact would be improved if at least part of the reductants could be produced from Biomass. One possibility could be to use gasified Biomass to produce DRI (Directly Reduced Iron). This is studied in a cooperative project where LTU, MEFOS, ETC and five industries in the areas forestry & pulp, mining, iron and gas are involved. The investigation is made in four parts where the first one is on the supply of biomass. A large amount of Biomass has to be delivered into a single site to exchange a large amount of fossil reductant. Also, forestry by-products should be used as most of the round wood is reserved for other uses. Harvesting, logistics and economics are considered. The second part is on the gasification of the biomass, where 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. The third part is on the metallurgical processes, where 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. The fourth part of the project uses process integration to model the whole process chain. The results from the other project parts are used to build the system model. It is then used for technical economic optimization the whole system harvesting-transport-gasifier-direct reduction-use of DRI. The first use of the system model has been to find the best supply road (harvesting, pretreatment and transport) for a chosen production case The simulations indicated that the supply of residuals is possible but will need material from a large part of the north Sweden wood area, and that a relatively large amount of gas recirculation is needed. The continuing work is focused on further development of the optimization tool and the use of it for more extensive studies of the trade-off between parameters of metallurgy, gasification and supply. The result can be important for evaluation of future industrial applications. It could also help in understanding the effect of governmental control instruments. The paper will mainly focus on the process integration study.

Keywords:

Energy, Biomass, Gasification, Iron making. DRI, Process Integration, System Models.

1 Introduction

1.1 Technical/Economical background

1.1.1 Steelmaking and climate gas

The major primary steel production uses an ore based route: Coke is produced from coal in a coke plant → Hot liquid metal is produced in a blast furnace using ore and coke→ the hot metal is refined into steel in a basic oxygen converter. The Swedish production of crude steel was 4.4 million tonnes in 2013. Almost two thirds of that was ore based [1]. According to Fig. 1 the consumption of coal for that production was in the range of 16-17 TWh; it was lower in 2013 because of a lower production rate.

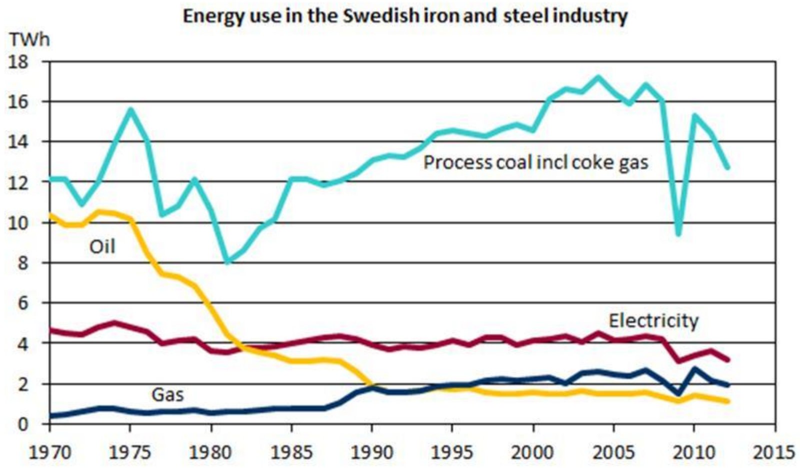


Fig. 1 Energy consumption in Swedish steel industry [2]

The main part of the coal is converted to CO_2 in the process and/or subsequent use of the process gases It is important to find ways to exchange the fossil fuels or reductants with renewable energy carriers in order to decrease the climate effect. In Sweden a recent project was carried out in order to exchange the fuel for steel reheating with biomass [3][4] and another study was made on the possibility to exchange injected coal in Blast furnaces with "Biocoal" [5]. Extensive research has been carried out in national and international break-through initiatives e.g. the European cooperative research program ULCOS (Ultra-Low CO_2 Steelmaking) [6]. One concept was ULCORED [7], [8] (and patent application [9]), where natural gas was used to produce DRI (Directly Reduced Iron). A simplified flow sheet is shown in Fig. 2.

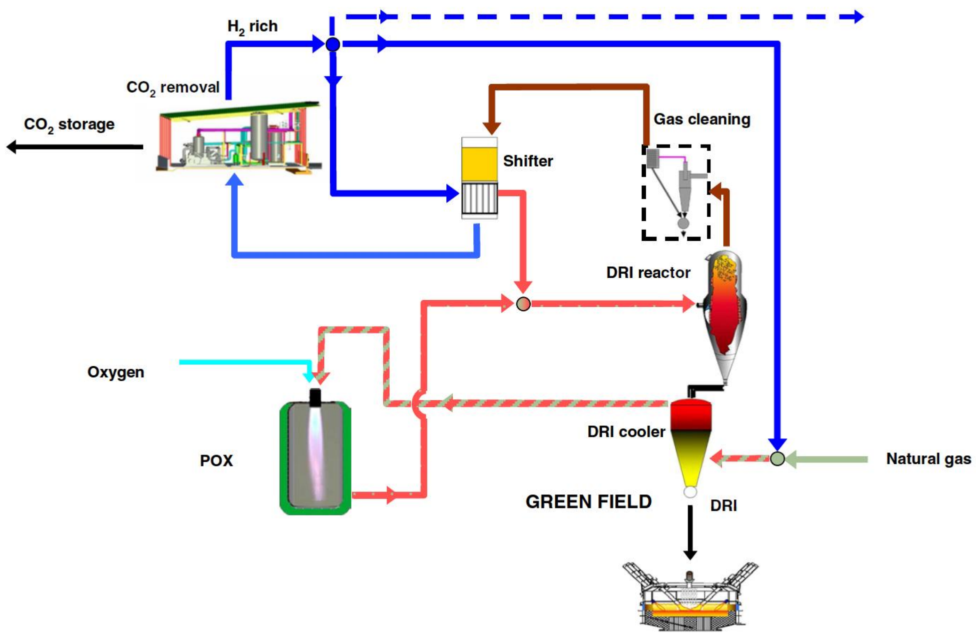


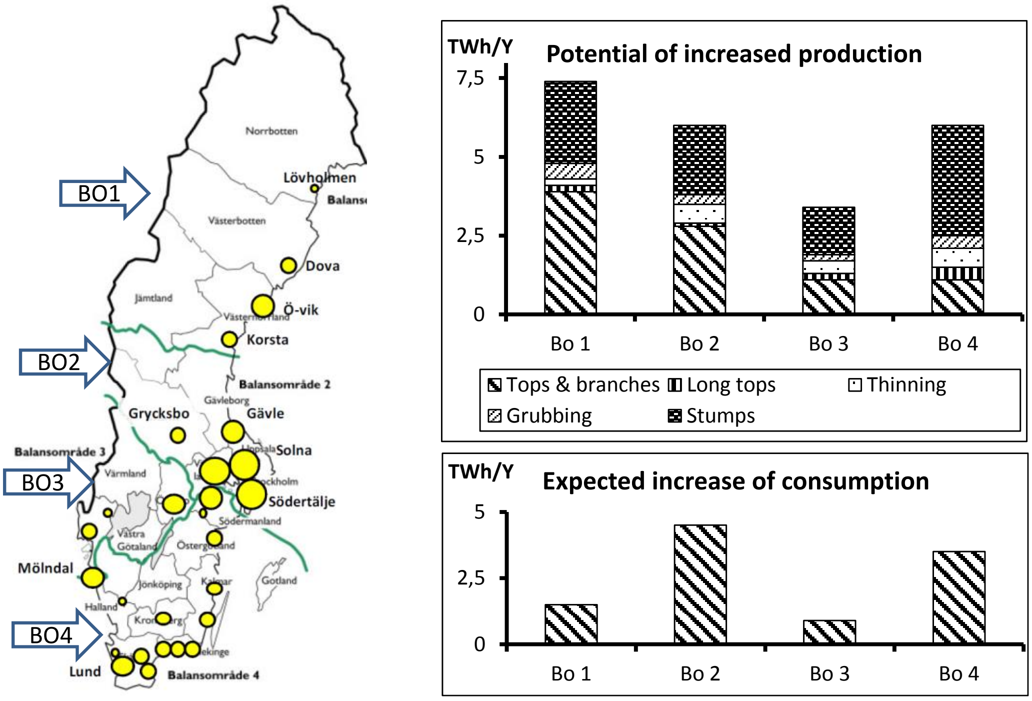
Fig. 2 ULCORED concept: lower climate gas emission with natural gas and DRI production [7].

Natural gas is converted to hot syngas with Oxygen (POX unit). The hot gas is sent into a DRI reactor where it reacts with iron ore pellets to produce DRI, which is cooled and melted in Electric arc Furnace (EAF) or Blast (BF) to produce liquid iron or steel. The gas is recirculated after gas cleaning, CO conversion in a shifter, CO2 removal and drying. The main effect of the shifter is a higher H_2/CO ratio in the recirculation gas. Also Buergler and Donato [10] made a study where the syngas was created from Biomass in a fluidized bed gasifier with high pressure oxygen. Their recirculation was made without shifter and there was also a heater before injection into the reactor. The CO_2 content of the syngas was set at 5.5 %. This seems a little bit too

low. It could be compared e.g. with a technology assessment of a similar type of equipment that was carried out for the American National Research Laboratory by Worley and Yale [11]. That study indicates CO_2 contents in the range 19-27% (vol. dry) for full scale equipment (1,000 oven dry metric tons/day of wood residue).

1.1.2 Biomass availability in Scandinavia

A recent update on availability of biomass from Swedish forestry was made by Thuresson [12].



a) *Balance areas (BO) and potential increase of use in these [12].*

b) *Estimation of unused techno-economic potential 2009 and expected expansion of consumption till 2015, TWh. Based on data from reference [12].*

Fig. 3 Potential for increased production of woody biomass. Based on data from reference [12].

The studies was based on division of the wood area into balance areas (BO1-BO4) as defined in Fig. 3 a. The upper diagram in Fig. 3 b shows that there is a potential for increased Biomass harvest. The lower diagram and the circles in Fig. 3 a show that this is partly consumed by an increased expansion of biofuel users especially in the BO2 and BO4 areas. The net effect is a considerable surplus in the northern area (BO1) and to a limited extent in the western area (BO3). The areas of most interest in this study are BO1 for the northern case (DRI to a steel plant in Luleå) and BO4 for the southern case (DRI for powder production in Höganäs and/or Halmstad).

In principle a new user can chose between two strategies:

Strategy A. Avoid competition, i.e. use volumes that are not booked for increased consumption by other parties i.e. use the difference between the two diagrams in Fig. 3.

Strategy B. Accept competition with other users and higher price, i.e. use the total increase in volume according to the upper diagram in Fig. 3

1.2 System studies. Process integration

The development of process integration started in the 70's when B Linnhoff introduced the Pinch methodology [13]. Later on other methodologies were introduced, e.g. exergy analysis [14] and mathematical programming, e.g. methods based in MILP (Mixed Integer Linear Programming). The most common of these in Sweden is MIND [15]. It has later been further developed into reMIND which is presently used e.g. for steel applications. Examples of the use in Swedish pulp and paper mills are given in [15], [16]and [17] and of the use in Swedish steel industry in [18], [19] and [20].

1.3 Project idea and structure

The climate gas impact would be improved if at least part of the reductants could be produced from Biomass. This study is part of a cooperative project where LTU, MEFOS, ETC and five industries in the areas forestry & pulp, mining, iron and gas are involved. The production chain studied is: 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 are considered. 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.

1.4 Scope of paper

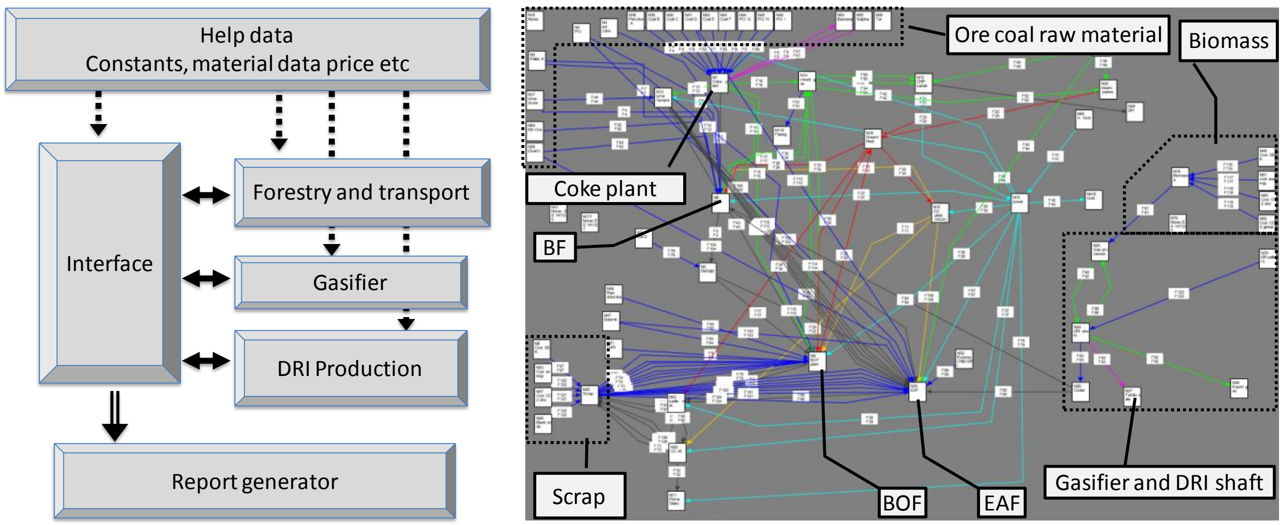
The scope of the paper is to describe the work in the system study

2 Process integration models

The available data and process models were expressed as linear equations, suitable for MILP optimization. These relations and data were then used in system models with two ambition levels.

a) An Excel simulator. This was primarily built as a test bench for the linear relations. However it turned but also to be a useful system evaluation tool in itself.
b) A system optimization Tool, using Mathematical programming in reMIND

The principal structure of these two models is shown in Fig. .



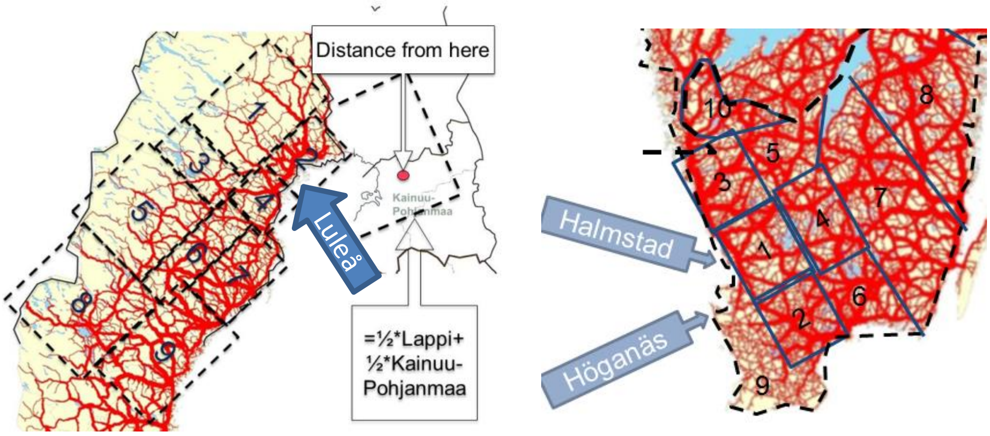
a) Excel simulator *b) reMIND optimizer, graphical interface & explanations*

Fig. 4 Principal structures of system models.

2.1 Modelling with Excel simulator

The model was built in Excel. The principal structure is shown in Fig. a. It is similar to the one that has successfully been used in previous system models, E.g. the “Totmod” at SSAB and MEFOS [21], the system models of Jernkontorets project 50156 on biofuel for steel reheating furnaces and LTU:s BLF (Black liquor fractionation) project. The model uses sub models that are connected to a common interface model (one sheet per sub model). All information exchange between the sub models goes through this interface. Direct exchange between them is not allowed, because of risk of bugs. There are some common tables with data constants that are common for all models. The sub models can access these data directly through one way communication. There is also a report generator with a one way communication from the interface sheet. The purpose of the excel simulator was both to be a forceful simulation tool in itself and to test the linear models that are needed for the reMIND model. For this reason the same equations were used in both models.

The forestry sub model uses balance areas that are divided into subareas. The subdivision used for the simulation of northern and southern case is shown in Fig. 5. A map of total forestry transport is used as a background. It is taken from a study on forestry transports in 2012 [22]. The case in Fig. 5 a includes the balance area BO1 divided into 9 subareas + 1 area from northern Finland. Forestry data from the Finnish Forestry Statistics [23] were used to model that area. The case in Fig. 5 b includes BO4 divided into 9 subareas + 1 area from BO3. (BO1-BO4 are defined as in Fig. 3 a.)



c) Subdivision for northern case   *d) Subdivision for southern case*

Fig. 5 Subdivision of balance areas for simulation of northern and southern case

The relative distribution of production between the subareas was estimated from their measured surface and the local transport activity according to the background map. After harvesting the biomass was estimated to be chipped at the forestry landing and then transported to a local terminal. From there it was further transported with another type of truck to the user. A model for the harvesting cost of was created from a diagram in reference [24]. The marginal cost for both GROT and stumps was nonlinear and showed a very high progressive increase with increased harvesting volume. It was higher for stumps. The reMIND model needs a linear expression. For this reason the marginal harvesting cost was approximated with a constant value that increased stepwise. The cost for chipping + transport from landing to terminal was estimated from reference [24]. The cost for transport from terminal to user was modeled from data and knowledge in reference [25] and [26]. These data were given both for truck and truck + rail. The forest industry partners hinted that they only used truck transport. Thus, truck transport was used for the calculations in this paper.

An optimization routine was included as an Excel MACRO, which was based on the existing sorting and copying routines in Excel. This made it possible for the model to choose the most economical combination of deliveries from the available sub-areas.

A calculation was also included for the effect of recirculation with CCS refining on the composition of input gas to the DRI reactor. This model is iterative as the recirculated gas influences the composition of injected gas, and this in turn influences the top gas composition in the next round etc.

The gasification is presently studied by experiments with oxygen and biomass in pilot scale entrained flow equipment at ETC and also by theoretical calculations [27]. One reason for choosing this process was that it can be stalemated to get relatively close to equilibrium. The experiments are still going on. Waiting for the results a gas composition with around 4 % CO2 above adiabatic equilibrium has been used. This was estimated by ETC from previous knowledge. The equations for the DRI reactor and CO_2 + H_2O removal were preliminarily modeled from data in the paper by Buergler and Donato [10]. Also experiments in LKAB:s laboratory are used to study the effect of the syngas on the DRI reduction [28].

The simulations are controlled from the interface. At present input is provided for the following control parameters:

- Degree of recirculation for DRI top gas
- Lambda value for Gasifier
- Biomass transport method (Truck, truck + train or both)
- Competition strategy (Paragraph 1.1.2), i.e., compete or use only quantities that are not utilized by others.
- Northern case: Finland included or not included

The chipping is assumed to be carried out at the terminal in all cases

2.2 ReMind model of the total system forestry →DRI→steel

The reMIND model uses an interface and program created in JAVA to create equation matrix that can be evaluated in the commercial software CPLEX. CPLEX delivers an output in a text file, that is then evaluated in excel. The input routine has a graphical interface which is shown in Fig. b. The position for the subprograms for coke plant, BF, BOF, gasifiers etc. have been manually included. The processes, sources and end products are shown as rectangular nodes that use an excel-like table for input of data and equations. The flows are symbolized with arrows that also use a similar input table.

The model uses objective functions which are defined in the model as cost, energy and CO_2 emission. Generally the objective function is imbedded within the optimization model but can in mathematical terms be written as follows.

$$\min\ z = \sum_{i=1}^{n} c_i x_i \qquad (1)$$

where z is the objective function for the minimization problem. It could be cost, energy or CO_2 emission, depending on what objective is set for the optimization. x is studied variables and c is coefficients set for the corresponding objective function and depends on which objective function. Some examples of coefficients set for the corresponding objective functions are shown in Table 1.

Table 1. Example on coefficients used for different objective functions

	Unit	Cost SEK	Energy	CO2 Site ton	CO2 global
Iron ore pellet	ton	312	0	0	0.051
Lime stone	ton	475	0	0.428	0.428
Mn ore	ton	0	0	0	0
Quartz	ton	220	0	0	0.01
Raw Dolomite Lime	ton	290	0	0.465	0.465
Dolomite Lime	ton	925	0	0	0.465

The set shown in Table 1 contains four coefficients per material, and the optimization can be set to maximize or minimize the contribution from any one of those. To make sure to get reasonable results, necessary boundaries are introduced. The boundary conditions, which can describe variations in the system, maximum and minimum for various variables can be expressed as follows.

$$x_i \le b_i, \quad i = 1,\ldots,n \tag{2}$$

where the x_i variable could be the corresponding flow variables, and the boundaries b_i, are the corresponding restrictions.

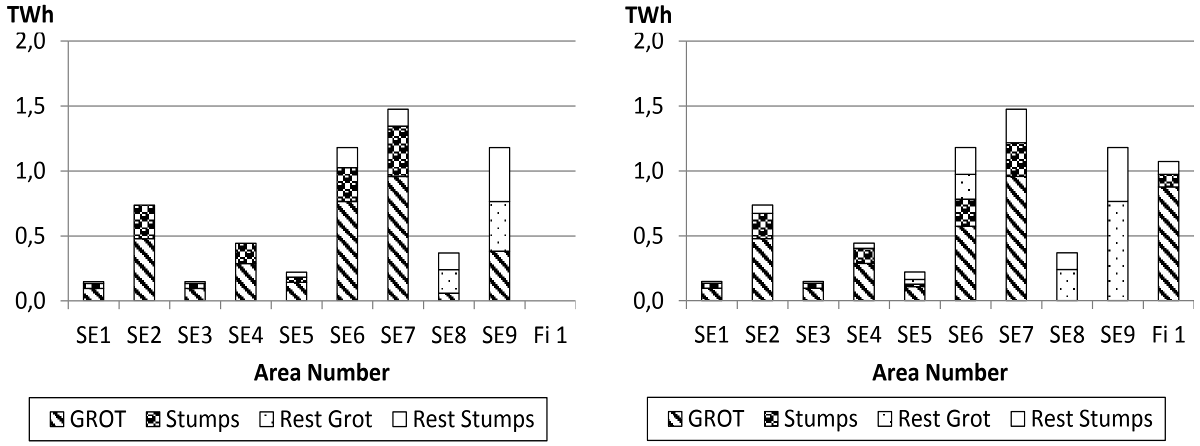
3 Results

3.1 Evaluation with the excel simulator

Fig. 6 shows the distribution of deliveries from different subareas in northern Sweden to the steel plant in Luleå. The definitions on the x-axis refer to the subareas defined in Fig. 5a. The calculation was made for the following case:

- Production level = Steel production in the environmental report for 2012
- 70% recirculation of DRI top gas
- Gasifier with Lambda =0.35
- The biomass transport was carried out by truck. The chipping is assumed to be carried out at the terminal.
- The Strategy A in 1.1.2 was chosen, i.e., only quantities that are not used by others are utilized.

Each bar shows (from the bottom and up): Used GROT, Used stumps, Unused GROT and Unused stumps. The left hand diagram shows the distribution if biomass is only taken from northern Sweden. The right hand picture also includes an area that corresponds to 50% of the expected production of the same residuals in the Lappi and Kainuu-Pohjanmaa areas in Finland.



e) Delivery only from Northern Sweden

f) Delivery also from close by area in Northern Finland

Fig. 6 Supply from subareas in BO1 + Northern Finland for Reference case Luleå

The diagrams show:

- The program minimizes transport cost by preferably picking from the closest area, but:
- Because of the progressive rise of harvesting marginal cost it is often profitable to leave the last quantity from a given area and instead go to a more far away area to get the cheaper initial quantity.
- GROT is preferred to Stumps because of lower harvesting cost.
- Inclusion of Finland causes a heavy decrease of the load on the more distant areas

The case corresponding to Fig. 6b, i.e. with Finland included has been chosen as a reference for the comparative studies below.

Sensitivity study: A series of simulations for the Northern case was carried out with different Degree of recirculation and different approach to competition, see Fig. 7. It was carried out for both strategies mentioned in paragraph 1.1.2

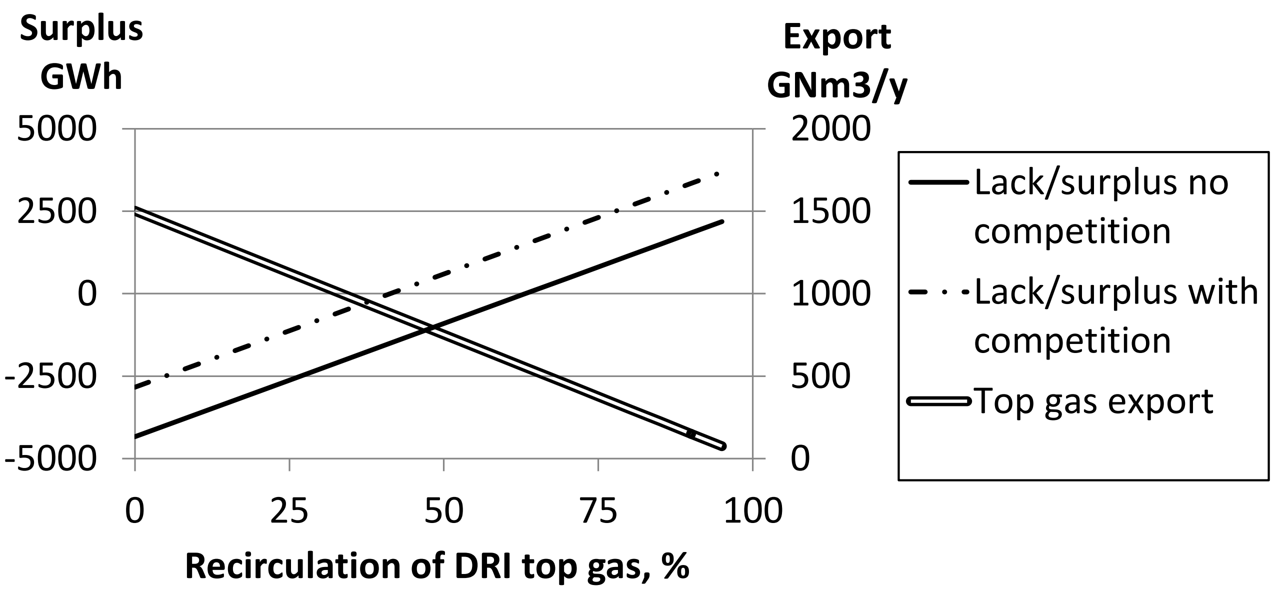
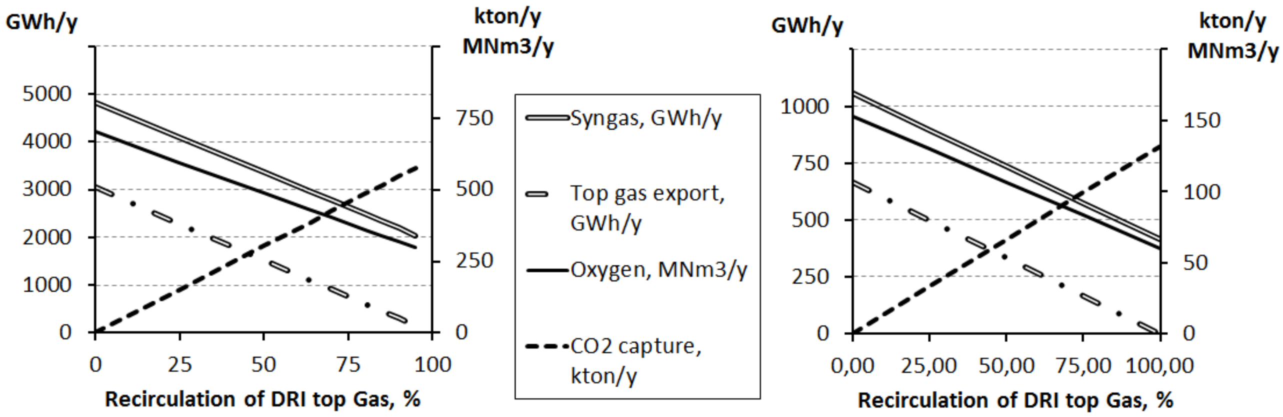


Fig. 7 Effect of recirculation rate on top gas export and biomass balance for the northern case

The left hand axis shows the unused surplus of biomass. A negative surplus shows that the available biomass in Sweden and northwest corner of Finland is not enough but that we have to import from elsewhere. The diagram shows that a recirculation of around 70 % is needed if we chose we use a no competition strategy, i.e. we use only biomass that no one else has booked. If we chose to compete and use all the biomass in BO1 we can manage with a little bit more than 40% recirculation. An advantage with lower recirculation is that we can export green top gas for other purposes and hopefully get some governmental support, e.g. green certificates



- *Southern case: DRI to EAF*
- *Northern case: DRI to BF*

Fig. 8 Sensitivity of heat and material balance to some parameters

- Fig. 8 shows the effect on some more parameters same for both the northern and southern case and also the oxygen consumption is shown. A higher recirculation rate saves oxygen as less biomass on the other hand a higher amount needs to pass the CO2 separation unit.

3.2 reMIND optimization

The reMIND model for system optimisation (i.e. bio-DRI plant that produce DRI that can be used in either blast furnace or electric arc furnace) has been tested and found to be executable and produce results that are in line with what is to be expected considering previous results from investigations of implications of use of DRI in the included subsystems (integrated steelmaking, and electric steelmaking and bio-DRI production).

The system effects of the bio-DRI plant in connection to the steelmaking systems have however not yet been evaluated. The current status of the ReMIND model is validation of calculation results regarding the connecting flows (in terms of energy and materials) between the sub-systems and total resource consumptions (energy consumption, CO2 emissions, production costs, etc.) for the entire system.

After validation the next step will be to define relevant optimisation scenarios and boundaries. Examples of scenarios to be executed are:

- Optimum composition of DRI (metallization degree and carbon content) to the blast furnace and the electric arc furnace, considering the process and quality related restrictions in the metallurgical processes and the operating span of the bio-DRI production facility.
- Optimal location of the bio-DRI plant.
- Optimal bio-mass mix for the bio-DRI plant.
- Optimal production rate and operating conditions of bio-DRI considering the demand of the steel industry.
- Calculation of value-in-use for bio-DRI in blast furnaces and electric arc furnaces.
- Calculation of bio-DRI demand for the steel industry considering varying prices on bio-mass, CO2-emissions, iron ore, steel scrap, etc.

4 Discussion

The position of the project is that the Excel simulator is has been developed and used to test and calibrate functions and parameters for the reMIND simulator. It has also been used as tool for evaluation of a system consisting of: - gasifier - DRI production. The results in paragraph 3 above are from that simulation. The Excel simulator includes an optimization tool that chooses the combination giving the lowest cost for Biomass harvesting and preparation +Transports to terminal and user. It uses copying and sorting tools for data tables. An increased scope would increase both the amount and size of these tables and create a large and unmanageable model and an increased probability for bugs. For this reason more extensive system optimizations should be carried out using the reMIND model, which is presently in a final phase of development.

The total reminds optimization involves processes and procedures carried out by operators in several branches. An important problem is that both nomenclature and definitions change when the material passes the process chain. E.g. in forestry the volumes are defined as cubic meters; transports can be defined for cubic meters or tons, in official statistics biomass is often defined in GWh, the metallurgical users usually measure weight in ton. Also the time base of operation can be different, calculations on continuous processes like blast furnace tend to use tons / hour. Other operators use tonnes per year or week or tonnes per ton steel etc. It is important to have a well defined system for defining of units and parameters throughout the model and a good documentation on this.

The reduction experiments at LKAB [28] indicated that the content in the reduction gas could be crucial, and that a high recirculation degree might not be enough. A straightforward solution could be to mix the gas with the top gas from the DRI reactor and let follow through the gas cleaning and CO_2 removal (see Fig. 2). Another solution for the southern case could be to mix a limited amount of natural gas which is available on the net there and for the northern case a limited amount of coke oven gas (contains methane). Preliminarily these roads should be included in the model.

The forestry model in the excel simulator was originally created as a separate excel model which was later on merged into the larger model. That model in itself is a general tool that could be used also for other biomass implementations.

5 Conclusions

- A simulation tool and has been created and used to simulate the process from harvesting to finished DRI and to find the cheapest harvesting /transport combination for a given case some calculation results are given.
- The Harvesting/transport model is general and could be of interest also for other biomass applications.
- A MILP (Mixed integer linear programming) optimization tool has been designed and is presently being finalised

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