Role of Ferrous Raw Materials in the Energy Efficiency of Integrated Steelmaking

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The role of ferrous raw materials and iron ore agglomeration in energy consumption of integrated steelmaking has been evaluated using a system-wide model. Four steelplant cases were defined: typical European steelplant with sinterplant; Nordic steelplant with sinterplant; European steelplant with sinter:pellet ratio of 50%, and Nordic steelplant charging pellets and a small amount of briquettes. Energy consumption in the mining system were estimated from published statistics at 150 MJ/t for lump ore and sinter fines, 650 MJ/t for pellets made from magnetite and 1,050 MJ/t for pellets made from hematite. An integrated steelplant model including all major unit operations was used to calculate overall system energy consumption from iron ore mining to hot rolled coil. Adjustments were made accounting for energy benefit of ground granulated blast furnace slag in cement production, energy required for cement production required for briquetting, and excess BF and BOF gas producing electricity in a 32% efficient power plant. The system-wide net adjusted energy in the first three steelplant cases showed marginal improvement with use of high grade sinter fines and decrease of pellet/sinter ratio to 50% compared to typical European case. Nordic steelplant charging pellets and briquettes had a reduction in system-wide energy of 5% to 8% for charging pellets from hematite or magnetite respectively compared to the typical European steelplant charging sinter and pellets made from hematite ore. Replacement of sinter with pellets was mainly responsible for the improvement with smaller contributions from magnetite ore in pelletizing.

KEY WORDS: iron ore; pellets; sinter; blast furnace; integrated steelmaking; energy.

1. Introduction

Steelmaking accounts for circa 7% of anthropogenic CO2 emissions worldwide.1) The integrated steelmaking route (blast furnace, BF – basic oxygen furnace, BOF) is the dominate production method. It is energy intensive with typical energy consumption figures on the order of 16–21 GJ/t crude steel with the value highly depend on system boundary definition.2) The majority of the energy comes from coal. In the integrated steelmaking route, the blast furnace relies mostly on virgin iron ores as a source of iron. The iron ores are agglomerated via sintering or pelletizing processes. Pelletizing is more energy efficient than sintering, however the sinter plant performs the important function of recycling materials within the steelplant and thereby improving the material efficiency. Because pelletizing is more energy efficient, a recent European Commission report recommends increasing the ratio of pellets in the ferrous burden to at least 50% on average in blast furnaces.3)

In the Nordic countries sintering has recently been eliminated altogether. The role of the sinter plant for recycling has been taken over by cement bonded briquettes. The Nordic ferrous burdens consist of almost 100% pellets plus briquettes and trim additives.3) The elimination of sintering resulted in a net gain in energy efficiency in the chain from mine to steel which we have described in an earlier work.5) In addition, the dominant source of iron ore for pelletizing and sintering is very high grade. The use of high grade iron ores has been cited as a Best Available Technology (BAT) in order to improve productivity and reduce blast furnace reductant consumption.5)

The pelletizing process uses much finer particle size feed compared to sinter plants which favor coarser ores. Regional differences in availability of iron ores has led to dominance of pelletizing in the Nordic countries and North America where fine grinding and beneficiation is required to achieve acceptable grades for ironmaking. Sintering dominates in much of Asia and Europe where coarser fines are imported largely from Australia and Brazil. However, there has been a decline in run of mine ore grades and exploitation of lower grade deposits that is increasing the need for further beneficiation.7) As the ore supply has become finer and characteristics changing, numerous adaptations of the sinter plant to improve granulation thereby improving efficiency and productivity have been developed, for example Mosaic Embedded Iron Ore Sintering (MEBIOS).8) Gas recycling systems have also been introduced at some sinter plants, e.g. the
Emissions optimized sintering (EOS) which can lower energy consumption in sintering.\textsuperscript{49} These adaptations which enhance agglomeration of the strand charge and internal gas recycle reflect the design of pellet plants, although the heat front of sinter plant remains perpendicular to the strand movement. Heat profile in pellet plants follows the movement through different temperature zones thus allowing for efficient gas recycle from different zones. Although pelletizing has been recognized as more efficient, the dominance of sintering and supply of suitable iron ores for sinter means that development of sintering efficiency is important for reduction of energy consumption and associated greenhouse gas emissions.

Sintering and pelletizing are only a part of the steelmaking system. The objective of this work is to compare system-wide differences between the use of sinter and pellets for an integrated steelworks for generalized mining and integrated steelmaking systems that are typical today. The system includes mining of ores, agglomeration techniques considering mineral type, and value of relevant by-product production, in particular BF slag.

2. Methods

Mathematical modeling was used to make system analyses to calculate energy consumption of integrated steelmaking for selected cases which varied charged pellet:sinter ratio to the blast furnace, and source pellets made from hematite or magnetite ores. Carbon dioxide emissions are also considered.

2.1. System Boundaries

The system from iron ore mining to steel production is divided into the mining site which includes pelletizing, and the steelmaking site. Fig. 1. The energy consumption for iron ore mining products of direct shipped ores (DSO), magnetite fines and pellets are carried through as input to the steel site. Energy for transporting to exporting port are included, however energy for shipping is excluded. An integrated steelplant producing 4 MT production of hot rolled coil (HRC) is assumed. Each major sub-process is included along with ancillary processes. Electricity production from blast furnace gas and basic oxygen furnace gas is included. The system from the BOF to hot-rolled coil is fixed. Energy values for exported by-products of coking which are tar, BTX (benzene, toluene, xylene) and sulphur, and also energy savings from use of GGBFS (ground granulated blast furnace slag) replacing clinker are also considered in the system.

2.2. Modeling

The energy consumption of the mining sites for production of lump ore, fines and pellets are estimated from available industrial statistics. The mining system is considered a black box.

The integrated site modeling uses the Masmod model which has been described in an earlier work.\textsuperscript{49} The model contains sub-models for major processes including coking, sintering, blast furnace, BOF, ladle metallurgy, casting, reheating, rolling, power plant, oxygen plant and lime kiln. The BF model is based on heat and mass balances around an operating point determined by thermal reserve zone temperature and shaft efficiency. Coke production is balanced to meet BF and sinter plant coke breeze demand. The full integrated steel plant model was adapted from a previous work evaluating CO\textsubscript{2} emissions from integrated steelmaking from a typical European plant.\textsuperscript{10}

2.3. Data Sources

For mining and pelletizing, publically available data derived primarily from corporate sustainability, environmental and annual reports, published articles have been used to analyze energy consumption for the iron ore products.\textsuperscript{5,11–29} No adjustments were made to account for efficiency of imported electricity production. Where fines moisture was not reported, a nominal value of 5\% was applied to calculate dry weight. Where fuel weights rather than energy were reported, energy was calculated using standard factors\textsuperscript{27} or regionally reported factors.\textsuperscript{28} Data where elevated energy consumption was attributed to mining area preparation were excluded.

Energy consumption figures for pelletizing were more difficult to ascertain because they are not typically reported separately from other ore products. Annual reports and historical information is used to estimate energy consumption for magnetite pelletizing with an increase in energy consumption estimated for use of hematite pellet feed compared to magnetite pellet feed in the induration.\textsuperscript{25–30}

Integrated steelmaking reference data were derived from industrial statistics from a previous work\textsuperscript{10} Adjustments made for the cases evaluated in this work are described below.

2.4. Case Descriptions

Four integrated steelmaking cases were evaluated as shown in Table 1. Two subcases whereby magnetite or hematite feed for producing pellets were evaluated. Ironmaking raw materials mixes for the integrated steelworks were adjusted to reflect four steelmaking scenarios: a typical plant in middle Europe charging roughly 63\% sinter made from mostly hematitic and geothitic fines together with pel-
lets and lump ore; a “Nordic Sinter” case where sinter is made from high iron content fines and charged together with olivine pellets and a small amount of high silica lump ore; a “Nordic Pellet” case where olivine pellets with a small amount of cement-bonded briquettes are charged to the BF. An additional case, modified from the typical European case is a 50:50 sinter:pellet ratio which is recommended in a recent European Commission report. The composition of the ores chosen to reflect typical compositions imported to middle Europe or Sweden are shown in Table 2 along with

| Table 1. Cases modeled. |
|-------------------------|
| Case description        | Acronym for Steelplant | Acronym for steelplant using pellets derived from magnetite | Acronym for steelplant pellets derived from hematite |
| Reference European steelplant | ES | ESM | ESH |
| European steelplant with 50:50 sinter:pellets | 50:50 | 50:50M | 50:50H |
| Nordic Steelplant with sinter plant | NS | NSM | NSH |
| Nordic Steelplant importing only pellets | NP | NPM | NPH |

| Table 2. Ore feeds into sinter mix. |
|------------------------------------|
| Steelplant type | Hematite | Goethite | Magnetite 1 | Magnetite 2 |
| Source | Brazil | Australia | Sweden | Sweden |
| ES kg/t sinter | 647 | 78 | 54 |
| 50:50 | 609 | 73 | 51 |
| NS kg/t sinter | | | 780 |

Composition:

- Fe mass%: 66.0, 58.0, 69.8, 70.7
- CaO mass%: 0.1, 0.1, 0.4, 0.4
- MgO mass%: 0.1, 0.1, 0.4, 0.4
- SiO2 mass%: 3.0, 5, 1.2, 0.8
- Al2O3 mass%: 1.2, 2, 0.2, 0.2

| Table 3. BF burdens. |
|----------------------|
| Case | Sinter kg/t HM | Pellets kg/t HM | Lump ore kg/t HM | Briquette kg/t HM | BF slag kg/t HM |
| ES | 1000 | 476 | 100 | 0 | 260 |
| 50:50 | 721 | 721 | 100 | 0 | 215 |
| NS | 1000 | 486 | 30 | 0 | 210 |
| NP | 0 | 1320 | 0 | 121 | 160 |

| Table 4. Blast furnace ferrous feed compositions. |
|-----------------------------------------------|
| Material mass% | Sinter* | Sinter* | Lump ore (1) | Acid pellets | Sinter* | Olivine pellets | Lump ore (2) | Briquette* |
|----------------|--------|--------|-------------|-------------|--------|----------------|-------------|-----------|
| Cases | ES | 50:50 | ES; 50:50 | ES; 50:50 | NS | NS; NP | NS | NP |
| Fe | 56.6 | 55.7 | 63.6 | 66.9 | 60.6 | 66.8 | 55.0 | 49.9 |
| CaO | 10.4 | 11.5 | 0.1 | 0.55 | 7.8 | 0.45 | 0.1 | 11.2 |
| MgO | 1.8 | 1.8 | 0.1 | 0.52 | 1.8 | 1.3 | 0.1 | 1.3 |
| SiO2 | 5.8 | 5.2 | 4.0 | 2.6 | 3.9 | 1.8 | 19.0 | 5.2 |
| Al2O3 | 1.3 | 1.0 | 1.4 | 0.2 | 0.4 | 0.3 | 1.4 | 1.1 |
| Crystal water | 0 | 0 | 3.2 | 0 | 0 | 0 | 0 | 0 |
| Moisture | 0 | 0 | 3.3 | 1.5 | 0 | 1.5 | 3.3 | 8.0 |
| Carbon | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13.4 |

* balance from system model

| Table 5. Treatment of dusts and sludges. |
|-----------------------------------------|
| Sinter dust | Total mass kg/t HRC | mass% to sinter or briquette | mass% to BF | mass% to sales | mass% to waste |
| BF charge screen-off | 25/31/21/43 | 0 | 0 |
| BF dust | 15/15/15/21 | 100 | 0 | 0 |
| BF sludge | 4 | 0 | 100 |
| BF slag | 260/215/210/160 | 0 | 100 | 0 |
| Desulph slag & spill | 13 | 37 | 63 |
| BOF slag | 118 | 0 | 0/0/0/26 | 46 | 26 |
| BOF coarse sludge | 11 | 100 |
| BOF fine sludge | 22 | 100 |
| Ladle slag | 9 | 100 |
| millscale | 24 | 100 |

*Screen-off at BF charging sent to sinter or briquettes; 2% BF coke, 5% lump, 2.5% pellets, 3% additives. Returned sinter is included in sinter plant balance.

3) ES/50:50/NS/NP
the proportions used in sintering. The BF slag rates were fixed to reflect a typical range at 260, 210 and 160 kg/t hot metal (HM) for the European sinter, Nordic sinter and Nordic pellet cases respectively, and a slag rate of 215 kg/t HM slag for 50:50 sinter:pellet operation. Blast furnace burden materials and compositions are given in Tables 3 and 4. Minor trims of limestone and quartzite were used to balance BF slag composition and volume for the cases with sinter. Larger amounts of limestone were charged in the Nordic pellet case.

Dust and sludges are considered in the system with fixed ratio returns and compositions from different processes, shown in Table 5. It was assumed that the revert materials to sintering are sent to briquetting in the absence of sinter plant, except BOF slag which is recycled to the BF at the same rate as the other cases. An adjustment was made for the NP case to take into account reported increases in BF dust for pellet and briquette burdens.31,32) BF dust has a negative impact on briquette strength and it is preferred to inject in the blast furnace as is being practiced at SSAB Oxelösund,33) however in the Nordic Pellet case, BF dust is assumed to be recycled via briquettes.

Sinter plant coke breeze consumption was fixed for both European and Nordic sinter cases at 50 kg/t sinter which corresponds to typical consumption levels for German sinter plants,34) and values reported for Ruukki’s sinter plant producing higher iron content sinter from high grade magnetite fines.35)

Other key parameters for the integrated steelmaking system in the model are shown in Table 6.

There is an energy benefit of replacing clinker for cement production with ground granulated blast furnace slag (GGBFS). Cement production has been reported to have an energy consumption of 3 478 MJ/t and processing of BF slag to GGBFS at 232 MJ/t.36) Net energy savings of GGBFS use is estimated as the difference at 3 246 MJ/t. In the case of

| Table 6. Process parameters. |
|-----------------------------|
| Process                     | Parameter                  | Unit          | Value       |
| Sinter plant, all           | Coke breeze rate           | kg/t sinter   | 50          |
| Sinter plant, all           | Ignition fuel              | MJ/t sinter   | 73          |
| Sinter plant, all           | Electricity consumption    | kwh/t sinter  | 32          |
| Blast Furnace               | Top gas temperature        | ºC            | 144         |
| Blast Furnace               | PCI rate                   | kg/t HM       | 152         |
| Blast Furnace               | O2 enrichment              | %             | 4.5         |
| Blast Furnace               | Blast moisture             | g/Nm³         | 16          |
| Blast Furnace               | Blast temperature          | ºC            | 1 118       |
| Blast Furnace               | Flame Temperature          | ºC            | 2 039–2 050 |
| Blast Furnace Main Blower   | Electricity consumption    | Adiabatic eff. | 76%        |
| Blast Furnace, excl. blower | Electricity consumption    | kwh/t HM      | 30          |
| Blast Furnace               | Hot metal production       | kg HM/t HRC   | 994         |
| Blast Furnace               | Slag basicity              | CaO/SiO₂      | 1 – 1.1     |
| Steelplant                  | Scrap in BOF               | kg/t LS       | 188         |
| Steelplant                  | BOF slag                   | kg/t LS       | 109         |
| Steelplant                  | BOF gas                    | MJ/t LS       | 611         |
| Steelplant (BOF->Hot rolling)| COG consumption            | MJ/t HRC      | 1 765       |
| Steelplant (BOF->Hot rolling)| Electricity consumption   | kwh/t HRC     | 165         |
| Coke plant                  | Fuel consumption           | MJ/t coke     | 4 500       |
| Coke plant                  | Electricity consumption    | kwh/t coke    | 35          |
| Coke plant                  | COG production total       | MJ/t coke     | 7 798       |
| Coke plant                  | By-product energy          | MJ/t coke     | 2 216       |
| Coking coal                 | Low heating value          | MJ/t coal     | 31.1        |
| Coke plant                  | Coal/coke ratio            | t coal/t coke | 1.3         |
| Coke plant                  | Coke carbon content        | mass%         | 88          |
| Coal                        | LHV                        | MJ/t dry      | 31.1        |
| Briquette plant             | Cement addition            | wt%           | 10          |
| Briquette plant             | Electricity consumption    | kwh/t briq.   | 100         |
| Auxiliary (lime, misc)       | Fuel consumption           | MJ/t HRC      | 1 765       |
| Auxiliary plants (lime, oxygen, misc.) | Electricity consumption | kwh/t HRC | 87        |
| Power Plant                 | Efficiency (LHV)           | %             | 32          |
briquettes, a penalty of 3478 MJ/t cement is applied.

3. Results

The results are divided into the mining system where the energy consumption for ore products is estimated; the total system energy; and sensitivity of the results to several factors.

Energy consumptions are reported as net adjusted energy consumption considering the following:

- excess BOF and BF gas are considered to produce electricity at 32% efficiency, i.e. their energy value is reduced by 68%
- the adjustments for GGBFS and cement use in briquettes are made
- imported electricity is included after adjustment for on-site electricity production, electricity imported is assumed to be produced at 100% efficiency
- deficit in coke oven gas available for metallurgical processes is made up with natural gas

3.1. Mining System

Figure 2 shows estimates based on the reported statistics for lump and fines, which are Direct Shipped Ores. An energy consumption of 150 MJ/t dry basis DSO is assumed, and is in good agreement with the figure estimated by Norgate and Haque who estimated 153 MJ/t.\textsuperscript{37) }LKAB’s fines are similar to DSO as they are crushed and go through only dry magnetic separation rather than extensive grinding and wet beneficiation as is more common for producing other high grade magnetite concentrates. A recent estimate of production energy consumption for LKAB magnetite fines is also near 150 MJ/t,\textsuperscript{5) }and therefore they are assigned the same energy consumption as DSO.

In the case of pellet production, limited data were available to compare pellets produced from magnetite or hematite and use of overall mine site statistics are difficult due to production of multiple products including DR pellets, BF pellets, fines and concentrates. Figure 2 shows data from five pelletizing sites divided into predominately hematite or magnetite feeds. Data from an older shaft kiln site using magnetite feed is shown which has higher energy consumption than modern straight-grate or grate-kiln plants. Data from the modern plants with predominately magnetite feed show a total energy of approximately 650 MJ/t pellets. Older data shows that differences in direct fuel consumption for induration of magnetite based pellets range from about 400 to 800 MJ/t pellets compared to hematite-based pellets, Fig. 3.\textsuperscript{20) }Recent data for magnetite-based pellets from modern production facilities show similarly low direct fuel consumption for magnetite feeds.\textsuperscript{20} The theoretical energy from oxidation of pure magnetite contributes about 500 MJ/t pellets. Due to lack of data, the total energy consumption for hematite-based pellets is taken as 1050 MJ/t pellets, or a conservative difference of 400 MJ higher than magnetite-based pellets. Although it is noted that the difference may be underestimated and subject to differences depending on individual plant fuel efficiency and efficiency in mining and beneficiation.

3.2. Total System

The results of total energy consumption modeling are given in Table 7. Figure 4 shows the net adjusted energy as a function of pellet rate and pellet type on the net adjusted energy consumption. The net adjusted savings when moving from the European sinter case with hematite pellets to Nordic pellets are on the order of 1.2 to 1.7 GJ/t pellets, depending on pelletizing feed, with pellets made from magnetite giving the greater benefit. The adjustment for power production efficiency and cement in briquette has little impact, however

![Energy for production of DSO (fines, lump ore) and pellets.](image)

![Fuel energy consumption for pelletizing versus energy available from magnetite oxidation.](image)

| Pellet feed type | ES | 50:50 | Nordic Sinter | Nordic Pellet |
|-----------------|----|-------|--------------|--------------|
| Mining          | 0.64 | 0.45 | 0.87 | 0.57 | 0.64 | 0.44 | 1.41 | 0.87 |
| Steelmaking     | 17.82 | 17.82 | 17.23 | 17.24 | 17.58 | 17.58 | 15.53 | 15.53 |
| Net unadjusted  | 18.46 | 18.27 | 18.10 | 17.81 | 18.23 | 18.03 | 16.95 | 16.41 |
| Saving GJ/t HRC | Base | 0.19 | 0.36 | 0.66 | 0.24 | 0.44 | 1.52 | 2.06 |
| % Saving        | Base | 1.1 | 2.0 | 3.6 | 1.3 | 2.4 | 8.2 | 11.1 |
| Adjustments:    |     |     |     |     |     |     |     |     |
| GGBFS           | –0.84 | –0.84 | –0.69 | –0.69 | –0.68 | –0.68 | –0.52 | –0.52 |
| Cement to briquette | – | – | – | – | – | – | 0.04 | 0.04 |
| Power Production | 3.89 | 3.89 | 3.80 | 3.80 | 3.80 | 3.80 | 3.89 | 3.89 |
| Net adjusted    | 21.51 | 21.32 | 21.21 | 20.92 | 21.35 | 21.15 | 20.36 | 19.82 |
| Saving GJ/t HRC | Base | 0.19 | 0.30 | 0.59 | 0.16 | 0.36 | 1.16 | 1.69 |
| % saving        | Base | 0.9 | 1.4 | 2.8 | 0.8 | 1.7 | 5.4 | 7.9 |
the credit for GGBFS clearly reduces the difference between cases by improving the net energy consumption for the higher slag rate operations.

As the proportion of pellets increases and sinter decreases, the net adjusted energy consumption is reduced. Energy from the mining system contributes only a small fraction to the net adjusted energy requirement, less than 7% even with 100% pellet burden using pellets made from hematite. The role of magnetite in pelletizing is shown clearly in Fig. 5 where the net adjusted energy consumption in the NP case is markedly lowered when using magnetite pellets instead of hematite pellets.

### 3.3. Sensitivity

The two most important factors for the energy consumption which are changing in the system are sintering which is the most energy intensive agglomeration process, and in blast furnace which is by far the largest consumer of energy in the entire system. In order to assess the sensitivity to the sintering efficiency, the coke breeze rate in the EHS case was recalculated with a coke breeze reduction of 10 kg/t sinter. All hematite cases were recalculated with BF parameters to represent very high and very low efficiency, shown in

| Change | Base | More efficient | Less efficient |
|--------|------|----------------|----------------|
| Sinter plant | coke breeze | 50 kg/t sinter | 40 kg/t sinter | N.A. |
| All cases, hematite pellets | BF shaft efficiency & top gas temp.* | TGT: 144°C, SE: 95% | TGT: 125°C, SE: 100% | TGT: 175°C, SE: 90% |

* Reserve zone temperature fixed to base case values

Figures 6 and 7 show the results of the sensitivity analysis. Despite large variations in BF coke rate which overlap strongly the net adjusted energy consumption in the NPI case remains lower than all other cases. Note that using magnetite instead of hematite pellets will yield the same relative results as only the steelmaking system has been altered.

### 4. Discussion

The total energy consumption and BF reductant rates are within expected ranges. Table 9 shows industrial reported reductant consumption for European BFs, charged predominately with sinter plus pellet and lump ore, and the Nordic for both sinter and pellet/briquette operations. In the case of SSAB, Luleå works, the pellets are normally charged dry therefore a lower coke rate can be anticipated. Ruukki injects oil with a higher heating value than pulverized coal and also charges dry quenched coke which favors a lower reductant rate. The reported industrial reductant consump-
tions are in general agreement with the results of this study, however it is noted that more detailed operating statistics are required to correct for blast temperature, oxygen enrichment, fuel type, material compositions and other factors.

It was expected that the blast furnace energy efficiency should improve with increased quality of iron ores which lead to lower slag rates. Elimination of sintering was expected to make the greatest contribution, based on previous industrial system analysis. In this analysis the benefit for change from Nordic sintering to pellet plus briquettes is 1.4 GJ/t Liquid Steel (excluding the adjustment for GGBFS) whereas in the previous investigation of the industrial system the saving was estimated at 1.1 GJ/t Liquid Steel. Insufficient details are available to analyze the reasons for the difference.

The majority of the energy saving is coming from elimination of sintering and replacement with pellets rather than a decrease in coke rate from lowered slag rate and carbon in briquettes which is clearly seen in the sensitivity to BF efficiency in Fig. 6. The reductant carbon rate charged to BF is, in fact, calculated to the highest for the NP case, Fig. 8. This result is somewhat surprising but highlights that coke rate alone does not necessarily determine the energy consumption of the system.

Replacing all sinter with pellets and briquettes places a higher energy demand on the blast furnace from two main factors which have been reported to be important factors in all-pellet operations:

- Limestone required for slag formation is calcined in the BF instead of sinter plant
- Energy requirement for drying increases when wet pellets replace dry sinter

These impacts are partly compensated by the lower slag volume, and limestone addition can be minimized by charging of more BOF slag to the BF. Recalculation of the Nordic Pellet case for higher BOF slag and lower moisture charged to the BF are shown in Fig. 9. The approximate impacts of slag, moisture and limestone are given in Table 10. The calculated impact of slag rate on coke requirement is slightly lower than the typically used rule of thumb of 0.2 kg coke/kg slag. Moisture charged to the furnace has been reported to influence BF coke rate negatively. However, numerical data for comparison have not been found.

In the first adjustment, increasing the BOF slag from 33 to 46 kg/t HRC recycle (the level reported some years ago at SSAB Luleå works) lowers the coke rate further by reducing limestone addition in an approximately 1:1 ratio. A recent analysis of BOF slag recycle limits highlighted the role of phosphorus and permitted limit in hot metal and BOF slag practice. Low phosphorus loading from incoming raw materials favors higher recycle rates leading to lower BF coke rate and lower limestone consumption. Other elements including vanadium and chromium have also been reported to be elements limiting BOF slag recycle.

### Table 9. Industrial reductant rates compared to calculated cases; excluding C in briquette.

| Factor                | Coke | PCI | Other | Total |
|-----------------------|------|-----|-------|-------|
| European average 36)  | 383  | 103 | 13    | 499   |
| European sinter case – calculated | 342 | 152 |       | 494   |
| Nordic Sinter – Ruukki 30) | 358 | 100 (oil) | 458   |
| Nordic Sinter – Ruukki 30) * | 388 | 74 (oil) | 462   |
| Nordic sinter case – calculated | 330 | 152 |       | 482   |
| Nordic Pellet – SSAB 37) | 326 | 139 |       | 465   |
| Nordic Pellet – Ruukki 30) * | 397 | 67 (oil) | 463   |
| Nordic Pellet case – calculated | 329 | 152 |       | 481   |

* average for two furnaces

### Table 10. Impact of slag, limestone and burden moisture on coke rate for 100% pellet operation.

| Factor                  | Coke rate |
|-------------------------|-----------|
| +1 kg slag              | +0.15 kg  |
| +1 kg limestone         | +0.22 kg  |
| +1 kg charged water     | +0.34 kg  |
In the second adjustment, the burden moisture of the NP case is adjusted to the same level as the ES case at the base BOF slag recycle and limestone charge rates. This clearly has a significant impact on coke rate and highlights pellets moisture as an important quality factor. Depending on individual operating parameters, such as oxygen enrichment levels and blast temperatures which affect the volume of top gas, it can be expected that charge moisture, limestone addition and slag rates will affect operations differently.

Carbon dioxide emissions are largely a direct consequence of energy consumption. Overall system CO₂ emissions cannot be calculated without a large number of assumptions regarding power generation and fuel type in pelletizing, however direct steelmaking site emissions have been calculated. The direct CO₂ emissions for the steelplant sites, i.e. excluding imported electricity, emissions from iron ore production, and benefits of GGBFS are shown in Fig. 10. The differences in site emissions are largely driven by change in coke breeze consumption in sintering. The difference from ES to NP cases is approximately 15%, however this is attenuated if emissions from pelletizing are included with indicative estimates also marked in Fig. 10. Emission factors for magnetite pelletizing have been reported to be about 35 kg/t pellets from Swedish ores for direct emissions with indicative estimates also marked in Fig. 10. Emission factors for magnetite pelletizing have been reported to be about 35 kg/t pellets from Swedish ores for direct emissions only which is consistent with the corporate data reporting 40 kg/t including electricity. The main fuels in the production of Swedish pellets are coal and oil. An emission factor on the order of 80 kg/t pellets is estimated from reported data for pelletizing of hematite including indirect emissions. For hematite pellets the emissions from vegetation removal and manure fermentation were excluded in the estimate because they are too site-specific. The major direct fuel for firing the hematite pellets in this estimate is natural gas which gives an advantage in emissions relative to energy consumption. Using these indicative emission levels, the savings from NS to NP including pelletizing is on the order of 9% for magnetite-based pellets which is consistent with recent work comparing industrial data from the Nordic system. CO₂ savings from ES to NP cases are estimated to be on the order of 13% and 10% for magnetite- and hematite-based pellets respectively.

The role of high grade ores in sintering is also apparent, both from the energy consumption figures shown earlier and the steelplant CO₂ emissions. Arrow “a” in Fig. 10 illustrates the improvement using high grade iron ore fines between the ES and NS cases, whereby use of high grade fines lowers the BF coke rate through slag rate reduction, lowers limestone required for fluxing BF slag and total amount of iron ore products required. Arrow “b” shows the trend for elimination of sintering which has a much stronger impact.

There are numerous technical considerations when replacing part or all the sinter with predominately pellets which require further investigation and more detailed industrial experience to quantify. Effects of dramatic changes in sinter/pellet ratio such as change in angle of repose and optimal charging patterns, softening and melting properties of the burden, screening efficiency at stockhouse, and change in blast furnace gas heating value affect the ironmaking operations. These should be investigated further on an individual site basis.

From practical and commercial perspectives, replacing sintering with pelletizing involves a change in cost of raw materials, investments and depends on availability of suitable ores or purchased pellets. Therefore sintering can be expected to remain dominant in regions where coarse sintering fines are readily available. However, the changes occurring in the iron ore supply can lead to improved efficiency of integrated steelmaking on regional or site levels through introduction of larger quantities of finer concentrates which are more highly beneficiated and then pelletized rather than sintered.

5. Conclusions

Overall energy use in the chain from iron ore mining to integrated steelmaking is dominated by the steel production site.

For the modeled systems, the Nordic-style operations with pellets and briquettes are more energy efficient than sinter-based operations and more so when pellets are made from magnetite ores. In this analysis, compared to predominately sinter-based European integrated steelmaking case with hematite pellets, the Nordic pellet operation shows a decrease in total adjusted energy consumption of between 1.2 and 1.7 GJ/t HRC for pellets made from hematite or magnetite feeds respectively. This represents net adjusted savings of 5 to 8% compared to the European sinter case. Furthermore steelplant site direct CO₂ emissions are estimated to be reduced by about 320 kg/t HRC or about 15% compared to the European sinter case. Adjusting for the additional emissions from pelletizing attenuates this saving, however a significant reduction in CO₂ emissions remains.

The energy savings from using magnetite feed in pelletizing become more significant as the proportion of pellets in the burden increases. Savings are estimated to be on the order of 0.5 GJ/t HRC when switching from hematite to magnetite pellets in all pellet burdens.

The use of high grade iron ores in sintering to lower the BF slag rate which reduces BF coke rate, limestone requirement and total amount of iron ore products contributes to.
lower net energy consumption and lowered CO₂ emissions in integrated steelmaking, although the impact is smaller than elimination of sintering. Briquetting provides a method of recycling various revert including some carbon which should be taken into consideration when evaluating furnace redundant and total carbon consumption rate.

Two important factors for maximizing the benefits of high pellet and low slag rate operations are minimizing of the pellet moisture and minimizing limestone rate to the blast furnace in order to obtain as low as possible coke rate. Maximized recycling of BOF slag reduces limestone consumption in the blast furnace and is subject to limitations in build-up of recirculating elements. BF dust rate has been reported to increase in pellet-briquette burdens compared to sinter operations that warrants further investigation to establish cause and possible mitigation techniques.

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