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Research Paper

# Potential for energy savings by heat recovery in an integrated steel supply chain

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## HIGHLIGHTS

- The potential for energy savings of an average steel mill is estimated.
- Pinch analysis is used to optimise an integrated network of heat exchangers.
- Proposed networks may save up to 3.0 GJ per tonne of hot rolled steel.
- Limited savings may be obtained from the integration with other industries.

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## ABSTRACT

Heat recovery plays an important role in energy saving in the supply chain of steel products. Almost all high temperature outputs in the steel industry have their thermal energy exchanged to preheat inputs to the process. Despite the widespread development of heat recovery technologies within process stages (process heat recovery), larger savings may be obtained by using a wider integrated network of heat exchange across various processes along the supply chain (integrated heat recovery). Previous pinch analyses have been applied to optimise integrated heat recovery systems in steel plants, although a comparison between standard process heat recovery and integrated heat recovery has not yet been explored. In this paper, the potential for additional energy savings achieved by using integrated heat recovery is estimated for a typical integrated steel plant, using pinch analysis. Overall, process heat recovery saves approximately 1.8 GJ per tonne of hot rolled steel (GJ/t hrs), integrated heat recovery with conventional heat exchange could save 2.5 GJ/t hrs, and an alternative heat exchange that also recovers energy from hot steel could save 3.0 GJ/t hrs. In developing these networks, general heat recovery strategies are identified that may be applied more widely to all primary steel production to enhance heat recovery. Limited additional savings may be obtained from the integration of the steel supply chain with other industries.


## 1. Introduction

The steel industry operates at some of the highest temperatures of all industrial processes and the whole supply chain involves multiple cycles of heating and cooling. These high temperatures are fundamental to the operation of the supply chain—either to enable the reduction of iron ore into iron, to alter the microstructure to improve product properties, or to soften the metal so it may be formed to the desired shape. These several high temperature processes result in significant energy losses in hot output flows.

Heat exchangers may be implemented to transfer thermal energy from hot output flows into a cold incoming flow, reducing the burden of external fuel required for heating and so improving energy efficiency. Technologies exist for heat recovery from most of the hot outputs in the supply chain, but have been developed with a focus on each individual process stage, where the energy transfer occurs between the outputs and inputs of the same process (*process heat recovery*). However, *integrated heat recovery*, where a series of processes are considered together and outputs of one process are linked to inputs of another, may allow for a larger energy saving through better matching of hot and cold flows. The substantial distance between process units limits the affordability of unrestricted heat exchanging, particularly when applied to existing plants and their operating constraints. In this paper, the method of pinch analysis is used to estimate the potential for additional savings through implementing integrated heat recovery across all processes in the primary steel supply chain. This analysis is applied to a generic steel plant in design phase, thus not subject to limitations associated with the location of existing equipment.

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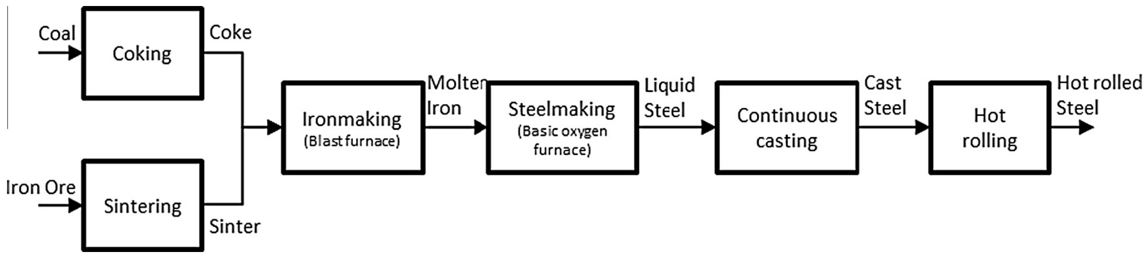


**Fig. 1.** Overview of supply chain for primary steel production.

### *1.1. Processes in primary steel production*

Primary steel production involves the reduction of sintered iron ore with coke in a blast furnace (BF) and subsequent treatment in a basic oxygen furnace (BOF). This is distinct from secondary steel production, in which scrap is remelted in an electric arc furnace. In primary production, molten steel output is typically continuously cast and hot rolled to make a range of stock products that are sold for subsequent fabrication into consumer products. These fabrication steps are frequently carried out cold and therefore have no potential for heat recovery, so are not included in this analysis. An overview of how the processes in primary steel supply chain are linked is given in Fig. 1, and the changes taking place in each process are described below. The processes are described in more detail by IISI [9].

Cullen et al. [6] calculate global mass flows through the steel supply chain from a range of data sources. The supply chain shown in Fig. 1 covers 95% of all steel production.

The energy required to manufacture steel products is commonly quoted as a sum of the energy inputs to each process in the supply chain divided by the mass of steel in the product. In this paper, the unit gigajoules of primary energy per tonne of hot rolled steel product (henceforth GJ/t) is used. Where necessary, electricity or final energies are denoted by the subscripts $GJ_e/t$, and $GJ_f/t$ respectively. A lower energy consumption per tonne of steel indicates a more efficient supply chain.

Through an industry survey of 16 sites, IISI [9] have calculated an average energy consumption of 19.2 GJ/t for primary steel production in the BF-BOF route described in Fig. 1. A range of process heat recovery options are included, although they are implemented to varying degrees across the different sites surveyed. A more recent survey by Worrell et al. [15] combines the lowest reported process energy consumptions to define best practice for hot rolled steel as 18.2 GJ/t via a similar process route, down to 16.3 GJ/t using thin slab casting to integrate casting and hot rolling. Best practice includes implementation of all commercially viable heat recovery technologies. De Beer et al. [2] estimate available heat energy across the whole supply chain as 5.5 GJ/t (Table 13, pp. 189) with a significant proportion recoverable, so an energy consumption of over 20 GJ/t would be expected with no heat recovery at all. Various process heat recovery technologies are described for each of the hot output flows, and are summarised in Table 1.

Some general trends in process heat recovery are observed. The use of recuperative or regenerative heat exchangers for heat recovery from hot exhaust gases are common across all processes and widely applied. In addition to thermal energy, some gaseous outputs have chemical energy that may be recovered via combustion, and dry cleaning of the gas must be employed in order to recover both the thermal and chemical energy. The granulated solid outputs (sinter, coke, and slag) are all used to preheat air, which may be taken as a direct input to combustion, or undergo a further heat exchange step to preheat an input. Heat recovery from solid steel is rare, with only isolated examples quoted in the literature. A separate strategy exists where the output product of one process is not allowed to cool, thus carrying the heat to the following process, for example taking molten iron from the blast furnace for

**Table 1**
List of hot outputs from the steel supply chain with potential heat recovery methods currently available and average energy saving obtained if implemented. Data compiled from IISI [9] except where noted.

| Process | Output | Temp (°C) | Thermal energy (GJ/t) | Other energy[a] (GJ/t) | Heat recovery method | Energy saving[c] (GJ/t) |
|---|---|---|---|---|---|---|
| Coking | Coke oven gas | 700 | 0.18 | 0.69 | District heating | 0.13[d] |
| | Coke | 1100 | 0.55 | – | Coke dry quenching to generate steam | 0.59 |
| | Flue gas | 250 | 0.10 | – | Fuel preheating | 0.04 |
| Sintering | Sinter | 700 | 0.88 | – | Dry cooling – preheated air input | 0.32 |
| | Stack exhaust | 350 | 0.34 | – | Recirculation | 0.19 |
| Ironmaking | Blast furnace gas | 180 | 0.32 | 4.12 | Dry cleaning and top recovery turbine | 0.19 |
| | Blast stove exhaust | 250 | 0.06 | – | Incoming air preheat | 0.10 |
| | BF Slag | 1500 | 0.49 | – | Dry granulation – air used to generate steam | 0.21[b] |
| Steelmaking | BOF exhaust | 1700 | 0.18 | 0.13 | Waste heat boiler to generate steam | 0.19 |
| | BOF Slag | 1700 | 0.05 | – | Dry granulation – air used to generate steam | 0.00 |
| Casting | Steel | 1200 | 0.70 | – | – | – |
| | Steel latent heat | 1200 | 0.27 | – | – | – |
| Hot rolling | Reheat exhaust | 700 | 0.20 | – | Recuperative or regenerative burners | 0.11 |
| | Steel out | 900 | 0.53 | – | Space heating (hypothetical) | 0.01 |
| Totals (GJ/t) | | | 4.9 | 4.9 | | 2.0 |

[a] Other energy includes chemical energy that may be recovered by combustion and energy stored in high pressure gas outputs.
[b] From Barati et al. [1].
[c] Average energy saving that could be obtained if heat recovery method is implemented. These values are the current average of plants surveyed, which may be different from energy saving obtained in specific state-of-the-art steelworks.
[d] District heating energy saving is used outside the steelworks and consequently it does not affect the overall energy intensity of producing hot rolled steel. Therefore, this potential energy saving is not included in the total potential energy saving presented in the table.

steelmaking. This strategy is distinct from heat recovery because no heat exchange is involved.

Potential process heat recovery achieves energy savings of 2.0 GJ/t, provided all processes are implemented (Table 1). The difference between this energy saving and the available thermal energy may be explored further through pinch analysis, as discussed in the next section.

### 1.2. Thermodynamic limits – optimising a network for maximum heat recovery

An opportunity for further energy savings exists beyond process heat recovery because it is possible to match streams optimally based on their flow rates, heat capacities and temperatures, to achieve maximum heat recovery. With more streams available in the consideration of a network of processes, more heat recovery is theoretically possible. The method of '*pinch analysis*' allows the calculation of a theoretical maximum for heat recovery in a network of streams. This method was used by Linnhoff and Hindmarsh [12] who have developed a procedure for designing an integrated heat recovery network that may approach this theoretical maximum.

Pinch analysis is a commonly used method for optimisation of heat recovery in the chemicals industry, for example described by Yoon et al. [16] for an industrial ethylbenzene plant, calculating potential energy savings of 6%. It has previously been applied in the steel industry by Isaksson et al. [10] for the SSAB EMEA steel plant in Luleå, Sweden, covering primary processes from coking to casting, and by Matsuda et al. [13] for an unknown 'large scale steel plant'. Isaksson et al. identify savings from cooling coke oven gas to make steam, which is used elsewhere on site. In their study, the potential for integrated heat recovery is limited by only applying it at the process level due to geographic constraints. Matsuda et al. [13] suggest rearranging the use of utilities in the plant to avoid heat transfer across the pinch point, again operating within the constraints of the existing process locations.

The analyses above provide compelling examples of the application of integrated heat recovery for some particular plants. However, these analyses do not disclose the full data set used to carry out the analysis, in particular mass flows, making it impossible to relate them to the process heat recovery savings quoted previously (Table 1). Furthermore, existing analyses are limited by the constraints of the exiting process locations of the examined sites, which mask the ultimate potential for heat recovery of a complete integrated network included as part of the initial plant design. In this paper, it is assessed whether additional energy savings are possible and it is hypothesised how the required heat exchange networks would be designed in practice for an average site. The potential integration of a primary steel supply chain with supply chains of other materials is also examined.

## 2. Methodology

The work carried out is described in two parts. First, complete mass and energy balances of the flows in and out of the processes in the steel supply chain are compiled from various sources in literature and verified (Section 2.1), and then a pinch analysis of these flows is undertaken to determine the potential energy savings from heat recovery and to propose a network that can achieve these savings (Section 2.2).

### 2.1. Mass and energy balance

The process mass and energy data were checked so that they balance across processes, and the consistency of overall supply chain energy data was verified against average values from IISI [9], De Beer et al. [2] and Worrell et al. [15]. Complete details of the data sources and the adjustments made may be found in Appendix A, together with tables detailing the actual data used to complete the pinch analysis.

Where possible, papers with detailed mass and energy balances for individual processes in the supply chain have been used. Ertem and Özdabak [8] and Ertem and Gurgen [7] document measured mass and energy balances for a Turkish steel production facility for the coking and ironmaking processes respectively. Sintering data was taken from the average industrial figures given in IISI [9]. An overall exergy balance for steel production by Costa et al. [5] was used for the steelmaking and continuous casting processes. For steelmaking, a 10% scrap addition is used, corresponding to the industry average from IISI [9]. Depending on the grade, liquid steel may be treated with a range of secondary metallurgy steps such as vacuum degassing or the addition of alloying elements. The energy consumption and heat generation varies with alloy, but these changes are typically small, and therefore ignored. A continuous casting process may be used to produce a range of shapes (billet, bloom or slabs), but the mass/energy balance is approximately the same, so the analysis will apply equally to any shape.

Finally, data for hot rolling is taken from Chen et al. [4]. It is assumed that the cast steel is hot charged to a reheat furnace at 700 °C. This is at the upper end of achievable transfer temperatures, but would be feasible with a properly designed plant. Additional data for the processes, particularly the output temperature of some waste streams, was compiled from IISI [9] and some material properties were taken from Campbell [3]. Process yields from Worldsteel Association [14] were used to link the individual process data together to provide a mass and energy balance for the supply chain.

### 2.2. Pinch analysis

Pinch analysis involves a description of a set of streams of materials in terms of an inlet and outlet temperature, and a 'heat capacity flow rate' (the product of mass flow rate [kg/s] and heat capacity of the stream [J/kg K], indicating in W/K the rate at which heat may be transferred to or from the stream, per °C of temperature change). The streams either require heating to go from a low temperature to a higher temperature ('cold streams'), or start at a high temperature and have energy available for heat recovery ('hot streams'). This heating/cooling energy requirement is the 'heat duty' of the stream [J/kg, or GJ/t for ease of comparison]. Considered together, the streams should describe a system, which conserves both mass and energy. Further details on the application of the pinch analysis methodology are given by Kemp [11].

The pinch analysis is carried out using the instructions and spreadsheet tools from Kemp [11]. A set of hot and cold streams representing the most significant flows (those with greater than 1% of the hot or cold stream with maximum energy) was selected. Composite hot and cold curves were generated by integrating the heat capacity flow rate of these streams between the inlet and outlet temperature. Minimum temperature differences ($dT_{min}$) were applied to each individual stream. These were assigned according to the physical state of the stream, which in this case may be a solid (for example a steel sheet), a granulated solid (for example slag), or a gas. When matching streams for heat exchanged, the real temperature difference between the streams is greater than or equal to the sum of the $dT_{min}$ contributions from each stream, and therefore the assignment of $dT_{min}$ by physical state allows the relative difficulty of heat transfer between streams of different states to be accounted for. Representative values were taken from data for real heat exchangers and are given in Table 2. It is harder to predict $dT_{min}$ for economical heat recovery from solids as it is not presently undertaken. Chen et al. [4] calculate a difference in temperature between gas and solid metal of 100 °C at exit in the

**Table 2**
Minimum temperature differences used for individual stream contributions depending on their state.

| State of flow | Minimum temperature difference, $dT_{min}$ (°C) | Reference |
|---|---|---|
| Gas | 10 | Yoon et al. [16] |
| Granulated solid | 150 | Barati et al. [1] |
| Solid | 300 | Chen et al. [4] |

description of a hot rolling reheat furnace. This value may vary considerably within the furnace, so we have assumed a conservative $dT_{min}$ of 300 °C for individual solid stream contributions to reflect the difficulty in carrying out such heat recovery. Since the possibility for maximum heat recovery depends strongly on the chosen minimum temperature differences, we have performed a sensitivity analysis on these values, which is presented and discussed in Section 3.4.

This pinch analysis makes several assumptions. Heat capacities are treated as constant, with average values taken over the stream temperature range. While there is some variation of heat capacity over the temperature range considered, other methods could have been used, namely using linear functions of temperature, but the impact of such methods in the results is likely to be small, since most of the heat capacities vary by less than 20% over most of the temperature ranges of the steams. Heat exchange is allowed to occur between any streams in calculating the maximum possible energy saving, but the practical networks require heat exchange with at least one stream as a gas. This analysis provides an estimate for options to improve energy savings in a generic integrated mill, and therefore a specific set of streams is considered and no geographic limitations are placed on the analysis.

Pinch analysis have been designed to be employed to networks of continuous processes. Since several processes in the steel supply chain are batch operations (such as the steelmaking in the basic oxygen furnace), the use of pinch analysis for steel supply chains presented hereafter presumes the necessary mechanisms for averaging flow rates of all processes, so they can be treated as quasi-continuous and all running simultaneously.

The pinch analysis tools of Kemp use the input date to produce hot and cold composite curves. The allowable overlap while respecting $dT_{min}$ reveals the maximum potential for heat recovery and therefore a theoretical target for integrated heat recovery. In practice this may be limited by the complexity of the network of heat exchangers required, so consideration was given to the practicalities of heat recovery.

The integrated heat recovery networks proposed in this paper are designed using the 'Pinch Design Method' proposed by Linnhoff and Hindmarsh [12]. This involves invoking the property that heat should not be transferred across the pinch temperature. The heat exchanger network may therefore be split in two and choosing heat exchange that satisfies conditions at the pinch temperature first of all, and then at the extremes of temperature away from the pinch. Where required, streams were split into parallel branches to meet the conditions for matching.

The effectiveness of this practical heat exchange network is compared to the theoretical maximum heat recovery, to the datum no heat recovery case, and to fully implemented process heat recovery. This comparison is used to decide whether it is worthwhile investigating a more integrated primary steel production site further.

## 3. Results

In this section, a summary of the mass and energy-balanced system is given, and this data is used to carry out a pinch analysis to determine the maximum potential for heat recovery.

### 3.1. Mass and energy-balanced system

The flow of material and energy through the primary steel supply chain is given in Fig. 2. In these Sankey diagrams, the relative size of the flows is shown as the width of the bar. Fig. 2(a) shows the mass flows across the supply chain, from ore and coal through to steel and waste gases. The mass of air required for combustion and as a hot blast in ironmaking is the largest input. There is a small yield loss of iron in the slag, and the flue gases are significant. Of these exhausts, about 40% by mass contain useful energy that may be recovered through combustion.

Fig. 2(b) shows the energy flows across the supply chain, again from inputs on the left to outputs on the right. The largest energy-consuming process is ironmaking in the blast furnace, where iron ore is reduced using coke to make liquid pig iron. The energy for this chemical transformation is carried forward in the iron and steel streams in the subsequent processes, as is a small contribution of thermal energy of the liquid metal. The useful energy in the combustible gases is significant and is normally completely captured. This energy is more than the total thermal energy stored in the hot outputs from the supply chain even before the ease of recovery is considered. Losses include heat loss to the environment (e.g. through furnace walls), inefficiencies in the process equipment, and chemical energy in waste streams (e.g. slag) that cannot be recaptured.

Fig. 3 summarises the energy inputs and outputs of the whole system. Fig. 3(a) breaks down the energy input by type (as shown in the left-hand side of Fig. 2(b)), and Fig. 3(b) shows how this energy is used. Only about 20% of the energy input is used to reduce iron ore. There is significant chemical energy stored in waste gas streams: coke oven gas, blast furnace gas, and basic oxygen furnace exhaust. Traditionally, this energy is reused on site, and credit given by subtracting from the overall energy consumption giving a net total of 24 GJ/t. The energy in these gases is used as fuel for heating or for electricity generation.

The absolute maximum heat recovery potential can be estimated by the thermal energy in the hot outputs from the supply chain as 5.1 GJ/t. This is broken down further in Fig. 3(c), which shows the energy content by physical state of the waste stream. There is an approximately even distribution between energy in hot exhaust gases, granular solids (coke, sinter, and slag), and the solid metal itself. However, this thermal energy is only useful if there is an available sink. Pinch analysis is required to define the limit for useful heat recovery, but the exergy of these hot streams indicates the maximum potential for useful work. The total exergy is 4.4 GJ/t, which denotes the high quality of the energy of these streams, as a consequence of their high temperatures.

A full list of cold and hot streams considered for the pinch analysis is given in Tables 3 and 4 respectively. These tables show the supply and target temperatures for each stream, the minimum temperature difference, the heat capacity flow rate and heat duty.

The indicated $dT_{min}$ is determined by the state of the stream, and heat capacity flowrate is the product of heat capacity and mass flow rate. The most important flows, i.e. those which require the largest energy input or have the most useful energy available, are mostly those with the largest mass flows in Fig. 2 – combustion air, sinter and ironmaking streams. These will be the most important when constructing a heat exchanger network.

Other notable flows include the latent heat released as steel solidifies during casting, which occurs at effectively a constant temperature. The steel input to casting is listed here as a hot flow, as liquid steel is output from the basic oxygen furnace with significant superheat above the melting temperature. This may be lost or used during the secondary steelmaking processes depending on the alloying and degassing steps but as those steps vary, the heat flow is included in this data for completeness. Neither this energy

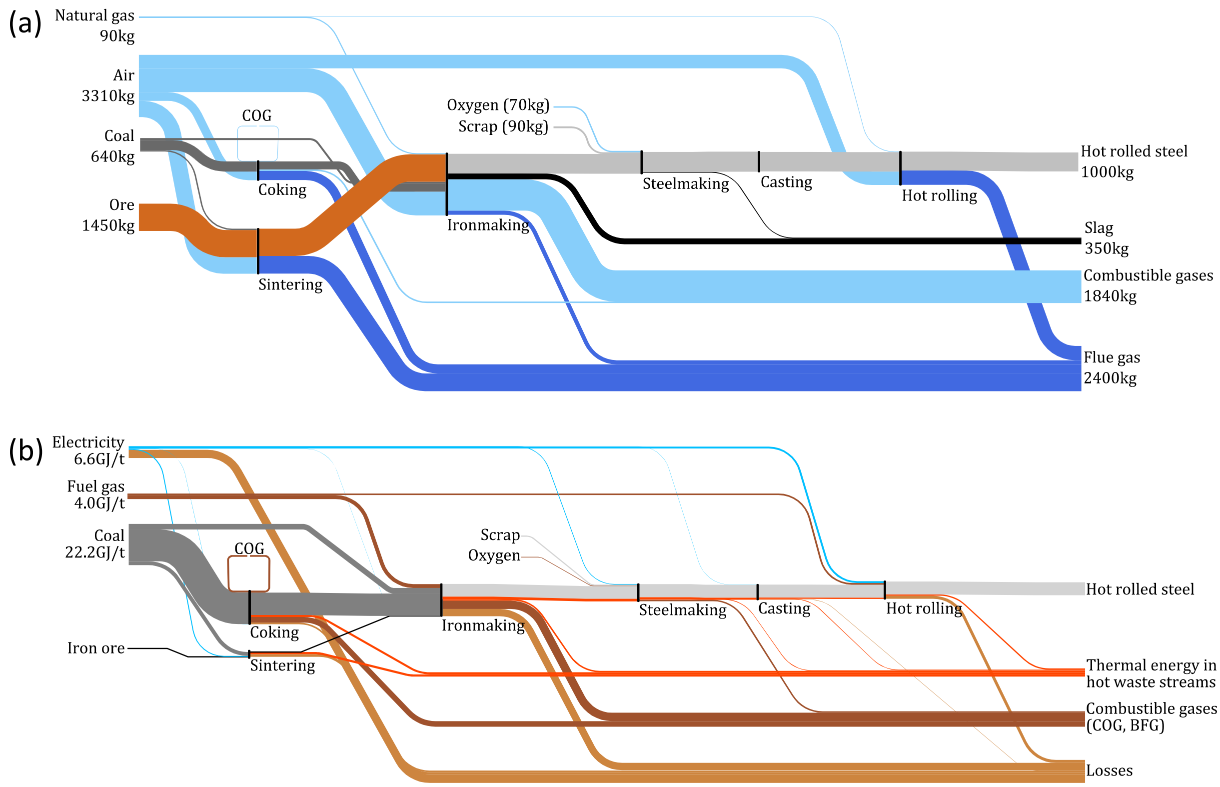


**Fig. 2.** (a) Mass and (b) energy Sankey diagrams for the primary steel supply chain.

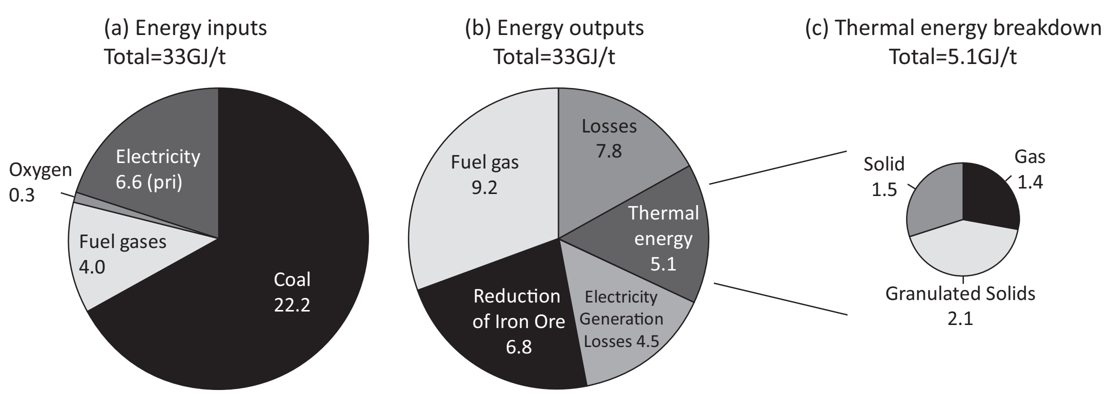


**Fig. 3.** Summary of energy input and output across primary steel supply chain.

nor the latent heat are used in the proposed heat exchanger networks.

The data was checked for mass and energy balances on each individual process, and the process energy consumptions compared to De Beer et al. [2] and Worrell et al. [15] (see Appendix A, Table A8). De Beer and Worrell present best practice figures that account for heat recovery and the use of thin slab casting with a direct link to hot rolling. When these energy saving measures are accounted for, the process energy consumptions agree to within approximately 10%.

A further validation of the data was carried out by applying heat recovery between the streams with the process heat recovery pairings identified in the literature review. The heat recovery network for this situation is shown in Fig. 4. An actual average energy saving of 1.8 GJ/t was calculated, which is approximately equal to the 2 GJ/t potential predicted saving when adding all the process heat recovery options described in the literature review. Small differences are to be expected given the range of sources used, but as the savings are approximately the same the data is at least broadly consistent with reality.

Two pinch analyses of a fully integrated steel supply chain were undertaken. Firstly, to give a fair comparison with existing process heat recovery, only hot streams where heat recovery is currently applied were considered (Case A); therefore the heat energy in hot metal from the continuous casting and hot rolling processes is unavailable. Secondly, to show the maximum potential heat recovery, all streams are considered with a large minimum temperature difference applied to the solid metal streams to reflect the difficulty in extracting useful heat energy from them (Case B).

**Table 3**
Cold flows for pinch analysis from mass and energy balance.

| Stream | | Supply temp (°C) | Target temp (°C) | $dT_{min}$ (°C) | Heat capacity flowrate (W/K) | Heat duty (GJ/t) |
|---|---|---|---|---|---|---|
| C1 | Coal in – coking | 20 | 1100 | 200 | 693 | 0.748 |
| C2 | Coke oven gas in – coking | 60 | 1100 | 10 | 81 | 0.084 |
| C3 | Air in – coking | 20 | 1100 | 10 | 462 | 0.499 |
| C4 | Coke breeze in – sintering | 20 | 1300 | 200 | 109 | 0.139 |
| C5 | Ore in – sintering | 20 | 1300 | 200 | 898 | 1.150 |
| C6 | Combustion air in – sintering | 20 | 1300 | 10 | 869 | 1.113 |
| C7 | Coke in – ironmaking | 20 | 1200 | 200 | 530 | 0.626 |
| C8 | Coal in – ironmaking | 20 | 1200 | 200 | 132 | 0.156 |
| C9 | Sinter in – ironmaking | 20 | 1200 | 200 | 1238 | 1.461 |
| C10 | Air in – ironmaking | 20 | 1180 | 10 | 1717 | 1.992 |
| C11 | Iron in – steelmaking | 1500 | 1700 | 50 | 952 | 0.190 |
| C12 | Scrap in – steelmaking | 20 | 1700 | 300 | 55 | 0.093 |
| C13 | Oxygen in – steelmaking | 20 | 1700 | 10 | 106 | 0.178 |
| C14 | Steel in – hot rolling | 700 | 1200 | 300 | 590 | 0.295 |
| C15 | Air in – hot rolling | 20 | 1200 | 10 | 792 | 0.935 |
| C16 | Natural gas in – hot rolling | 20 | 1200 | 10 | 58 | 0.069 |
| Total heat input requirement (GJ/t) | | | | | | 9.7 |

**Table 4**
Hot flows for pinch analysis from mass and energy balance.

| Stream | | Supply temp (°C) | Target temp (°C) | $dT_{min}$ (°C) | Heat capacity flowrate (W/K) | Heat duty (GJ/t) |
|---|---|---|---|---|---|---|
| H1 | COG out – coking | 700 | 20 | 10 | 334 | 0.227 |
| H2 | Coke out – coking | 1100 | 20 | 200 | 636 | 0.687 |
| H3 | Tar out – coking | 1100 | 20 | 300 | 21 | 0.023 |
| H4 | Flue gas out – coking | 250 | 20 | 10 | 523 | 0.120 |
| H5 | Sinter out – sintering | 700 | 20 | 200 | 1333 | 0.906 |
| H6 | Exhaust out – sintering | 350 | 20 | 10 | 1036 | 0.342 |
| H7 | BFG out – ironmaking | 180 | 20 | 10 | 1726 | 0.276 |
| H8 | Blast stove exhaust out – ironmaking | 250 | 20 | 10 | 239 | 0.055 |
| H9 | Slag out – ironmaking | 1500 | 20 | 200 | 296 | 0.438 |
| H10 | BOF exhaust – steelmaking | 1700 | 20 | 10 | 117 | 0.196 |
| H11 | Slag out – steelmaking | 1700 | 20 | 200 | 34 | 0.058 |
| H12 | Steel in – casting | 1700 | 1200 | 50 | 608 | 0.304 |
| H13 | Steel out – casting | 1200 | 700 | 300 | 608 | 0.304 |
| H14 | Steel out – latent heat – casting | 1200 | 1200 | 300 | N/A | 0.272 |
| H15 | Reheat exhaust – hot rolling | 700 | 20 | 10 | 676 | 0.460 |
| H16 | Steel out – hot rolling | 900 | 20 | 300 | 590 | 0.519 |
| | Total heat output availability (GJ/t) | | | | | 5.2 |

### *3.2. Case A – Pinch analysis based on existing heat recovery technologies (excluding heat recovery from solid streams)*

For Case A, only existing heat recovery technologies are allowed, and therefore the hot solid streams (H12, H13, H14 and H16) are excluded. The hot (red[1]) and cold (blue) composite curves for this case are shown in Fig. 5. The pinch temperature is 220 °C. From the cold curve, we can see that the total energy requirement for heating is 9.7 GJ/t, matching Table 3, and because the hot metal streams are ignored the available energy in the hot curve is lower than Table 4, only 3.8 GJ/t. The maximum potential heat exchange (indicated by the overlap of the hot and cold curves) is 2.7 GJ/t, reducing the heating requirement to 7.0 GJ/t. Therefore, a fully integrated network can potentially achieve up to 50% larger energy savings than process heat recovery alone.

The total energy available in this pinch analysis is still limited by ignoring flows where we do not expect to be able to recover any heat due to technological limitations, for example from hot rolled steel. From the energy balance, it is shown that this energy is significant, and it is interesting to consider the extra opportunity for energy saving should it become recoverable.

[1] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

### *3.3. Case B – Pinch analysis of all flows (including heat recovery from solid streams)*

A second pinch analysis was carried out, with all hot streams available, and the solid flows set to have a minimum temperature difference of 300 °C to reflect the difficulty in capturing this energy. The new composite curves for this case are given in Fig. 6, with the original hot curve shown as a reference. With the additional hot streams, the curve shifts to the right and with a larger overlap the maximum potential for heat recovery has increased from 2.7 to 4.3 GJ/t. This shows that the heat energy in hot steel could be useful even when taking into account the penalty of the large temperature difference applied. A step is observed in the hot curve where the latent heat of solidification is released at a constant temperature. The pinch temperature remains the same at 220 °C.

### *3.4. Sensitivity analysis*

The selection of the minimum temperature difference, $dT_{min}$, for each stream state (gas, granulated solid, or solid) is the largest uncertainty as it depends both on the available technology for heat exchange, which may improve with time, and on the economics of the process, which change both with location and time as energy prices and costs of capital equipment vary. The sensitivities of

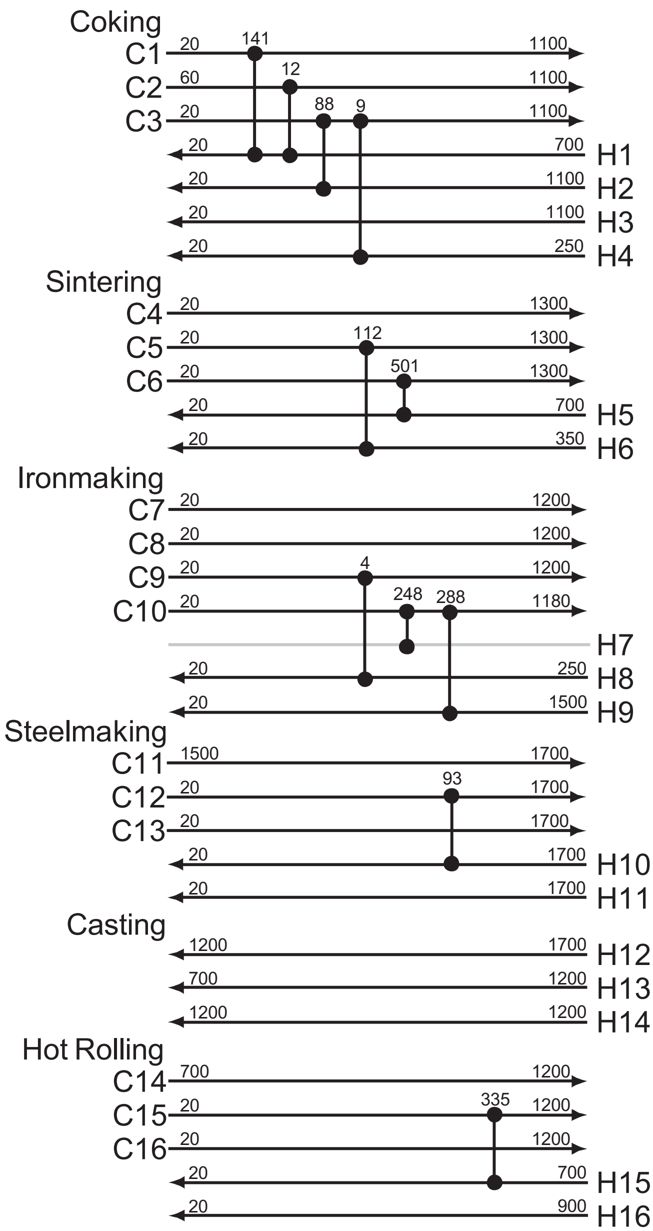


**Fig. 4.** Process heat recovery network. Cold and hot flows from Tables 3 and 4 are represented by horizontal arrows in this diagram, each with a supply and target temperature in °C. Vertical lines represent the heat recovery network limited to each process (coking, sintering, ironmaking, steelmaking, casting, and hot rolling). Heat energy transferred (MJ/t) is indicated for each heat recovery exchange.

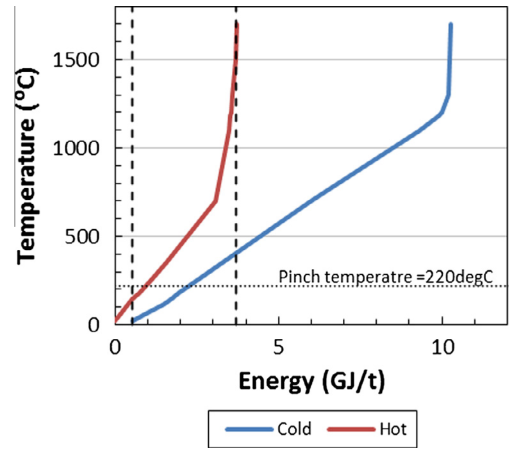


**Fig. 5.** Composite curves for pinch analysis of steel supply chain, excluding hot flows where no technology currently exists for recovery.

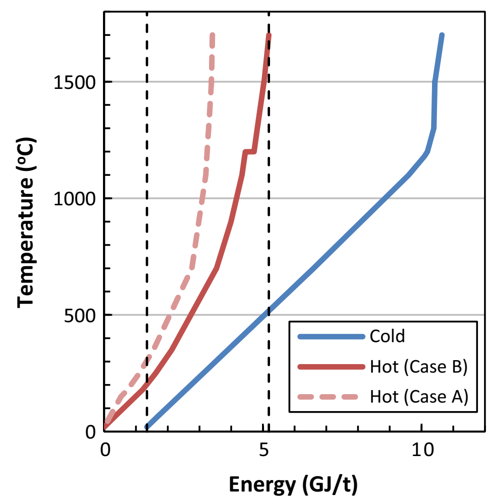


**Fig. 6.** Composite curves for pinch analysis of all flows in steel supply chain.

the maximum energy transfer to each of the selected $dT_{min}$'s are shown in Fig. 7.

The largest sensitivity to heat exchange is in the granulated solids; sinter, coke and slag, where the maximum potential heat recovery may vary significantly if the minimum temperature difference is adjusted. These streams have significant energy available, have a temperature range that crosses the pinch point, and all are either available at (granulated slag) or must be heated to (sinter and coke) a high temperature. The hot exhaust gases have more energy in total, but this is available at lower temperatures where heat demand is already satisfied. There is only one solid steel stream, where the metal is hot charged from casting to rolling, and as this is outside the temperature range of feasible heat exchange, changing $dT_{min}$ for solids does not affect the results at all.

## 4. Discussion

The results of the pinch analysis have shown that moving from process to integrated heat recovery could give additional energy savings of 0.9 GJ/t, and a further 1.6 GJ/t by exploiting all hot streams is possible in theory. Can these savings be achieved in practice, and how does this analysis indicate a future direction for heat recovery in the primary steel industry?

### *4.1. Case A – Pinch analysis based on existing heat recovery technologies (excluding heat recovery from solid streams)*

In this section, a feasible set of heat exchangers for Case A is proposed. Starting from the theoretical maximum energy saving given by pinch analysis, the practicalities of matching streams with suitable states, having a reasonable number of heat exchangers, and accounting for energy losses in heat transfer are considered.

An integrated heat recovery 'grid' network is proposed in Fig. 8. Horizontal lines represent the hot and cold streams from Tables 3 and 4, with low temperatures on the left and high temperature on the right. The vertical links are heat exchangers between hot and cold streams. To account for losses during heat exchange, a penalty of 10% of the energy of the hot stream is applied. Inlet and outlet temperatures, are shown for each stream. The heat energy

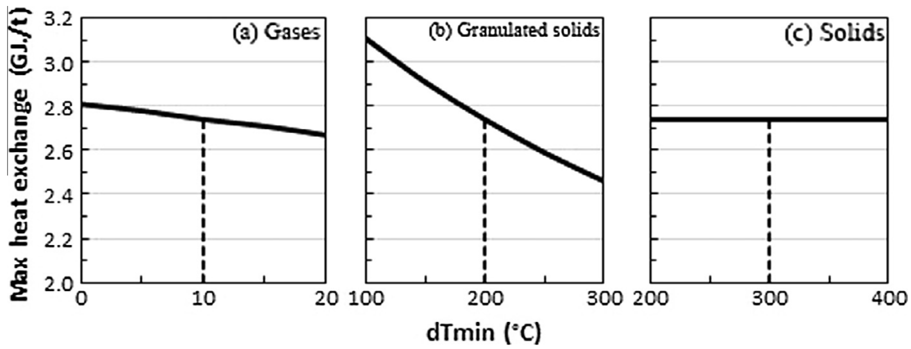


**Fig. 7.** Maximum heat exchange potential vs. $dT_{min}$ for gases, granulated solids, and solids.

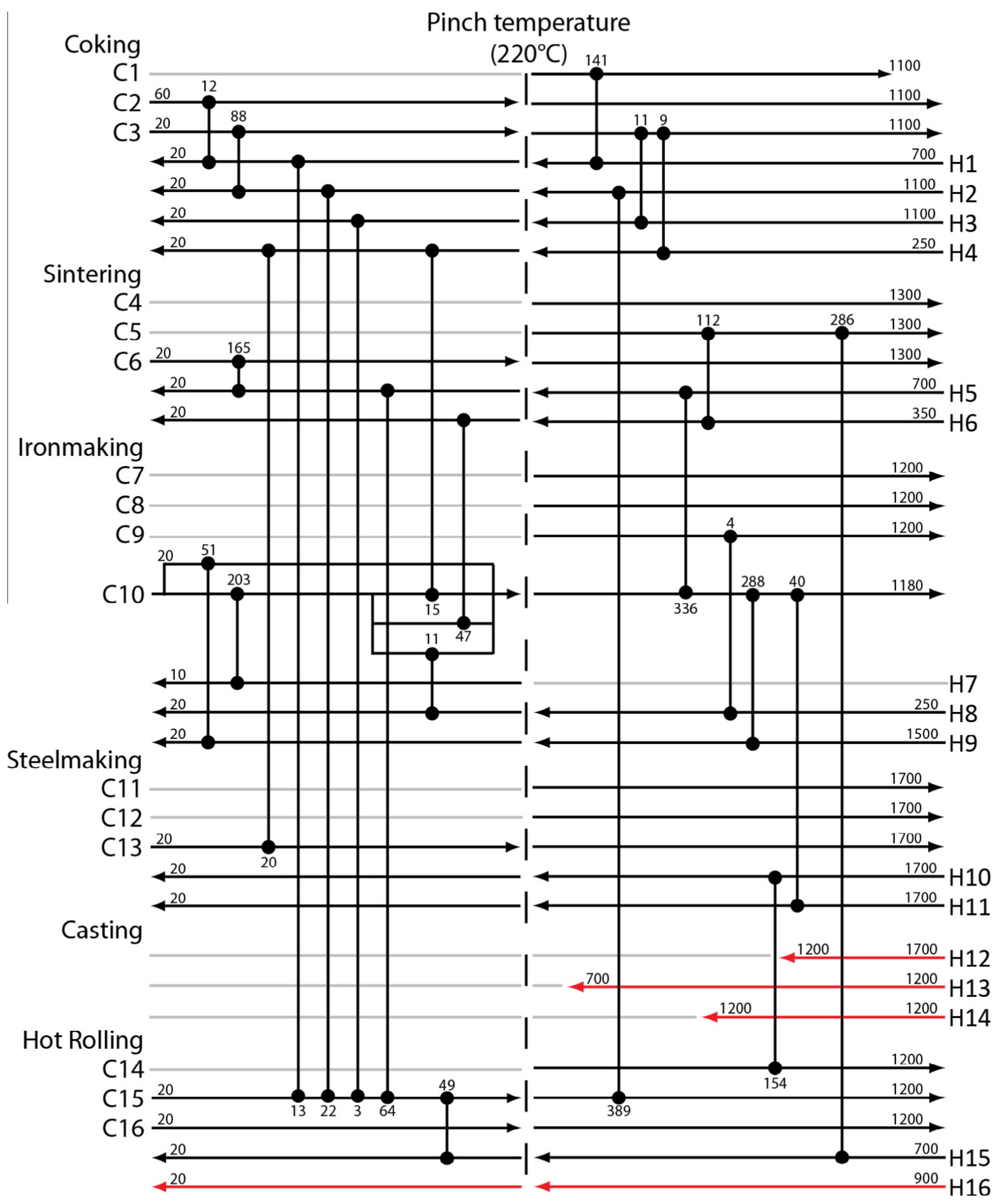


**Fig. 8.** Integrated heat recovery network for first pinch analysis between streams where heat recovery is already practiced (Case A). Physical temperatures (°C) and heat energy transferred (MJ/t) are indicated for each stream. Hot solid streams excluded from Case A analysis are shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

exchanged to the cold stream is given in MJ/t for each vertical heat exchanger link.

To achieve the theoretical minimum energy consumption, no heat exchangers should be placed across the pinch temperature; therefore the grid diagram is divided here. The reason the pinch temperature is 220 °C becomes clear from the grid diagram, as numerous cold streams (e.g. C1, C4, C5, C7 and more) begin at this shifted temperature. They correspond to the granular solid flows which are heated from room temperature with a $dT_{min}$ of 200 °C, highlighting why the choice of $dT_{min}$ is critical.

The most challenging stream to be heated is the air into the blast furnace (C10), which has a large demand for thermal energy and a large thermal mass, and therefore it must be split into four stream branches and matched with five hot streams: coking flue gas (H4), sintering exhaust gas (H6), slag (H9), blast furnace gas (H7), and the blast stove exhaust (H8). The arrangement is complicated due to the flow rates of the hot streams being much less than that of the blast furnace air and heat recovery only being undertaken down to the dew point of the hot gas streams (below this temperature the gas would corrode any heat exchanger too quickly to be practical) so that the blast furnace air must be split into many parallel streams. Providing each stream is preheated to the same temperature, there is no penalty for mixing them at the pinch temperature. A similar issue exists for preheating air for combustion in the hot rolling reheat furnace.

With the exception of the matches between coking (H4), sintering (H6) and iron making (C10) described above, and the use of various streams to preheat air for hot rolling (C15), the proposed heat exchange pairs are within existing processes and are similar to conventional process heat recovery, as defined in Table 1. For example, dry quenching coke to preheat combustion air for that process (H2 and C3), air cooling of sinter (H5 and C6), or the use of a preheat zone in hot rolling reheat furnaces (H15 and C16).

Also notable from the grid diagram is that when taking shifted temperature into account a significant amount of the energy in unused hot streams is only useful for heating below room temperature. Again, this is due to the imposition of large $dT_{min}$. While 0.6 GJ/t of energy remains in the hot streams after heat exchange, a much smaller amount is actually useful. No external cooling utility is required for these streams, as given sufficient time they may all be allowed to cool in air.

Above the pinch, heat exchange becomes more complicated, with more links between processes. The majority of the available heat is at temperatures near the pinch point, either in granular solids that require a large minimum temperature difference or in exhaust gases at medium temperatures. All cold streams must be heated to high temperatures, and therefore it is impossible to entirely displace external heating in any one process.

Despite this, there is still a significant energy saving to be achieved through heat exchange, with the proposed network shown in the second half of the grid diagram in Fig. 8. Again, preheating air for the blast stoves in ironmaking is given priority, with three serial heat exchanges coming from slag and sinter quenching. The other large heat exchangers are from the hot rolling reheat furnace exhaust to preheat ore for the sintering process and quenching coke with air that is fed to the reheat furnace.

Overall, the proposed network achieves an energy saving of 2.5 GJ/t, 90% of the limit of 2.7 GJ/t calculated as part of the pinch analysis. This shows a practical improvement over existing process heat recovery, which can only save 1.8 GJ/t. This occurs for two reasons; firstly, instances of transferring heat across the pinch temperature are avoided in the optimised network, allowing the high temperature heat to be used at higher temperatures where heat energy is scarce. Secondly, heat exchange between processes, rather than just within processes, allows for better matching of the streams, with more complete use of the available heat energy as a result.

In practice, two main challenges exist in implementing such a network. Firstly, while most primary steel production occurs on a single site, there is still a significant physical distance between processes and it may not be possible to transfer flows without a large temperature loss and a large expenditure on infrastructure for physically transporting the flows. Secondly, the practice of not exchanging heat across the pinch temperature results in a more complicated heat exchange network, particularly when different streams are matched below and above the pinch. For instance, the preheated air stream for hot rolling is first of all heated to pinch temperature by heat exchange with the reheat furnace exhaust, but then must be used in the first stage of coke dry quenching reaching a temperature of 700 °C. The second stage of coke dry quenching, bringing the coke from 420 °C to 220 °C is used to preheat air for the coke ovens. Such a scheme would require careful control of flow rates.

### *4.2. Case B – Pinch analysis of all flows (including heat recovery from solid streams)*

The potential energy saving when including all flows was shown to be 4.3 GJ/t, an increase of 1.6 GJ/t over the existing solutions which ignore hot solid flows. In this section, the feasibility of a wider heat exchange network that includes these flows is investigated. As before, a practical heat exchanger network is proposed. Below the pinch, where a surplus of heat already existed, there is no benefit from the extra streams and therefore the proposed network is identical to that presented in Fig. 8 previously. The proposed network above the pinch temperature is shown in Fig. 9. The addition of the extra streams – cast and hot rolled steel – allows for additional preheating of the air for combustion in the sintering and hot rolling processes.

The proposed heat exchanger network saves 0.2 GJ/t extra over the network given in Fig. 8. This is lower than the maximum potential due to some streams not being used, and also due to the losses applied to heat exchange.

No heat exchange is proposed from the latent heat during continuous casting. The solidification process requires a fast removal of heat energy to achieve a reasonable level of productivity, hence the use of water-cooled copper moulds where the latent heat energy is instantly degraded to near room temperature. A process to capture this heat at a useful temperature would extract energy at a lower rate, slowing production and adversely affecting the metallurgy of the cast steel. Additionally, robust materials that can withstand the metal contact at high temperatures for a long period of time would be required. For these reasons, it is hard to envisage a way of capturing this heat practically.

Overall, the remaining potential for heat recovery is small, and may be partially superseded by the application of direct linking of casting and hot rolling processes for a significantly larger energy saving.

### *4.3. Integrating with other supply chains*

A final opportunity exists in including more flows in the pinch analysis so that the heat exchange can be matched more closely. In reality, this would involve linking the primary steel supply chain with other supply chains involving heating so as to find a symbiosis where the total energy consumption is reduced. This may be considered in two parts: the addition of cold flows below the pinch to use the extra heat available, and the addition of hot flows above the pinch to increase overall heat exchange.

It has already been shown that 0.6 GJ/t of energy remains below the pinch after heat recovery is implemented. An additional cold

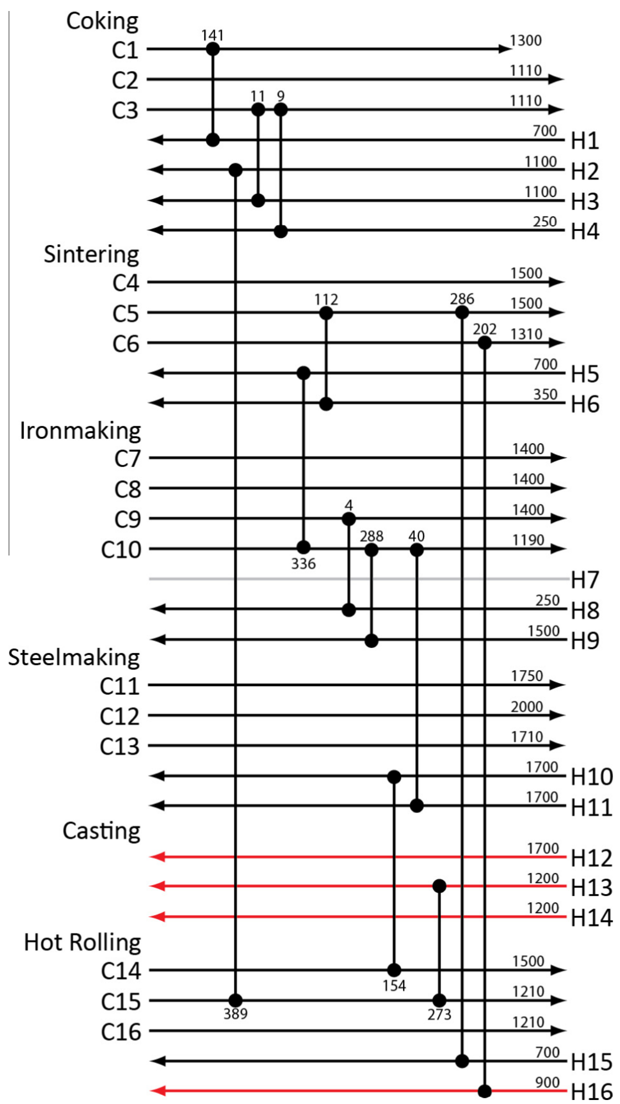

**Fig. 9.** Proposed heat exchanger network above the pinch (Case B). Extra streams considered beyond Case A are highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

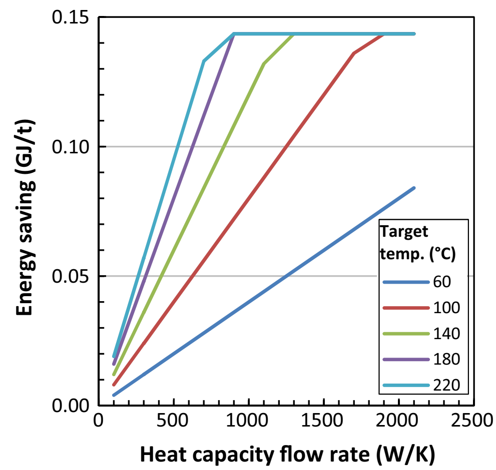

**Fig. 10.** Potential energy saving through use of excess energy below the pinch temperature.

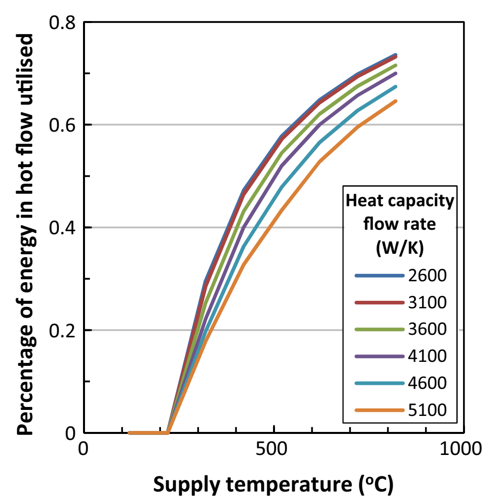

**Fig. 11.** Potential utilisation of a hot stream added to the primary steel supply chain, with varying supply temperature and heat capacity flow rates.

steam, supplied at 20 °C and with a variable target temperature and heat capacity flow rate, is added. By repeating the pinch analysis to determine how much heat may be transferred to this cold flow, it is possible to determine how much of this 0.6 GJ/t could be useful in applications like space heating. Fig. 10 shows the additional potential energy saving predicted by a pinch analysis of the steel supply chain (Case A) plus the added cold stream. The figure shows a plateau around 0.15 GJ/t energy saving and that there is an optimum balance of target temperature and heat capacity flow rate beyond which no further energy saving is possible. This is lower than the available energy because some of the hot streams have a large $dT_{min}$ applied, so that they are only available for heating cold streams below room temperature. Such cold streams do not exist, so this energy is effectively unavailable.

Fig. 11 shows the potential utilisation of an additional hot stream above the pinch temperature. Such flow is of course only useful when supplied above the pinch temperature of 220 °C and a bigger proportion of its energy may be exchanged if it has a higher source temperature. The variation with heat capacity flow rate is also shown, with the utilisation constant up to a heat capacity flow rate of 2600 W/K and falling at higher heat capacity flow rates. This is because the additional stream starts to alter the pinch point above this level, and less energy can be recovered overall as a result. Therefore, there are limits to the opportunity for energy saving by adding a hot stream above the pinch temperature.

From these results, the consequences for integrating the steel supply chain with another industry are twofold. Firstly, at low temperatures below the pinch, there are only very small opportunities, so space heating or paper/wood drying would not be complimentary partners. Secondly, at higher temperatures, cement and aluminium industries provide the best opportunities for integration, since they operate at approximately 1500 °C and 900 °C respectively. However, these industries can only be used if they are able to provide a hot stream at a temperature above the pinch (220 °C). Such a stream would only be available if the pinch temperature in cement or aluminium production was higher than for steel. Further work is required to determine if this is the case. The greater the difference between the pinch temperature of steel production and the industry from which the hot stream is provided, the more useful it will be in lowering overall energy use.

Finally, it is important to note the context of heat recovery against other preventative options for reducing heat demand. If a requirement for heating can be eliminated entirely, larger energy

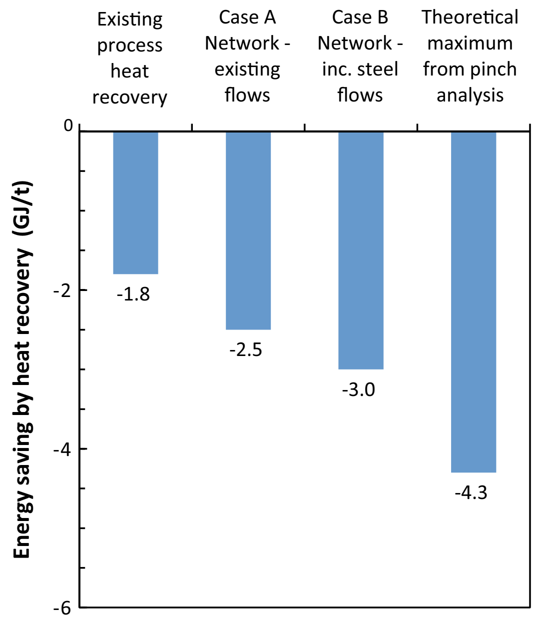


**Fig. 12.** Comparison of energy savings with different heat recovery options.

savings can typically be made. For example using direct strip casting to eliminate the hot rolling step or by directly linking the casting and hot rolling processes so as to eliminate the need for a reheat furnace. Energy savings in both cases are approximately 0.5 GJ/t compared to 0.3 GJ/t by heat recovery, and therefore these strategies should be pursued first.

## 5. Conclusions

The detailed mass and energy balance and pinch analysis have identified opportunities for further energy savings by integrated heat recovery, albeit small savings relative to the total energy input. In Fig. 12, the options for heat recovery are compared. Using the data from the energy balance, from a total net energy use of 17.3 GJ for production of one tonne of hot rolled steel, 9.7 GJ/t is required to raise the temperature of the inputs to the operating temperature of the processes in the supply chain. The remaining energy is used as electricity for purposes other than heating, or is lost to the environment (e.g. as heat or as chemical energy in species that are not recovered). Process heat recovery already plays an important role in the steel supply chain, saving 1.8 GJ/t. Through pinch analysis of the whole system, a maximum energy saving for heat recovery of 4.3 GJ/t has been calculated. Predictions that account for the practicalities of developing a network of heat exchangers lie somewhere between these. Case A, which uses process heat recovery technologies but integrated over the entire supply chain, saves 2.5 GJ/t, while Case B adds heat recovery from hot steel streams with a large $dT_{min}$ for a saving of 3.0 GJ/t.

To achieve these savings in practice, two strategies are required. Firstly, following the thermodynamic principles used in the method of pinch analysis, no heat may be exchanged across the pinch temperature (calculated as 220 °C) and no external heating should be used below this temperature. The pinch temperature from the steel supply chain is strongly affected by the minimum temperature difference applied to the 'granular solid' inputs and outputs: coal, coke, ore, sinter and slags, and any approaches which can improve heat transfer in these instances could result in even greater savings than given above. Secondly, there are remaining heat recovery opportunities from solid metal products that are not utilised today but which may be useful even with a large temperature difference applied to ensure a viable heat exchanger. In particular, the steel outputs of casting and hot rolling should be cooled by preheating air to make use of this opportunity.

While process heat recovery already plays an important role in today's steel supply chain, an integrated network of heat recovery is an option for further energy savings in the future. To develop this initial prediction further, the strategies identified should be applied to a real plant design to determine the validity of the assumptions made. Furthermore, an assessment of the investment and maintenance costs of the proposed integrated heat recovery networks should be required to examine the eventual economic benefits of this option.

## Acknowledgements

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## Appendix A

The details of the data sources and any modifications made to achieve consistency (overall mass and energy balances, as well as ensuring different elements are conserved) are described here. The processes are compiled for the entire steel supply chain and verified against sources from the literature.

### *A.1. Individual process data*

The inputs and outputs of each process are presented below.

#### *A.1.1. Coking*

A mass and energy balance for a coking plant in an integrated steelworks in Turkey was carried out by Ertem and Özdabak [8]. The coking process takes place at 1100 °C, with the energy for heating the streams provided by a combination of recycled coke oven gas, which is combusted, and the slowly burning coal which becomes coke. Air is needed for the combustion process to occur.

The hot coke must be quenched to ambient temperature to stop the combustion process; this may occur optionally by water or air (wet- or dry-quenching respectively). Dry quenching with air is assumed, although the air flow is not included here as it may be provided as an opportunity for heat exchange (see Table A1).

#### *A.1.2. Sintering*

The sintering process data was taken from the industry survey averages provided by IISI [9]. The sintering process takes place by combusting a mixture of coke breeze and iron ore followed by quenching with air. As with coking, this cooling air flow is omitted as it may be provided through heat exchange, and therefore the outlet temperature of sinter is taken as 700 °C.

Other solid fuels and gas, which make up less than 10% of total energy input, are ignored as individual streams and their energy included as a larger coke breeze flow. The combustion airflow was determined by assuming all a stoichiometric combustion with the coke breeze, which is assumed to be entirely made up of carbon (see Table A2).

#### *A.1.3. Ironmaking*

The ironmaking process covers two linked steps in the steel supply chain. Air is preheated in blast stoves, and fed into a blast furnace filled with coke and sinter. A mass and energy balance for a Turkish Ironmaking plant was produced by Ertem and Gurgen [7]. The blast furnace surveyed is old but was recently refurbished.

**Table A1**
Mass and energy flows in the coking process.

| Stream | Mass flow ($t_{stream}/t_{coke}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy (GJ/t) | Chemical energy (GJ/t) | Other energy (GJ/t) | Total energy (GJ/t) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Coal | 1.3 | 20 | 1100 | 1300 | 32.10 | 0.0 | 40.3 | 0.0 | 40.3 |
| COG | 0.1 | 60 | 1100 | 2980 | 37.10 | 0.0 | 2.4 | 0.0 | 2.4 |
| Air | 1.1 | 20 | 1100 | 1010 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity | 0.0 | 20 | 20 | 0 | 0.00 | 0.0 | 0.0 | 0.3 | 0.3 |
| Input total | 2.4 | | | | | 0.0 | 42.7 | 0.3 | 43.0 |
| *Outputs* | | | | | | | | | |
| Coke | 1.0 | 1100 | 20 | 1500 | 28.60 | 1.6 | 28.6 | 0.0 | 30.9 |
| COG | 0.2 | 700 | 20 | 4040 | 37.10 | 0.5 | 7.2 | 0.0 | 7.7 |
| Tar | 0.1 | 1100 | 20 | 920 | 37.70 | 0.1 | 2.1 | 0.0 | 2.1 |
| Flue gas | 1.1 | 250 | 20 | 1080 | 0.00 | 0.3 | 0.0 | 0.0 | 0.3 |
| Losses | 0.0 | 1100 | 1099 | 0 | 0.00 | 0.0 | 0.0 | 2.0 | 2.0 |
| Output total | 2.4 | | | | | 2.5 | 37.9 | 2.0 | 43.0 |
| Net | 0.0 | | | | | 2.5 | −4.8 | 1.7 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | 4.8 | 0.3 | $GJ/t_{coke}$ |

The coke input is supplemented with the addition of coal for an extra energy input. A mixture of natural gas, coke oven gas or blast furnace gas may be used to fire the blast stoves depending on availability, but the properties of the mixture will be approximately the same and pure natural gas is assumed here. The peak temperature in the blast furnace will be higher than 1200 °C and varies through the bed, but this is taken as a sensible feed temperature with a hot blast slightly below this.

The main output is pig iron, with a carbon content of approximate 4 wt% that is removed in the subsequent steelmaking process. The blast furnace gas is assumed to be dry cleaned and the small dust stream from this cleaning process is ignored. No top recovery turbine is used to generate electricity from the pressure of this gas. The slag is tapped as a liquid and solidifies as heat is removed. No cooling stream is applied, but in subsequent analyses it will be assumed to be dry granulation with air and the stream is treated as a granulated solid (see Table A3).

### *A.1.4. Steelmaking*

To produce steel, the carbon content of pig iron is reduced by bubbling oxygen through the liquid metal in a basic oxygen furnace. An exergy balance of the process was completed by Costa et al. [5], with 'indicative' values given for mass and energy flows. Temperatures were taken from IISI [9], and specific heats carried forward from Ertem and Gurgen [7].

The reaction of oxygen with carbon in the pig iron is exothermic, and therefore the steelmaking process has excess energy available. This is balanced with an input of cold scrap that may be melted, accounting for approximately 10% of the total steel mass. There is a 90% yield from pig iron and scrap to steel due to changing alloy content and some loss of iron in the slag (see Table A4).

### *A.1.5. Continuous casting*

The steelmaking process is followed by a series of liquid metal treatments, for example degassing and alloying. The exact choice of treatments depends on the alloy grade being made and its application, and typically these do not involve significant changes in temperature so are ignored for the purposes of this pinch analysis.

After treatment, the steel is continuously cast by pouring into a water-cooled, oscillating copper mould, where the outer shell solidifies, and then cooled further with water sprays down to approximately 700 °C, where it is charged to a reheat furnace before hot rolling. The temperatures and mass flows are taken from IISI [9], while the latent heat of steel is from Campbell [3]. As this latent heat is released over a small temperature range, it is treated as a separate flow with a high apparent specific heat capacity for the purposes of the pinch analysis (see Table A5).

### *A.1.6. Hot rolling*

Finally, the cast steel is hot rolled at a temperature of 1200 °C. While it is possible to achieve a direct link between casting and hot rolling so no reheat is required, the solution is not widespread and therefore a reheat furnace is needed. Data for energy use of the furnace and for hot output streams is taken from Chen et al. [4] who captured operational figures for a hot strip mill in Taiwan. The reheat exhaust temperature is taken as the direct output of the furnace before heat recovery is applied (see Table A6).

## *A.2. Linking processes to form steel supply chain*

Each process has a primary output that feeds into the next step in the supply chain, with the overall output being hot rolled steel. The mass of coke and sinter required are defined by the Ironmaking process inputs given by Ertem and Gurgen [7]. The iron ore input is considered entirely in sinter form, ignoring pellets; according to IISI [9] this is the trend in the steel industry as a whole and their analysis also assumes 100% sinter.

As steelmaking melts scrap to offset the energy released in the process, only 90% of the iron input to the basic oxygen furnace is pig iron from the blast furnace. The process yield for iron given by IISI [9] is 90%, so the blast furnace must still produce approximately 1t of iron for every 1t of hot rolled steel. Finally, there are small yield losses in continuous casting and hot rolling. These are given as 97% and 96% respectively by the Worldsteel Association [14]. Working backwards from 1 t of hot rolled steel, these yield losses infer the relative outputs of each process relative to one tonne of hot rolled steel produced in the supply chain, given in Table A7.

## *A.3. Verification*

From data on the relative output of each process (Table A7), it is possible to define the total energy use in each process and in the production of one tonne of hot rolled steel, shown in Table A8.

**Table A2**
Mass and energy flows in the sintering process.

| Stream | Mass flow ($t_{stream}/t_{sinter}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy ($GJ/t_{sinter}$) | Chemical energy ($GJ/t_{sinter}$) | Other energy ($GJ/t_{sinter}$) | Total energy ($GJ/t_{sinter}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Ore | 1 | 20 | 1300 | 620 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Coke breeze | 0.05 | 20 | 1300 | 1500 | 29.3 | 0.0 | 1.5 | 0.0 | 1.5 |
| Combustion Air | 0.6 | 20 | 1300 | 1000 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity | 0 | 20 | 20 | 0 | 0 | 0.0 | 0.0 | 0.4 | 0.4 |
| Input total | 1.7 | | | | | 0.0 | 1.5 | 0.4 | 1.8 |
| *Outputs* | | | | | | | | | |
| Sinter | 1 | 700 | 20 | 920 | 0 | 0.6 | 0.0 | 0.0 | 0.6 |
| Exhaust | 0.65 | 350 | 20 | 1100 | 0 | 0.2 | 0.0 | 0.0 | 0.2 |
| Losses | 0 | 20 | 20 | 0 | 0 | 0.0 | 0.0 | 0.0 | 1.0 |
| Output total | 1.7 | | | | | 0.9 | 0.0 | 0.0 | 1.8 |
| Net | 0.0 | | | | | 0.9 | −1.5 | −0.4 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | 1.5 | 0.4 | $GJ/t_{sinter}$ |

**Table A3**
Mass and energy flows in the ironmaking process.

| Stream | Mass flow ($t_{stream}/t_{iron}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy ($GJ/t_{iron}$) | Chemical energy ($GJ/t_{iron}$) | Other energy ($GJ/t_{iron}$) | Total energy ($GJ/t_{iron}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Coke | 0.410 | 20 | 1200 | 1250 | 28.6 | 0.0 | 11.7 | 0.0 | 11.7 |
| Coal | 0.102 | 20 | 1200 | 1250 | 28.4 | 0.0 | 2.9 | 0.0 | 2.9 |
| Sinter | 1.394 | 20 | 1200 | 920 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Air | 1.220 | 20 | 1180 | 1360 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Natural gas | 0.058 | 20 | 1180 | 2200 | 34.5 | 0.0 | 2.0 | 0.0 | 2.0 |
| Electricity | 0.000 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Input total | 3.184 | | | | | 0.0 | 16.6 | 0.1 | 16.8 |
| *Outputs* | | | | | | | | | |
| Pig iron | 1.000 | 1500 | 1500 | 920 | 87.7 | 1.3 | 6.6 | 0.0 | 7.9 |
| Blast furnace gas | 1.600 | 180 | 20 | 1042 | 2.7 | 0.3 | 4.3 | 0.0 | 4.6 |
| Slag | 0.300 | 1500 | 20 | 954 | 0 | 0.4 | 0.0 | 0.0 | 0.4 |
| Blast stove exhaust | 0.210 | 250 | 20 | 1100 | 0 | 0.1 | 0.0 | 0.0 | 0.1 |
| Losses | 0.000 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 3.7 |
| Output total | 3.110 | | | | | 2.1 | 4.3 | 0.0 | 16.8 |
| Net | −0.074 | | | | | 2.1 | −12.3 | −0.1 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | 12.3 | 0.1 | $GJ/t_{iron}$ |

**Table A4**
Mass and energy flows in the steelmaking process.

| Stream | Mass flow ($t_{stream}/t_{steel}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy ($GJ/t_{steel}$) | Chemical energy ($GJ/t_{steel}$) | Other energy ($GJ/t_{steel}$) | Total energy ($GJ/t_{steel}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Pig iron | 0.98 | 1500 | 1700 | 920 | 0 | 1.3 | 8.6 | 0.0 | 1.3 |
| Scrap | 0.09 | 20 | 1700 | 590 | 0 | 0.0 | 0.6 | 0.0 | 0.0 |
| Oxygen | 0.07 | 20 | 1700 | 1430 | 0 | 0.0 | 0.3 | 0.0 | 0.3 |
| Electricity | 0.00 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.3 | 0.3 |
| Input total | 1.13 | | | | | 1.3 | 9.4 | 0.3 | 1.8 |
| *Outputs* | | | | | | | | | |
| BOF exhaust | 0.10 | 1700 | 20 | 1100 | 1.5 | 0.2 | 0.7 | 0.0 | 0.9 |
| Slag | 0.03 | 1700 | 20 | 954 | 0 | 0.1 | 0.0 | 0.0 | 0.1 |
| Steel | 1.00 | 1700 | 1700 | 590 | 0 | 1.0 | 6.6 | 0.0 | 1.0 |
| Losses | 0.00 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | −0.1 |
| Output total | 1.13 | | | | | 1.2 | 7.3 | 0.0 | 1.8 |
| Net | 0.00 | | | | | −0.1 | −2.1 | −0.3 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | −0.5 | 0.3 | $GJ/t_{steel}$ |

**Table A5**
Mass and energy flows in the continuous casting process.

| Stream | Mass flow ($t_{stream}/t_{steel}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy (GJ/$t_{steel}$) | Chemical energy (GJ/$t_{steel}$) | Other energy (GJ/$t_{steel}$) | Total energy (GJ/$t_{steel}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Steel | 1.00 | 1700 | 1200 | 590 | 0 | 1.0 | 0.0 | 0.0 | 1.0 |
| Electricity | 0.00 | 20 | 20 | 0 | 0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Input total | 1.00 | | | | | 1.0 | 0.0 | 0.1 | 1.1 |
| *Outputs* | | | | | | | | | |
| Steel | 1.00 | 1200 | 700 | 590 | 0 | 0.7 | 0.0 | 0.0 | 0.7 |
| Steel latent heat | 0.00 | 1200 | 1199 | 272,000 | 0 | 0.3 | 0.0 | 0.0 | 0.3 |
| Losses | 0.00 | 20 | 19.99 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.2 |
| Output total | 1.00 | | | | | 1.0 | 0.0 | 0.0 | 1.1 |
| Net | 0.00 | | | | | 0.0 | 0.0 | −0.1 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | 0.0 | 0.1 | GJ/$t_{steel}$ |

**Table A6**
Mass and energy flows in the hot rolling process.

| Stream | Mass flow ($t_{stream}/t_{steel}$) | Inlet temp (°C) | Outlet temp (°C) | Specific heat capacity (J/kg K) | Calorific value (MJ/kg) | Thermal energy (GJ/$t_{steel}$) | Chemical energy (GJ/$t_{steel}$) | Other energy (GJ/$t_{steel}$) | Total energy (GJ/$t_{steel}$) |
|---|---|---|---|---|---|---|---|---|---|
| *Inputs* | | | | | | | | | |
| Steel In | 1.00 | 700 | 1200 | 620 | 0 | 0.4 | 0.0 | 0.0 | 0.4 |
| Natural gas In | 0.03 | 20 | 700 | 2200 | 34.5 | 0.0 | 0.9 | 0.0 | 0.9 |
| Air In | 0.72 | 20 | 700 | 1100 | 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Electricity In | 0.00 | 20 | 20.1 | 0 | 0 | 0.0 | 0.0 | 1.0 | 1.0 |
| Input total | 1.75 | | | | | 0.4 | 0.9 | 1.0 | 2.3 |
| *Outputs* | | | | | | | | | |
| Reheat exhaust | 0.76 | 700 | 20 | 890 | 0 | 0.2 | 0.0 | 0.0 | 0.2 |
| Steel out | 1.00 | 900 | 20 | 620 | 0 | 0.5 | 0.0 | 0.0 | 0.5 |
| Losses | 0.00 | 20 | 19.99 | 0 | 0 | 0.0 | 0.0 | 0.0 | 1.6 |
| Output total | 1.76 | | | | | 0.8 | 0.0 | 0.0 | 2.3 |
| Net | 0.01 | | | | | 0.3 | −0.9 | −1.0 | 0.0 |
| | | | | | | | Chemical | Electrical | |
| | | | | | | Energy inputs | 0.9 | 1.0 | GJ/$t_{steel}$ |

**Table A7**
Relative outputs of processes.

| Process | Process output | Relative output ($t_{process\ output}/t_{hot\ rolled\ steel}$) |
|---|---|---|
| Coking | Coke | 0.42 |
| Sintering | Sinter | 1.45 |
| Blast furnace | Iron | 1.04 |
| BOF | Steel | 1.06 |
| Casting | Steel | 1.03 |
| Hot rolling | Steel | 1.00 |

The chemical and electrical energies are shown separately so as to highlight the different nature of both sources. Two totals are given; a sum of the chemical and electrical energies, and the total energy on a primary basis assuming an electricity generation efficiency of 33%.

These overall energy consumptions are consistent with the range of figures presented in literature. For example, IISI [9] cites 18 GJ/t energy consumption with 10% scrap used in steelmaking, and the average of all the reported sites is 20.4 GJ/t (both figures are a direct sum of chemical and electrical energies). The data generated gives an equivalent figure of 19.5 GJ/t which lies between the two quoted values.

De Beer et al. [2] break down best practice energy consumption by process, presenting a total primary energy consumption 19.1 GJ/t compared to 23.9 GJ/t calculated here. The difference may be explained by a lack of heat recovery application (2.1 GJ/t), no top recovery turbine used, and by the large difference at

**Table A8**
Summary of energy consumption from data collected.

| Process | Energy consumption (GJ/t hrs) | | | | | |
|---|---|---|---|---|---|---|
| | Chemical | Electrical | Final (=*Chemical* + *Electrical*) | Primary (=*Chemical* + *Electrical*/0.33) | Best practice primary, from De Beer et al. [2] | Best practice primary, from Worrell et al. [15] |
| Coking | 2.0 | 0.1 | 2.2 | 2.4 | 1.8 | 2.2 |
| Sintering | 2.1 | 0.5 | 2.6 | 3.7 | 2.5 | 1.1 |
| Ironmaking | 12.7 | 0.1 | 12.9 | 13.1 | 11.8 | 12.4 |
| BOF | −0.5 | 0.3 | −0.2 | 0.3 | 0.3 | −0.3 |
| Casting | 0.0 | 0.1 | 0.1 | 0.4 | 0.6 | 0.5 |
| Hot rolling | 0.9 | 1.0 | 1.9 | 3.9 | 2.1 | 2.4 |
| Totals | 17.3 | 2.2 | 19.5 | 23.9 | 19.1 | 18.3 |

the hot rolling stage where De Beer assumes direct linking of casting and hot rolling and a smaller cast thickness to reduce electricity consumption. When these are taken into account, the process energy consumptions match well and therefore the mass- and energy-balanced data has been shown to be representative of a typical steel supply chain.

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