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Regular Article

Case study of industrial symbiosis for improved residual material utilisation in the steel industry

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Abstract. Steel production is a material and energy intensive industry which, in addition to steel products, generates residual materials such as metallurgical slag, dust and sludge. These residual materials are recycled and used to a great extent as well in-house as for external purposes. Even so, some materials are currently landfilled due to difficulties in finding use or recycling possibilities. This applies, for example, to zinc-containing sludge and dust from ore-based steel production and certain iron-rich, lime and carbon-containing materials from scrap-based steel production. A case study has been performed with the aim to develop a methodology for evaluating industrial symbiosis possibilities in regard to increased material efficiency in steel production systems. The methodology is based on system analysis of steel production routes in combination with economical assessment of hypothetical business concepts by using residual materials from one industry as secondary raw materials in another. The paper presents case study results and indicates how this methodology could be applied to maximise the residual materials utilisation. By the methodology discussed and with a circular-economic perspective, it is shown that high economic potential for one material could be used to increase the utilisation of other materials with lower economic potential.

Keywords: steel industry / residual materials / industrial symbiosis / system analysis / economic concept

Résumé. Étude de cas sur la symbiose industrielle pour une utilisation améliorée des matériaux résiduels dans l'industrie sidérurgique. La production d'acier est une industrie à forte intensité de matériaux et d'énergie qui, en plus des produits en acier, génère des matières résiduelles telles que les scories, les poussières et les boues métallurgiques. Ces matières résiduelles sont recyclées et utilisées dans une large mesure tant en interne qu'à des fins externes. Néanmoins, certains matériaux sont actuellement mis en décharge en raison de difficultés à trouver des possibilités d'utilisation ou de recyclage. Cela concerne, par exemple, les boues et poussières contenant du zinc provenant de la production d'acier à base de minerai et certains matériaux riches en fer, contenant de la chaux et du carbone provenant de la production d'acier à partir de ferraille. Une étude de cas a été réalisée dans le but de développer une méthodologie pour évaluer les possibilités de symbiose industrielle en ce qui concerne l'augmentation de l'efficacité des matériaux dans les systèmes de production d'acier. La méthodologie repose sur une analyse système des filières de production d'acier, associée à une évaluation économique de concepts commerciaux hypothétiques en utilisant des matières résiduelles d'une industrie comme matières premières secondaires dans une autre. Ce document présente les résultats des études de cas et indique comment cette méthodologie pourrait être appliquée pour maximiser l'utilisation des matières résiduelles. La méthodologie discutée et une perspective économique circulaire montre qu'un potentiel économique élevé pour un matériau pourrait être utilisé pour accroître l'utilisation d'autres matériaux présentant un potentiel économique inférieur.

Mots clés: industrie sidérurgique / matières résiduelles / symbiose industrielle / analyse de système / concept économique

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1 Introduction

Steel is the most recycled material in the world and used for a broad variety of applications in society. The steel production is nevertheless a material and energy intensive industry, which in addition to the produced steel also generates significant amounts of residual material such as slag, dust and sludge [1,2]. The steel plant residual materials often consist of considerable amounts of valuable contents, whereof it may be profitable to use them as secondary raw materials in-house or in other industries. Much work is devoted on finding applications and making further investigations of effects and potentials to utilising residual materials in other industries. One example from the literature is the use of steel production slags, such as basic oxygen furnace slag, in the fertiliser industry. Using the slag as a soil conditioner would promote improved sustainability of industrial activities for both the steel and fertiliser industries regarding natural resources savings, CO_2 emission reductions and decreased landfill [3].

Avoiding landfill and making use of the residual materials contributes to reduced use of virgin raw materials with positive effects on economy, space and the environment. Even so, some materials are currently long-term stored or deposited due to difficulties in finding external use or in-house recycling possibilities. This applies, for example, to zinc-containing sludge and dust from ore-based steel production and certain iron-rich, lime and coal-containing materials from scrap-based steel production [4–6].

Agendas like the UN's sustainable development goals and the European commission's circular economy package increases the society's expectations on sustainability [7,8]. These agendas along with corporate aspirations towards the zero-waste vision, costs and space related to storage-/landfill sites, are motivators for the further endeavour to increase the use of residual materials.

The concept of industrial symbiosis has been developed by collective and versatile industrial approaches to improve economic and environmental performance, for example, by using residual materials as substitutes for raw materials. Residual material from one industry branch can be a raw material source for another [9,10].

There are numerous on-going industrial symbioses and material stream exchanges. In a review of successful industrial symbiosis case studies in the steel industry, 11 steelmaking sites, in 6 countries, were analysed. The analyses were based on the steelmakers on-going industrial symbiosis exchanges as well as planned extensions to the current industrial symbiosis activities. In the review, 59 documented industrial symbiosis stream exchanges were analysed whereof 5 straightforward synergetic solutions were identified [11].

Two examples of industrial symbiosis are the industrial symbiosis initiative of Kalundborg (Denmark) and the sustainable neighborhood of BedZed (UK). These examples are presented in the literature and studied in regard to the energy transition context on industrial symbiosis in which materials played an important role. The results from the studies demonstrate the relationship of social impact to material utilisation and energy transition [12].

In a recent study, the exchange of materials in a network of industrial companies was analysed. The study involved a steelmaking plant with its generated residual materials such as slag, electric arc furnace dust, mill scale, and zinc sludge which was used as raw materials by a cement plant and a zinc smelting plant. The loop of material flows was closed by the zinc smelting plant as the zinc sludge was used as raw material for zinc ingots to be used by the steelmaking plant in the galvanization process of its wire rod manufacture. From the study, it was concluded that mutual interest is the main driving force of the network industrial symbiosis. Further relevant factors are environmental issues. However, industrial symbioses are strongly dependent on external factors whereof logistics and legal compliance are vital [13].

A literature review on material flow analysis for resource productivity indicators argues the need for integrated approaches towards a sound material-cycle society with reduced consumption of natural resources and limited waste generation [14]. A study on circular economy characteristics in relation to business model structures highlight the limited transferability and lack of supporting framework for companies in designing a circular business model [15]. Further, the results of a previous study concluded that industrial symbiosis in relation to iron- and steelmaking generated environmental and economic gains for the companies [16]. The authors also point out the need for developed decision-making tools for optimising material flows and value chains.

Another study in the literature shows an example of a simulation scenario and the use of an optimisation model on analysis of carbon emission reduction cooperation for the iron and steel industry. The study is made from the perspective of industrial symbiosis, by inter-firm collaboration, identifying the carbon footprint within the flows among the industrial firms and showing ways to achieve carbon emission reduction by sustainable consumption of waste resources [17].

A novel process involving two routes for simultaneous plastic waste pre-treatment, shredded plastic gasification/pyrolysis, steel scrap preheating and zinc recovery is described and assessed by simulation and optimisation modelling. The routes were modelled in an integrated flowsheet and evaluation of different scenarios according to economic and environmental criteria were made. The process optimisation resulted in potential energy savings in Electric Arc Furnace steel production of over 300 MJ/t of preheated scrap charged [18].

In this present work, a case study for enhanced residual materials use was performed by the Swedish research institute Swerim in collaboration with; the scrap-based steel producer Höganäs Sweden, SSAB Merox, the subsidiary company managing residuals of the ore-based steel producer SSAB, the base metals producer Boliden Mineral and the Swedish steel producers' association Jernkontoret's technical area 55, *Steel production residues*.

The aim of the case study was to develop a methodology to identify and evaluate possibilities for industrial symbiosis for increased and optimised utilisation of residual materials, currently placed on landfill or interim storage, pending possible utilisation. This paper presents the method (Sect. 2) and results (Sect. 3) from applying the methodology on residual materials and their potential use in different production systems. The methodology for evaluating the potentials for improved utilisation of residual materials was based on system analysis of the steel production systems in combination with an economical assessment by a differential cost evaluation of hypothetical business concepts. A few residual materials were selected for assessment where the selection was made with respect to the material's characteristics and composition, available quantities of the respective materials and the receiver's process capacity for utilisation. Opportunities to utilise valuable contents from the materials contributes to reducing the landfilled material amounts and decreasing the consumption of virgin materials such as iron ore, coal and limestone. The effects of the residual materials on the processes and thereby their suitability as secondary raw materials as well as their economic valuation was calculated. The calculated potential for the residual materials is mainly due to the content of valuable metals, energy carriers and slag formers, whereby they can replace raw materials in the production processes, but also their content of undesirable elements, e.g. sulphur and phosphorous. The paper describes the results of the study and indicates how this methodology could be applied to maximise the secondary material utilisation. Specific results on usable residual material amounts and ways of utilising the materials which meets process-related requirements for raw materials and demonstrate an economic potential in the production process are presented. From the methodology discussed (Sect. 4) and with a circular-economic perspective, it is shown that high economic potential for one material could be used to increase the utilisation of other materials with lower economic potential.

2 Method

The case study assesses a symbiosis of residual material use in Swedish ore-based steel production at SSAB EMEA AB in Oxelösund, scrap-based steel production at Höganäs Sweden AB and base metal production at Boliden Mineral AB. Identified concepts for the industrial symbiosis were evaluated by using production system analysis, taking a holistic system perspective approach, by which the overall most effective and sustainable solutions are distinguished. Six different residual materials were used in the case study assessment in which effects of the residual materials on processes as well as an economic valuation of the materials were calculated. The evaluated industrial symbiosis possibilities for enhanced utilisation of residual materials illustrated in Figure 1 includes:

– iron (Fe), coal (C) and lime (CaO) containing materials (labelled material A, B and C) from Höganäs for use as secondary raw material at SSAB;
– zinc (Zn), iron, and coal-containing residual material (materials D and E) from SSAB for use as secondary raw material at Höganäs;

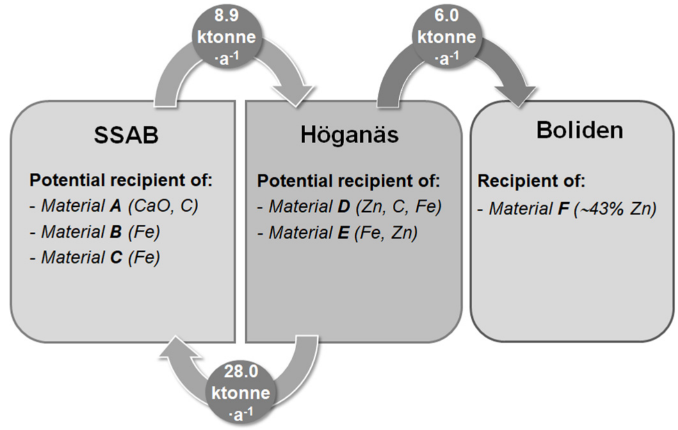

Fig. 1. Symbiosis system in the cases study of enhanced residual material use. Annually generated material amount is roughly 42.9 kilotonne (dry weight).

Fig. 1. *Système de symbiose dans l'étude de cas de l'utilisation accrue de matières résiduelles. La quantité de matière générée annuellement est d'environ 42,9 kilotonne (poids sec).*

– zinc rich dust (material F) from Höganäs which is currently used as secondary raw material in zinc production at Boliden.

The potential to utilise the residual material is primarily based on produced and available amounts, the material utilisation capacity of the recipient, and the materials characteristics and compositions, e.g. the materials grain sizes, moisture and contents. The residual materials characteristics influence the possibilities for its introduction into the process, i.e. in this case, given that the materials are fine-particulate dusts and sludge, by injection [19] or via agglomerates such as briquettes [20,21]. Valuable contents of iron, zinc, coal and lime in analysed residual materials are presented in Table 1.

System analysis of the SSAB process route was carried out using a developed Excel spreadsheet model including blast furnace (BF), desulphurisation (DeS) and basic oxygen furnace (BOF). The model is based on iterative heat and mass balances, including element distribution to metal, slag, dust and sludge and is used for process simulation and studies of various operating conditions [22]. The residual material value calculations from input in SSAB's system model is based on the sum of changes in the amount of input raw materials in the BF, DeS costs and consequential effects in the BOF. The case study scenarios were evaluated against a calibrated reference scenario which was established by using average production data and operational reports from SSAB EMEA AB, Oxelösund works, 2016.

Three scenarios were analysed and compared to the reference scenario:
– using 18 kilos per tonne of hot metal of material A as a raw material by injection in the BF;
– using 3.3 kilos per tonne of hot metal of material B as a raw material in briquettes to the BF;
– using 5.5 kilos per tonne of hot metal of material C as a raw material in briquettes to the BF.

Table 1. Annually generated amounts of the respective residual materials (ktonne $\cdot$ a^{-1}) and analysis of their main valuable contents (wt^{-}%) (N/A: not analysed).

Tableau 1. *Quantités générées annuellement des matières résiduelles respectives (ktonne $\cdot$ a^{-1}) et analyse de leurs principaux contenus précieux (% en poids) (N/A : non analysé).*

Material	Characteristics	Production (ktonne $\cdot$ a^{-1}, dry weight)	Valuable contents (wt^{-}%)			
			Fe	Zn	C	CaO
A	Dust	20.0	5.8	*N/A*	24.4	36.7
B	Iron dust	3.0	94.0	*N/A*	0.3	*N/A*
C	Iron dust	5.0	94.4	*N/A*	0.3	*N/A*
D	Sludge (~55% solid)	7.7	38.8	0.6	21.5	4.3
E	Dust	1.2	82.0	1.7	0.3	0.1
F	Dust	6.0	26.9	42.7	*N/A*	4.8
Total (ktonne $\cdot$ a^{-1})		42.9	14.3	2.6	6.6	8.0

The system analysis for SSAB with evaluation of materials A, B and C from Höganäs were based on the following process conditions for the blast furnace:
– hot metal production of about 900 kilotonnes on an annual basis;
– using a specific iron ore pellet mix;
– fixed input amount of; residual materials briquette, scrap, powdered coal injection and blast furnace dust injection;
– target silicon amount in hot metal;
– maximum allowed phosphorus amount in hot metal is adjusted with input of recycled BOF slag;
– target slag basicity CaO/SiO_2 ratio.

Modelling and analysis of the Höganäs process route was made using a modified version of a MATLAB-/Simulink model for the process unit's electric arc furnace (EAF) and ladle furnace (LF). The MATLAB-/Simulink model is a further developed version of a previously developed model based on Mixed Integer Linear Programming (MILP) [23].

The MATLAB-/Simulink model handles up to 32 different input materials each in the EAF and LF processes. Material parameters are included in the model such as, chemical composition, specific energy consumption and element specific exchange coefficients. Further comprised parameters are different process settings including steel temperature, oxygen consumption, power-off time and prices for making the evaluation and optimisation. The Simulink model is usually run with an optimising MATLAB script, with functions from the optimisation toolbox, identifying the material mix at the lowest cost based on given restrictions in the consumption of different materials, steel chemistry and slag chemistry. In this project, residual material from SSAB has been added as available material in the optimisation with restrictions on consumption of materials related to the reference material mix in order to evaluate the effects of the residual material from SSAB.

Given a specified material mix, the model calculates parameters such as steel and slag chemistry and quantity, electric energy consumption, dust chemistry and amount in the EAF and total production cost. The model calculates production cost as the sum of costs for added materials, energy types, furnace wear and consumption of graphite electrodes. Additionally, the dust generated in the EAF steel production at Höganäs was analysed considering effects on its use as secondary raw material in base metals production at Boliden. The reference scenario was established for the average material mix for unalloyed steel grades during a three-month period in the year 2017 at Höganäs Halmstad works.

Two scenarios were analysed and compared with the reference scenario:
– using 38.5 kilos per tonne of liquid steel of material D as a raw material in briquettes to the EAF;
– using 5.9 kilos per tonne of liquid steel of material E as a raw material in briquettes to the EAF.

The following conditions and parameters were applied to the scenarios using the EAF model:
– maintained charge weight of 48 tonnes in EAF by adjusting the inserted amount of a selected scrap quality;
– maintained coal content in the EAF liquid steel by adjusting the inserted amount of carbon powder;
– maintained slag basicity CaO/SiO_2 ratio in the EAF slag by adjusting the inserted amount of burnt lime;
– maintained MgO content in the EAF slag by adjusting the inserted amount of burnt dolomite lime.

Effects in production processes and within identified value-chains were analysed concerning:
– the residual materials suitability as secondary raw materials based on process related requirements and restrictions for maintained product quality (i.e. for maintained hot metal- and liquid steel quality) and residual materials generation;
– resource efficiency in production processes (i.e. the effects on raw material consumption and energy use);

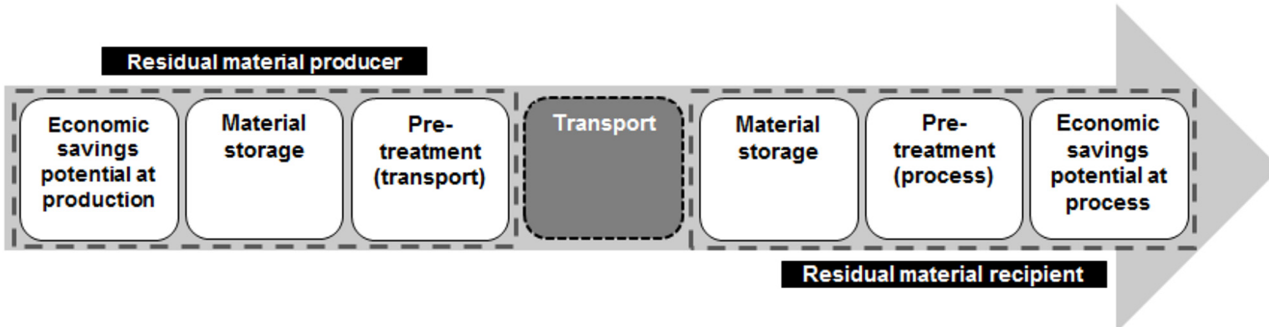

Fig. 2. Summarised costs and revenues at residual materials producer and at residual materials recipient.

Fig. 2. *Coûts et revenus résumés chez le producteur de matières résiduelles et chez le destinataire des matières résiduelles.*

– economic potential by evaluating the total cost effect on production cost when utilising residual materials. The residual materials price is given the value zero in order to calculate the value in use of the residual material at the point of addition (in SEK per tonne) compared to the reference scenario and raw material prices.

The results from system analyses were subsequently used in order to evaluate potential business concepts. The hypothetical business concepts are based on material characteristics related revenues and costs, including storage, transport and any pre-treatment costs that arise due to utilisation, illustrated in Figure 2.

The total cost calculations are based on the materials value i.e. costs or revenues at producer (V_p) and the calculated value in use at recipient (VIU_r) minus the cost estimates made concerning materials transport (T), equally divided between producer and recipient, and materials handling at both producer (H_p) and recipient (H_r) such as material storage and pre-treatment e.g. drying, agglomeration and injection. The methodology for evaluating the hypothetical business concepts is established from estimating the total cost effect at producer and recipient from making use of the residual material. Identifying cost and revenue aspects from both producer and recipient enables a total evaluation of the material's economic potential in use via a differential cost calculation according to:

$$d_c = PLSP - RHPP, \qquad (1)$$

$$PLSP = \min\{V_p - (T/2 + H_p); (T/2 + H_p)\}, \qquad (2)$$

is the Producer's Lowest Sales Price which either equals the corresponding profit at present or is free of charge (if the material currently constitutes a cost, e.g. landfill costs).

$$RHPP = VIU_p - ((T/2) + H_r), \qquad (3)$$

is the Recipients Highest Purchase Price which makes the utilisation of the material in the production system cost neutral.

This creates the basis of a methodology for illustrating economic conditions for possibilities of increased utilisation of residual material via industrial symbiosis.

3 Results

3.1 System analyses

The calculated production system effects, from making use of the residual materials, e.g. on input raw material amounts, slag, dust and sludge generation and total cost effects are summarised and presented in Table 2.

The potential unit process for input of the respective material and amounts possible for charging, by either briquettes or by injection, (i.e. depending on the recipient's capacity) as well as effects on the respective process are identified.

All the residual materials were calculated for utilisation of 100% of generated amounts, except for material A. The limited use of approximately 82% of the yearly generated amount of material A is due to restrictions on material injection. The main effects in process when utilising material A are reduced need for limestone and coke. The calculated decrease in input of BOF slag is due to phosphorous content in material A and the phosphorous restrictions in HM due to steel product quality. Further effects are increased sulphur content in HM and thereof increased desulphurisation cost. Also, the BF slag rate is increased and lesser increase in levels of trace elements in HM (such as vanadium, manganese and titanium) are calculated. From the summarised cost effect in process, material A is calculated to be of relatively low material value per tonne fed to the BF process.

Utilising either material B or material C in the BF briquettes results in reduced consumption of iron ore pellets, with basically no other significant effects noted. The materials high Fe content and very low levels of undesired elements results in insignificant impact on trace elements in hot metal. Both materials B and C are of high value per tonne fed to the BF.

Using material D as a raw material in briquettes to the EAF requires pre-treatment by drying as the material has a water-content of about 45%. The material reduces the EAF steel scrap consumption. However, it is a highly oxidised material which increases the consumption of pulverised coal and slag formers whereby an increased EAF slag rate and significant increased energy use is calculated. Material D also increases sulphur content in the liquid steel and is calculated to be of low value per tonne fed to the EAF.

Table 2. Annually generated residual material amounts, calculated use and main effects in processes as well as cost effect from using the residual materials in process compared to the reference scenario (tHM: tonne hot metal; tLS: tonne liquid steel; N/A: not analysed; UA: unaffected).

Tableau 2. *Quantités résiduelles générées annuellement, utilisation calculée et effets principaux dans les processus, ainsi que coût résultant de l'utilisation des matières résiduelles en cours par rapport au scénario de référence (tHM : tonne de métal chaud ; tLS : tonne d'acier liquide ; N/A : non analysé ; UA : non affecté).*

Material	A	B	C	D	E	F
Generation ($ktonne \cdot annum^{-1}$, dry weight)	20.0	3.0	5.0	7,7	1,2	6.0
Residual material input in unit process	SSAB BF via injection	SSAB BF via briquettes	SSAB BF via briquettes	Höganäs EAF via briquettes	Höganäs EAF via briquettes	Boliden fuming plant
Input amount in process	$18\,kg \cdot tHM^{-1}$[a]	$3.3\,kg \cdot tHM^{-1}$[a]	$5.5\,kg \cdot tHM^{-1}$[a]	$38.5\,kg \cdot tLS^{-1}$[b]	$5.9\,kg \cdot tLS^{-1}$[b]	*UA*
Use ($ktonne \cdot annum^{-1}$, dry weight)	16.3	3.0	5.0	7.7	1.2	6.0
Effects on process and material (± = diff. compared to ref.)						
Iron sources	*UA*	$-5\,kg \cdot tHM^{-1}$	$-8\,kg \cdot tHM^{-1}$	$-15.4\,kg \cdot tLS^{-1}$	$-5.0\,kg \cdot tLS^{-1}$	*N/A*
Coal sources	$-4.0\,kg \cdot tHM^{-1}$	*UA*	*UA*	$+3.6\,kg \cdot tLS^{-1}$	$+0.1\,kg \cdot tLS^{-1}$	*N/A*
Lime sources	$-3.0\,kg \cdot tHM^{-1}$	*UA*	*UA*	$+5.3\,kg \cdot tLS^{-1}$	$+0.2\,kg \cdot tLS^{-1}$	*N/A*
Other	BOF slag $-7.0\,kg \cdot tHM^{-1}$	*UA*	*UA*	Electricity $+42.6\,kWh \cdot tLS^{-1}$	Electricity $+0.7\,kWh \cdot tLS^{-1}$	*N/A*
Effects on output residual materials (± = diff. compared to ref.)						
Slag	$+6.0\,kg \cdot tHM^{-1}$	*UA*	*UA*	$+10.9\,kg \cdot tLS^{-1}$	$+0.3\,kg \cdot tLS^{-1}$	*N/A*
Dust and sludge	*UA*	*UA*	*UA*	Dust $+0.6\,kg \cdot tLS^{-1}$	Dust $+0.2\,kg \cdot tLS^{-1}$	*N/A*
Cost effect in process/tonne residual material used ($SEK \cdot tonne^{-1}$)	−368	−1036	−1053	−121	−2404	*N/A*
Summarised cost effect in process ($kSEK \cdot annum^{-1}$)	−6,000	−3,109	−5,263	−929	−2,885	*N/A*

[a] Production at SSAB is $904\,ktonne\ HM \cdot annum^{-1}$.
[b] Production at Höganäs is $200\,ktonne\ LS \cdot annum^{-1}$.

Material E is calculated to be of a high value per tonne used in the EAF process mainly by its iron content which reduces the steel scrap consumption. No significant negative effects were identified, only minor increases regarding chromium in liquid steel, the coal and lime raw materials consumption and energy use.

The effects, from using materials D and E, on the dust generated in the EAF (i.e. material F which is used as raw material in the fuming plant at Boliden) is minor, with no significant effects on Zn content, especially considering material E for which only a slight increase in dust generation of 0.2 kilos per tonne liquid steel (i.e. 40 tonne/a) is calculated.

3.2 Differential cost calculations

The hypothetical business concept and differential cost calculations methodology is prepared from the system analysis and total cost calculations for each material. The total cost calculations are based on the materials costs or revenues at producer and the calculated value in use at recipient minus the cost estimates made concerning materials transport and handling. In the calculations for the respective material, it is assumed that the selling price of the producer is the lowest price which either equals the corresponding profit as the present or is free of charge (if the material currently constitutes a cost, e.g. landfill costs). Regarding the recipient, the highest purchase price is the price which makes the utilisation of the material in the production system cost neutral.

Figure 3 presents the price difference, of which the producer's lowest achievable sales price is subtracted from the recipient's highest possible purchase price (in SEK per tonne and kilo SEK per year) for each material in relation to utilised material amounts (tonne). The differential cost calculations show economic profits for materials B, C and E, whereas the calculated economic results for materials A and D are negative.

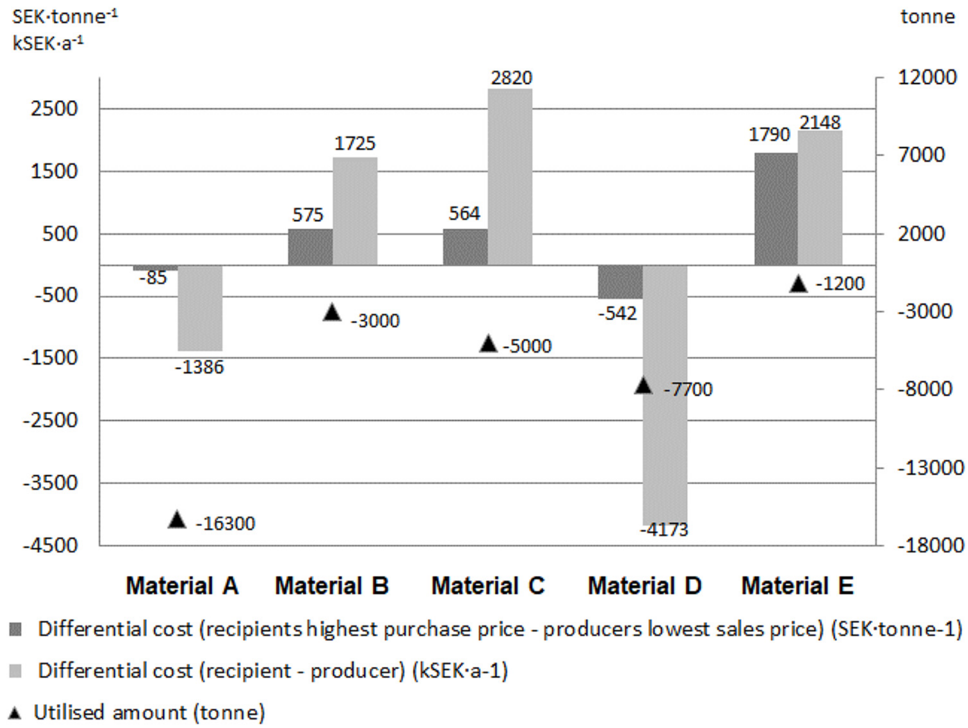

Fig. 3. Differential costs (in SEK per tonne and kilo SEK per annum) and potential amounts for usage of the respective materials (tonne).

Fig. 3. *Coûts différentiels (en couronnes suédoises par tonne et en kilo couronnes suédoises par an) et montants potentiels pour l'utilisation des matières respectives (tonne).*

From the calculations, a further enhanced potential of the industrial symbiosis, by maximised residual materials utilisation, is envisaged. This material use potential is achievable from the identified possibility of using more materials in exchange for profit. For example, by utilising all materials, the profit from using materials B, C and E could be exchanged against making use of materials A and D. From a circular economy point of view, the concept of utilising all materials would enable a total annual increase in residual materials utilisation equivalent to 33.2 ktonne (not including the 6 ktonne of material F from the EAF to the fuming plant), with a total profit of 1134 kSEK (Fig. 3). The summarised annual effects on raw material consumption are thereof decreased iron sources by some 11.8 ktonne iron ore pellets in the BF and 4.1 ktonne steel scrap in the EAF. Also, the coal raw material sources are decreased by 3.6 ktonne coke in the BF. However, the consumption of pulverised coal in the EAF is increased by 0.7 ktonne. Lime sources are decreased by some 2.7 ktonne limestone in the BF yet increased by 1.1 ktonne (lime and dolomitic lime) in the EAF. Further the electricity use in the EAF process is increased by roughly 8.7 GWh.

4 Discussion

The valuation of a residual material utilisation is in this case by savings in the process, which must compensate for costs such as materials handling, storage and transport. Based on the case study system analyses, the residual materials are all calculated to result in decreased total process costs. Even so, the process related gains are not high enough for materials A and D to carry the costs for handling, storage and transport. Material A is calculated to be of lower value in use owing to its contents in relation to process requirements and the raw material prices. Material D is of low calculated value in use and is not directly recommended for use in EAF mainly due to its highly oxidised nature and effect on electricity use. Materials B, C and E are of high value in use due to their iron contents and purity.

The developed methodology, where using system analysis in combination with a differential cost calculation, can assist in the work of evaluating and demonstrating opportunities for increased utilisation of residual materials via industrial symbiosis. A further question is though, how to distribute any economic gain within the symbiosis system. The exemplified concept in this study enables an annual increase in residual materials utilisation equivalent to 33.2 ktonne, with a total profit of 1134 kSEK. General effects from making use of the residual materials are decreased use of primary and virgin raw materials and decreased landfill or long-term storage.

Sensitivity analysis of raw material prices and cost calculations is recommended for an improved evaluation basis. However, this was not carried out within the framework of this study. Further, the differential cost for the respective materials is calculated based on the assumption that no profits are made from other usage possibilities, such as in-house re-melting of iron-rich materials. Enabling the business concept requires briquetting capacity for the additional material amounts, which is not investigated in this study. Nonetheless, by the studied concept, there are further opportunities to reduce the costs for transport, storage and handling of the materials by coordinating, sharing and optimising the symbiosis system and thus increasing the economic margins.

5 Conclusions

A case study has been performed with the aim to develop a methodology for evaluating industrial symbiosis possibilities regarding increased material efficiency in steel production systems. The methodology is based on system analysis of the steel production in combination with an economical assessment of hypothetical business concepts by using residual materials from one industry as secondary raw materials in another. However, the principle of the methodology and differential cost evaluation is applicable also to other industrial symbiosis systems.

By considering the cost and revenue aspects from both producer and recipient, an evaluation of economic conditions via cost differences can be made. This creates a basis for a methodology to illustrate and evaluate economic conditions for increased utilisation of residual material via industrial symbiosis.

Iron sources, with low contents of undesired elements at lower price than iron ore pellet or steel scrap, equals high value materials in the iron- and steel production system. However, when it comes to low-grade residual materials, an economic gain in utilisation is more difficult to achieve whereby the developed methodology can be used to motivate the use of materials with a lower monetary value.

By the methodology discussed and with a circular-economic perspective, it is shown that high economic potential for one material could be used to increase the utilisation of other materials with lower economic potential.

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