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Combining Steel and Chemical Production to Reduce CO_2 Emissions

Jouko Arvola, Janne Harkonen, Matti Mottonen, Harri Haapasalo, Pekka Tervonen

Department of Industrial Engineering and Management, University of Oulu, Oulu, Finland.
Email: {jouko.arvola, janne.harkonen, matti.mottonen, harri.haapasalo}@oulu.fi; pekka.tervonen@ruukki.com

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ABSTRACT

New legislation and emissions trading increase pressures for the industry to find new environmentally sound solutions. This research analyses the utilisation of carbon monoxide (CO), formed in steel mills from the emissions reduction viewpoint. The research studies possibilities of combining steel and chemical productions from economic and environmental perspectives. The analysis includes considering emissions costs and electricity price, when CO is converted into chemical products. The results prove the economic profitability of a steel mill selling CO gas to a chemical producer instead of using it for energy production, while CO_2 emissions are simultaneously reduced.

Keywords: *Emissions Trading, Carbon Dioxide, Carbon Monoxide, Steel Industry, Chemical Industry, Sustainability*

1. Introduction

Carbon dioxide (CO_2) and other green house gases are a widely recognised problem [1-5]. Use of carbon-based raw materials is largely the origin behind CO_2 increase in the atmosphere. The global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to 379 ppm [6].

New environmental legislation aims to tackle the effects of carbon dioxide emissions. The Kyoto Protocol treaty was negotiated to reduce the global greenhouse gas emissions in a globally coordinated manner [2]. The European Union countries in their "Energy policy for Europe" have set targets for national energy policies [7]. EU is committed to reducing its overall emissions, calculated as CO_2, to at least 20% below the 1990 levels by 2020.

Steel industry is a significant emissions source as globally 6% - 7% of CO_2 is caused by steel manufacturing [8]. The emissions in steel industry are influenced by used production routes, product mix, production energy efficiency, fuel mix, carbon intensity of the fuel mix, and electricity carbon intensity [8]. The production of steel has increased almost steadily during the last 40 years from 595 Mt/a in 1970 to 1327 Mt/a in 2008 [9]. Steel mill emissions are included in emissions trade scheme (ETS) [10], and consequently it is worthwhile considering new ways to reduce CO_2 emissions.

About 60 % of steel is made in blast furnaces (BF) through iron ore reduction [11], on which this article concentrates. Other alternatives, scrap steel melting in electronic furnaces and direct reduction of iron are out of the scope of this study.

A typical BF based steel mill consists of a coking plant, BF, basic oxygen furnace (BOF) , power house, hot strip mill and a sinter plant. Process gases are produced in coking plant, in BF and in BOF. Typically, 69% of CO_2 gases originate from BF, 7% from BOF gas and 6% from coke oven. The remaining 18% originate from other fossil fuels imported into a steel mill. Besides considering the origin of CO_2, one should also analyse from which physical locations the CO_2 comes out as emissions. Typically 39% of CO_2 emissions exit from a power plant, 19% from coke ovens, 14% from a sinter plant, 12% from heating hot stoves in BF, and the rest from other sources [12].

The literature discusses different ways of reducing CO_2 emissions in steel industry. As an example, CO_2 capture and storage combined with top gas recycling in blast furnaces, and use of charcoal instead of coal are considered as possibilities to reduce emissions [13-16]. In addition, Diemer *et al.* [17] present different ways of reducing CO_2 emissions by seeking for alternative uses for coke oven gases in steel mills.

One potential sustainable way to reduce CO_2 emissions is to utilise the CO_2 from industrial processes to produce various chemicals, material and fuels [18]. CO_2

emissions can also be reduced by removing already formed CO_2 and storing it permanently. In steel industry one solution is to prevent carbon monoxide (CO) from converting into CO_2. Some authors have reported direct conversion of BF gas to dimethyl ether [19] and using the gas to produce methanol [20].

New legislation and emissions trading increase pressures of finding new environmentally sound solutions. When considering emissions, the entire supply-chain ought to be considered [21]. Earlier, the availability of cheap raw materials, such as coal, oil and natural gas in chemical industry together with the complexity of handling steel mill gases have hindered the strive towards new solutions such as combining steel and chemical productions.

This research studies the reduction of CO_2 emissions formed when burning BF steel mills CO gases, by considering the utilisation of the CO for producing chemical products. This type of combination of steel and chemical industries has analogue solutions in the pulp & paper industry, where the bio-refinery concept aims to complement the basic bulk process with new chemical products. This study conducts economic calculations on the impact of a steel mill moving towards more sustainable solutions, including the influence of emissions trading. The above described can be condensed into the following research questions:

RQ 1 Can CO_2 emissions be reduced using carbon monoxide for producing chemicals by combining steel manufacturing and chemical production?

RQ 2 How can the financial benefits be estimated when producing chemicals from carbon monoxide instead of using it for energy production?

2. Methodology

Figure 1 illustrates the research process. Background information of this study included clarifying the current state in steel industry, followed by a benchmark from chemical industry. Based on these, analyses were conducted to construct a process model combining steel and chemical processes. The purpose of this model was to simultaneously acknowledge technical, environmental and economic aspects.

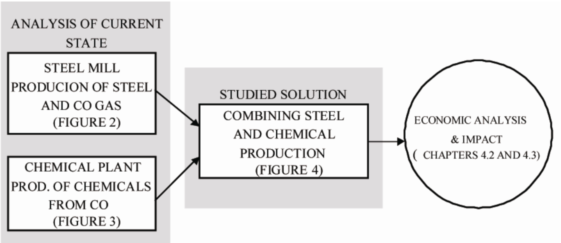

Figure 1. Research process.

First, the functioning of a steel mill was analysed to understand its gas flows and potential areas for improvement. Special attention was paid on CO sources. The case company, a large steel manufacturer, provided process information, gas compositions, etc.

Secondly, a benchmark was conducted in chemical industry to analyse how carbon monoxide is typically produced and utilised as a raw material for chemical production. This was realised through a literature review and discussing with experienced chemical engineers.

Finally, economic analyses were conducted by taking emissions costs, value of CO gas, and electricity price into account. Databases and stock market information were utilised to obtain price level information relating to electricity and CO_2 emissions trading, while CO gas price was obtained from scientific literature. These economic analyses included calculations that formed a basis for making conclusions on the viability of combining steel and chemical production.

3. Current state analysis

3.1. Current Gas Handling in Steel Mills

Figure 2 shows a typical production scheme of a steel mill. There are three typical sources where combustible gases can be attained. Coke oven gas contains mainly methane (CH_4) and hydrogen (H_2), blast furnace and basic oxygen furnace gases contain mainly carbon monoxide (CO) [e.g. 22,17]. Energy rich coke oven gas has uses in normal production processes in steel mills. Blast furnace (BF) and basic oxygen furnace (BOF) gases are often utilised for electricity production [23,24]. This carbon based energy produced in a power house, however, produces unwanted CO_2 emissions.

Therefore, from the sustainability perspective, other alternative uses for BF and BOF gases are worth analys-

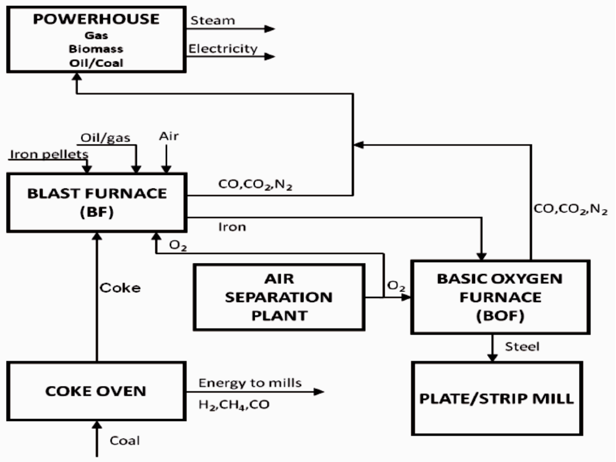

Figure 2. Typical production scheme of a steel mill.

ing.

3.2. Carbon Monoxide Utilisation in Chemical Industry

Typical chemical industry processes that can utilise CO directly, or after converting to hydrogen with shift reaction, are presented in **Table 1**. Global production volumes are also presented. Methanol, ammonia, and urea have the largest volumes. Acetic acid, formic acid, methyl formate are, however, simpler to produce directly from CO. Methanol and ammonia production require hydrogen with shift reactions and produce CO_2, which however, can be utilised for urea production. Nowadays, the above mentioned processes create the CO they require through gasification or steam reforming from coal, oil, or natural gas.

The chemical formulas on the above table can also be illustrated as a production process (**Figure 3**). The figure combines all the discussed chemical products, even though in practice a single chemical plant produces only one or few of these products. In addition to the presented, there are other potential chemical products that can be produced from CO and synthesis gas based on CO in the future [36-38].

3.3. Emissions Trading, Value of CO Gas, and Electricity Price

The calculations of this study require price levels for CO_2 emissions trading, CO gas, and electricity.

Emissions trading is stock market based, and forecasting future is difficult, therefore this study utilises price information from Nordpool. Currently, in August 2010, the CO_2 price is approximately 15 €/t CO_2 [39], and is forecasted to rise to 20 - 40 €/t CO_2 by 2020 [40,41]. The calculations, in the results chapter, are made with four different emissions cost levels of 10, 20, 30 and 40 €/t CO_2.

Table 1. Typical chemical processes that utilise carbon monoxide.

Product	Process information		
	Net reaction	*Production Mt/a*	*Ref.*
Formic acid	$CO+H_2O \rightarrow HCOOH$	0.5	[25]
Methyl/ethyl formate	$CO+CH_3OH/C_2H_5OH \rightarrow CH_3OOCH/C_2H_5OOCH$	n.a.	[26]
Acetic acid	$CO+CH_3OH \rightarrow CH_3COOH$	8	[27,28]
Methanol	$CO+2H_2 \rightarrow CH_3OH$	42	[29,30]
Ammonia	$3H_2 + N_2 \rightarrow 2NH_3$	110	[31]
Urea	$2NH_3+CO_2 \rightarrow NH_2CONH_2 + H_2O$	146	[32,33]
Hydrogen peroxide	$H_2 + O_2 \rightarrow H_2O_2$	3	[34,35]

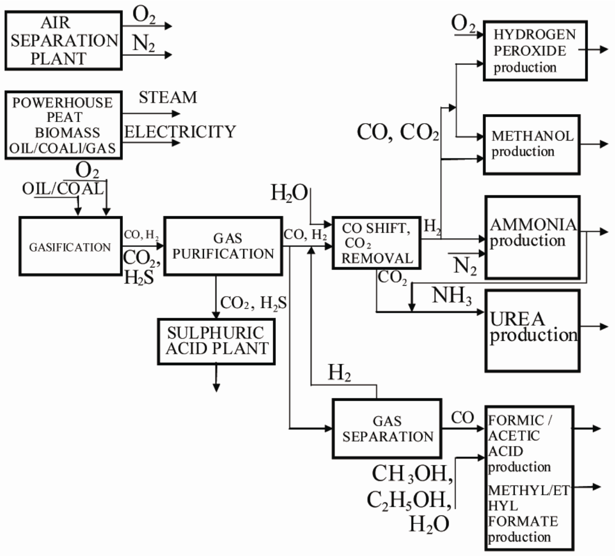

Figure 3. Production of different chemicals from CO gas.

CO gas has value for a steel mill and if used as raw material for other purposes, it will have a price. On the other hand, CO gas required by chemical industry, if obtained from a steel mill, cannot be more expensive compared to production via other means. The price of CO gas can be seen to consist of capital costs and productions costs, capital costs dominating. This study utilises price information from Blesl & Bruchof [42] and Basye & Swaminathan [43], and estimates price as per GJ. The capital cost of coal gasification plants given per GJ of synthesis gas (CO, H_2) output are seen to range from 13 \$/GJ for bituminous coal to 17.2 \$/GJ for subbituminous coal. The total syngas production cost decreases with increasing coal quality and ranges from 15.6 \$/GJ to 19.3 \$/GJ. When processed to hydrogen the costs are seen as 11.3 \$/GJ by partial oxidation of fuel oil, 15.9 \$/GJ by gasification of coal, and 21.7 \$/GJ by gasification of biomass. Based on the above, the CO gas price ranges from 11.3 to 21.7 \$/GJ. Converted into €/1000 normal m^3 this is roughly 150. A potential investor wishes to minimise capital costs and consequently the calculations must also be conducted with lower prices. Capital costs are minimised if using CO gas from a steel mill. Hence, the calculations in the results chapter, are made with three different CO gas price levels of 50, 100, and 150 €/1000 Nm^3.

A steel mill that has previously generated some of its electricity from CO gas, must replace this by purchasing electricity from the markets. Currently, in 2010, the market price for a major industrial user is approximately 50 €/MWh [44]. The calculations in the results chapter, are made with three different price levels of 40, 60 and

80 €/MWh.

4. Results and Discussion

4.1. Process Model

Based on analysing current blast furnace based steel manufacturing processes combined with information of production processes from CO utilising chemical industry, this study has constructed a process model that acknowledges the strive for sustainability (**Figure 4**). The figure illustrates the constructed process model, where the area highlighted in grey illustrates the proposed inclusion of chemical product lines to be integrated into the proximity of a steel mill. In the constructed model, gases from *blast furnace* and *basic oxygen furnace*, previously taken to a *powerhouse*, are now directed to *gas treatment*. In reality the gas treatment process is more complicated and includes e.g. compressing, gas purifications, and a possible water gas shift reaction.

Should the constructed process model be utilised, from the perspective of a steel mill, CO gas is valuable as it can be sold. In addition, emissions trade costs are removed as CO gas is not burned into CO_2. However, there is also a negative consequence as the electricity, previously generated from CO gas, must be replaced by purchased, or separately produced, electricity. In order to maintain sustainability, the electricity ought to be produced from non-fossil sources. The technical principles presented above, form the basis for economic calculations, discussed in the following chapters.

4.2. Calculations Required for Economic Analyses

Table 2 introduces the figures used in calculations, including both generic and case specific numbers.

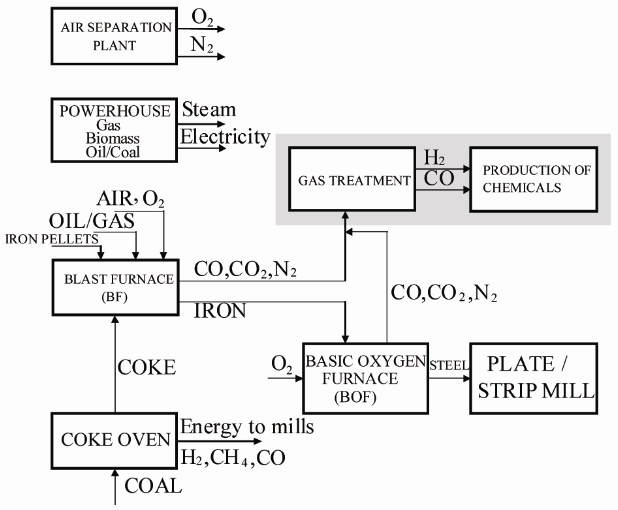

Figure 4. The constructed process model combining steel and chemical production.

Generic figures are obtained from the literature and the case specific ones have been provided by the case steel company. These production figures and gas compositions are typical to steel mills using BF technology.

Yield CO is the percentage of CO in the output of gas treatment compared to the input, when CO purity is 99%. The figures are based on VPSA (vacuum pressure swing adsorption) system described in the report of Xie *et al.* [45].

Total pure CO volume in **Table 2** is calculated as follows:

$$\mathrm{PureCO} = (\mathrm{BFgas} \times \mathrm{BFCO} + \mathrm{BOFgas} \times \mathrm{BOFCO}) \times \mathrm{YieldCO} \quad (1)$$

This calculation gives the amount of CO gas 578 million Nm^3/a. The quantity of CO_2 would be equal as the number of molecules is the same after burning. The amount of CO_2 emissions avoided can be calculated:

$$\mathrm{CO_2emis} = \mathrm{CO_2gas} \times (\mathrm{hours}) \times \mathrm{CO_2density} \quad (2)$$

This calculation leads to an annual CO_2 avoidance of 1.1 Mt. This is 25% of the emissions permit of the case steel mill.

4.3. Economic Calculations

The calculations are based on opportunity cost analyses. The assumption is that CO containing gas is sold to chemical producers instead of feeding it to a steel mill power house, and that chemical producers have made the investments needed for the gas treatment and their production processes. The chemical producers receive the gas with the same price or a little lower as would be the case if they would had made an investment to gas produc-

Table 2. Figures utilised in economic calculations.

Parameter	Value
Yield CO	0.88*
BF gas	2 125 million Nm^3/a
BF gas CO	0.24
BOF gas	212.5 million Nm^3/a
BOF CO	0.69
Total pure CO	578 million Nm^3/a
Emissions permit	4.5 Mt CO_2/a
Density of CO_2	1.98 t/1000 Nm^3
Power plant efficiency	0.3
Heating value of CO gas	3.5 MWh/1000 Nm^3
Gas price	50 -150 €/1000 Nm^3
Electricity price	40 - 80 €/MWh
Emissions trade cost	10 - 40 €/t CO_2

*yield for a VPSA Plant for CO separation from syngas [45].

tion, for example from coal. These calculations do not contain investments, as they are conducted by individual chemical actors. When a chemical actor considers new investment, it can either build new capacity independently, or locate to the proximity of a steel mill where CO is available. As both of these options require investments, they can be ignored in the following calculations.

By using the constructed process model and specific figures presented earlier, one can calculate the economic impact (EI) of the proposed transition by putting the values of CO gas (COvalue), emissions trading value of CO_2 (CO_2value) and electricity cost (Ecost) in Equation 3. Value of sold CO gas, value of avoided CO_2 emissions, and electricity cost, all are a result of two parameters, volume and unit value. Volume of saleable CO gas is the maximum capacity of 578 million Nm^3/a, as presented in **Table 2**. Volume of avoidable CO_2 in tonnes can be calculated by multiplying the maximum capacity with CO_2 density, resulting in 1.1 million tonnes. The amount of required additional electricity is obtained by multiplying the total pure CO volume by power plant efficiency (0.3) and heating value of CO gas (3.5 MWh/1000 Nm^3), resulting in 0.61 TWh.

Unit values, or market prices, for CO gas, CO_2 emissions and electricity have been simulated with three (or four) different rates. The impact of CO gas price has been calculated for 50, 100 and 150 €/1000 Nm^3. The emissions cost has been calculated for 10, 20, 30 and 40 €/t CO_2. The impact of electricity cost has been calculated for 40, 60 and 80 €/MWh.

$$\mathrm{EI} = \mathrm{COvalue} + \mathrm{CO_2value} - \mathrm{Ecost} \qquad (3)$$

As an example, when gas price 100 €/1000 Nm^3, emissions cost is 20 €/t CO_2, and electricity cost is 60 €/MWh, the formula (3) results in:

Economic impact (100, 20, 60) = (578 million Nm^3/a × 100 €/1000 Nm^3) + (1.1 million tonnes × 20 €/t CO_2) – (578 million Nm^3/a × 0.3 × 3.5 MWh/1000 Nm^3 × 60 €/MWh) = 43 million €/a. This example is highlighted in bold in **Table 4**.

Tables 3-6 illustrate the economic impact by using different values for gas price, emissions cost, and electricity cost.

The presented tables indicate that the proposed transition towards including chemical product lines into the proximity of a steel mill would be economically feasible in most cases. With current market price levels, the most realistic economic benefits can be obtained with emissions costs of 20 - 30 €/t CO_2, gas price of 100 €/1000 Nm^3, and electricity price of 40 - 60 €/MWh, resulting in positive economic impact of some 44 - 68 million €/a.

Table 3. Economic impact (M€/a) when emissions cost 10 €/t CO_2.

Emissions cost 10 €/t CO_2	Electricity cost (€/MWh)		
CO price (€/1000 Nm^3)	40	60	80
50	16	3	-9
100	45	32	20
150	73	61	49

Table 4. Economic impact (M€/a) when emissions cost 20 €/t CO_2.

Emissions cost 20 €/t CO_2	Electricity cost (€/MWh)		
CO price (€/1000 Nm^3)	40	60	80
50	27	14	2
100	56	**43**	31
150	84	72	60

Table 5. Economic impact (M€/a) when emissions cost 30 €/t CO_2.

Emissions cost 30 €/t CO_2	Electricity cost (€/MWh)		
CO price (€/1000 Nm^3)	40	60	80
50	38	25	13
100	67	54	42
150	95	83	71

Table 6. Economic impact (M€/a) when emissions cost 40 €/t CO_2.

Emissions cost 40 €/t CO_2	Electricity cost (€/MWh)		
CO price (€/1000 Nm^3)	40	60	80
50	49	36	24
100	78	65	53
150	106	94	82

The proposed transition would not only be economically viable, but also feasible from the environmental perspectives, providing that the required electricity is produced from clean sources. This way a steel mill minimises the use of carbon based electricity, while the carbon is utilised for producing chemical products instead of releasing it into the atmosphere, as is currently the case.

The results show the economic viability, however, a steel mill needs chemical actors to join this type of efforts. This study provides a fundamental principle for calculating the economic feasibility, but relevant actors should always conduct their calculations with exact figures relevant to their business reality.

5. Conclusions

New legislation and emissions trading increase pressures of finding new environmentally sound solutions in order to tackle climate change. There are pressures also in steel industry that causes some 6% - 7% of global CO_2 emissions. This research studies the reduction of CO gas, a pre-form of CO_2, formed in steel mills, by considering the utilisation of the CO for producing chemical products. This study conducts economic calculations on the impact of a steel mill selling CO gas to be used as raw material for chemical products by taking emissions costs, value of CO gas, and electricity price into account.

The results of this study show that carbon dioxide emissions caused by steel industry can be reduced by selling CO gas, from blast furnace and basic oxygen furnace, to chemical industry. As this CO gas is currently utilised for producing energy, the replacement electricity has to be bought from the markets. In order to meet the environmental requirements, this electricity must originate from sustainable sources.

The results prove the economic profitability of a transition from in-house electricity production from CO gas to selling it to a chemical producer. The financial benefits of producing chemicals from carbon monoxide produced by a steel mill, can be estimated by acknowledging potential gains and tradeoffs. A steel mill would gain the price obtained for sold CO gas, and the impact of emissions trading costs. The tradeoffs would include a steel mill having to replace the electricity, previously produced from CO gas, by energy purchased from the markets. This study calculated the economic impact of this type of transition with different parameters and compared to a true steel industry scale. With current price levels for electricity, CO gas, and the impact of emissions trading, a steel mill, producing a volume of 600 million Nm^3/a of total pure CO, would benefit of some 50 million € annually, if all of the CO gas would be sold for chemical production. CO_2 emissions trading roughly doubles the economic incentives for such a transition.

This study provides a potential model for managers in the steel industry for calculating alternative models for operations by using their own exact case-specific figures. This study supports combining economic facts with the strive towards sustainability. This article gives a tangible example on calculating CO_2 emissions trading in economic terms. The managers in the chemicals industry, especially those considering new investments, may find the proposed transition as a new opportunity to obtain raw materials without extensive investments to production capacity for CO gas.

The purpose of this article was to prove the viability of transition towards sustainability both technically and economically. However, this research did not cover the case specific realities of every steel or chemical producer. In addition, the CO quantities produced by steel industry are so vast that a single solution does not solve the environmental challenges of the entire sector. Also, the realities of chemical producers were not looked upon, e.g. market growth for chemicals and steel mill site locations in relation to markets. The future research could include, aside addressing the above described limitations, analysing the detailed differences of BOF and BF gases from the perspective of chemical production.

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