Metallurgical coal replacement and vehicle weight reduction compared

CCTC 2015 Paper Number 15700223289

N .P. Fitzpatrick
Vancouver, British Columbia, Canada

Abstract

The potential to reduce the greenhouse gas emissions (GHG) of the steel industry is compared with the scale of GHG reduction by vehicle light weighting. Blast furnace iron (BFI) and directly reduced (DRI) production are summarized. Coupled with renewably powered electric-arc furnaces (EAFs), natural gas based DRI reduces (GHG) emissions of crude steel production by up to two thirds over a metallurgical coal route. It is concluded that while an agreement to use less coal would grow Canadian exports of iron and steel to Asia, it would be hard to exceed the GHG reductions obtained by reducing vehicle weight.

Keywords: Steel; DRI; coal; coke; natural gas; GHG; vehicles; light weighting

Résumé

Le potentiel de réduction des émissions globales de gaz à effets de serres (GES) de l'industrie de l'acier est comparé avec l'ampleur de la réduction des GES depuis l'avènement de véhicules plus légers. Les aciers de haut fourneau (AHF) et le minerai de fer pré-réduit (éponge de fer) y sont résumés. Jumelé avec une fournaise à arcs électriques (FAE) fonctionnant à partir d'énergies renouvelables, la production d'éponge de fer par l'utilisation du gaz naturel réduit les émissions de gaz à effets de serre (GES) de la production brute de l'acier par deux tiers répartis sur le circuit de production du charbon (coke) métallurgique. Il est conclu que malgré qu'une entente de réduction de l'utilisation du charbon aurait tendance à accroitre l'exportation de fer et d'acier vers l'Asie, il serait difficile d'excéder la réduction des émissions de GES actuellement obtenue par la réduction du poids des véhicules.

Mots clés: Acier; éponge de fer; charbon; coke; gaz naturel; GES; véhicules plus légers

1. Introduction

It has been suggested that 80% of coal reserves need to stay in the ground from 2010 to 2050 to hold the global average surface temperature to a rise of 2℃ [1]. Reserve estimates of coal range from 892 to 1052 billion tonnes. [2] Total global coal production in 2013 was 7.8 billion tonnes. Using 20% of the lower number for reserves over 40 years is equivalent to cutting annual coal usage to 4.5 billion tonnes or 42% less than 2013 usage.

In 2013, 1.2 billion tonnes of metallurgical grade coal went to the steel industry, mostly to make the coke used in blast furnace iron production but a fraction is injected as powdered coal. Steel is made into a range of products in many countries, and the energy to make and ship a product such as wire or automotive sheet differs hugely from that to make a casting at an automotive plant. We are looking for the differences between processes. Helpfully, public data from the World Steel Association and the International Energy Agency can be combined to explore the broad shape of a steel industry as greenhouse gas emissions are reduced. [3] [4]

For decades, the steel industry has been improving the efficiency of its use of coke and coke-oven gas made from the coal. Asia imported and Europe and North America exported scrap steel in 2013 [5]. When scrap is melted in electric arc furnaces (EAF), operators seek lower carbon extra “iron units” more compatible with scrap than the output of a blast furnace. Operations near markets major in scrap melting. One example is an operation in Contrecœur, Quebec, owned by the world’s largest steel company, ArcelorMittal S.A. Another example is the largest US steel company, Nucor Corporation.

This paper suggests there might be scope for growth in Canada as the climate change challenge is met and the steel industry reduces its use of coal.

Overall the steel industry emits approximately 5% of global greenhouse gas (GHG) emissions.[4] The pace and scale of possible process actions to reduce this contribution will be compared with the pace and scale of the contribution from vehicle light weighting.

2. Steel and Vehicle Light Weighting

Though current emissions are higher, GHG emissions reported in 2011 by sector [6] are summarized in Table 1 to show the scale and proportion of road vehicle emissions.

Table 1. Global CO_2 emissions by sector in 2011, Megatonnes

	MT	
Electricity and heat		41.7%
Own use by energy industry	1,542.9	4.9%
Manufacturing/construction	6,508.7	20.8%
Road	***5,172.0***	**16.5%**
Other Transport	1,829.1	5.8%
Residential	1,851.6	5.9%
Other Sectors	1,371.3	4.4%
World	**31,342.4**	100.0%

Table 2 shows the global markets of steel in 2013 [3].

Table 2. Steel Uses 2013, Megatonnes

Market	MT
Automotive	*193*
Other Transport	77
Metal Products	201
Machinery	233
Electric equipment	48
Domestic appliances	32
Construction	823
Total	1,607

Total transportation applications were exceeded only by products for the construction industry. The durability of products for the two markets differs as construction products are not recycled for several decades while the average light vehicle is scrapped after 12 years. [5]

Vehicle mass reduction reduces GHG emissions and has proven to be a low cost step to meet new vehicle efficiency standards. In 2010 the IEA was able to report that new light duty vehicles standards were fully implemented or underway in Japan, the US, Canada, the EU and Korea. Heavy vehicle standards that Japan had in place in 2010 are currently in the "rule-making process" in the US and Canada. [7]

Lighter steel structures using stronger steel have contributed to vehicle mass reduction.[8] Adhesively bonded aluminium sheet structures are now supplanting steel in some vehicle platforms as over the vehicle life the fuel savings result in carbon neutrality,[9] and composite structures play a role. Mass reductions of up to 40% have been exemplified, but Alcoa suggest a typical reduction will be 28%.[10] For the purposes of this paper, whether this GHG reducing step is accomplished by stronger steels, composites, lighter metals or combinations thereof, it will mean less weight of steel is used in this market. Though higher sensitivities have been noted, a rule of thumb in the industry is that a 10% weight reduction reduces fuel use by 7%. [11] If only half of Alcoa's target, or say a 15% weight reduction is attained, then with the number of vehicles on the road in 2011 from Table 1 above, there would be a GHG reduction of approximately 500 million tonnes with an implementation time of the order of the replacement of the vehicle fleet. With vehicle growth more reductions would be needed, but we have left half of the potential weight reduction for a further step.

Vendors to the automotive companies participate in life cycle analysis, leading them to introduce more efficient production processes and design more recyclable products. Where these actions are cost effective they ripple across the steel industry and impact its supply chain.

3. Steel Making

"Steel may be taken as containing up to 2.0% carbon, none being present as graphite; with greater amounts of carbon the metal is known as pig-iron or cast iron." [12]

The understanding of the history of alternative steel making processes was recently enlivened in Canada with the analysis of iron made by Norse settlers at L'Anse aux Meadows, Newfoundland with a then standard technique. [13] In Europe until the 14^{th} century iron ore was converted *in the solid state* directly to porous sponge iron in which oxide impurities were entrapped as gangue. These were squeezed out by hammering. Some of the resulting product had the range of carbon content that categorizes steel. This original solid state process was the progenitor of today's directly reduced low carbon iron (DRI) processes from which the gangue is removed in electric arc furnaces (EAF).

As the early charcoal-fired furnaces evolved they became taller and temperatures in the reaction zone rose. Liquid pig-iron was produced with a carbon content straddling the binary alloy iron-carbon eutectic point (1150°C and 4.3% carbon). The carbon was partly in solution in iron, but there were extra elements that had dissolved while the metal was liquid. The output of the blast furnace is reported variously to contain up to 5% carbon. Though not as malleable as the early direct iron there were heat treatments to make cast iron less brittle and new methods were developed. [14] Production was easy and grew. But the higher temperature for liquid iron had added new elements that, along with carbon, are soluble in ferrite. One example, nitrogen, impacts fracture toughness severely and is hard to remove. [15]

Low cost mass production of steel from pig-iron awaited the arrival of the air-blown Bessemer process, a large scale means of burning out the carbon, though it tended to add nitrogen. With oxygen replacing air to avoid nitrogen addition and a basic (as opposed to acidic) flux designed to cope with nitrogen and other impurities, blast furnace iron is refined with the basic oxygen furnace (BFI/BOF route).

Though renewably produced charcoal was the main fuel for both direct reduction and the "indirect" blast furnaces until coal was brought into play, it has been estimated that the GHG emissions did not fall below 10 tonnes CO_2e per tonne of steel until Bessemer steelmaking arrived in the 19th century. [16]

We should note that the blast furnace is a vertical shaft furnace down which solids (coke, iron ore and limestone) fall while gaseous combustion products move upwards. Coke provides support to the iron ore as it converts to iron through the high temperature Bosh region where liquid pig-iron is formed. [13][17] It is essential that the coke which yields carbon-monoxide to reduce the iron ore does not fall to powder too early in the process. Metallurgical coal specifications limit impurities, residual ash level and ability to soften and form a coherent porous structure when heated. [17]

Not all coal can make coke, and scarcity and cost has led to a search to improve blast furnace efficiency with supplemental and alternative fuels. The reaction rate can be increased, while reducing coke use, by adding hydrogen rich fuels below the Bosh region. Coke-oven gas, powdered coal, waste oils, plastics and municipal waste are all richer in hydrogen than coke. The ratio of coke to hot metal weight dropped by a factor of three in the half-century from 1955 to 2005 and improvements continue. [17]

In 1980 the US EPA reported that in 1978 there were 55 direct reduction plants in operation. Of these, 37 used a gas reductant, 25 used a solid reductant and the rest used gases from solid fuel. The bulk of gas plants were the Midrex process, an up-blown shaft furnace, or the Hyl process, a closed retort. [18]. A Hyl process had been started up in 1957 by HYLSA-Monterray in Mexico. The first listed Midrex process was started up by Oregon Steel Mills in 1969. Both these plants were fired with natural gas. The report mentions that natural gas fired Midrex plants were started in 1973 and 1977 by Sidbec-Dosco at Contrecœur near Montreal. These are now operated by ArcelorMittal Canada.

As the millennium turned, more DRI process types came into play but the front runners using natural gas were still the Midrex and Hyl processes. The high quality of the metal from DRI allowed lower quality scrap to be used. In some locations the use of DRI overcame constraints caused by scrap availability. Developing countries with access to natural gas were adding capacity but some were adding coal fired systems. [19] Quality, scalability, short commissioning time and payback advantages of the DRI/EAF route over the BFI/BOF route were being noted. Table 3 lists 21 countries reporting DRI production in 2013. [3]

Table 3. DRI Production 2013

	Kt	
India	17,770	23.8%
Iran	14,458	19.3%
Mexico	6,100	8.2%
Saudi Arabia	6,070	8.1%
Russia	5,329	7.1%
Egypt	3,432	4.6%
Trinidad and Tobago	3,290	4.4%
United Arab Emirates	3,075	4.1%
Venezuela	2,584	3.5%
Qatar	2,386	3.2%
Oman	1,470	2.0%
Argentina	1,466	2.0%
South Africa	1,444	1.9%
Malaysia	1,399	1.9%
Canada	1,250	1.7%
Libya	956	1.3%
Bahrain	780	1.0%
Indonesia	757	1.0%
Germany	498	0.7%
Sweden	113	0.2%
Peru	93	0.1%
World total	**74,720**	100.0%

Though not producers in 2013 other countries which have operated DRI plants in production are Australia, Brazil, Myanmar, New Zealand, Nigeria and the United States.[3] Natural gas availability and cost play a key role.

Energy use is minimised when DRI is fed directly or later to an electric arc furnace (EAF) for combining with scrap and finishing. Cold porous sponge iron is quite reactive, and for safe storage, shipping and ease of handling compressed at around 650℃ as hot briquetted iron [HBI]. This process is so successful that some countries with excess natural gas, such as Qatar and Trinidad, import ore for their DRI facilities and ship HBI to the market. For countries with "stranded" natural gas and access to ore HBI is an alternative export to liquefied natural gas (LNG).

The Midrex process, which has about 60% of the DRI market, is sold by Japan's Kobe Steel. Kobe claim that natural gas fired DRI/ electric arc furnace (EAF) facilities may emit only one-third of the CO_2 when compared with a blast furnace BF/BOF complex per tonne of steel produced. The DRI process can also utilize reducing gases made from thermal coal in coke ovens and utilize municipal waste and biomass. 25.7% of the 2008 DRI tonnage was made using coke or reducing gases from coal rather than natural gas. [20] Hatch Corporation is studying the merits of coke oven gas (COG), and in China there is ongoing fundamental research to improve the efficiency of DRI. [21] [22]

4. Global Crude Steel Produced

Table 4 is extracted from World Steel Association 2013 production figures [3]. Note that half of all steel that year was produced in China.

Table 4. Crude Steel Produced in 2013. Kt

European Union	166,208
Europe Other	38,762
C.I.S.	108,256
North America	118,942
South America	45,822
Africa	16,078
Middle East	26,967
Asia	1,122,680
Oceania	5,588
World Total	**1,649,303**
China (49.8%)	821,990

There are three main sources of crude steel (steel yet to be formed to a product): scrap returned from outside the industry which is melted with internal industry scrap; refined blast furnace iron (BFI); and refined directly reduced iron (DRI). Table 5 presents global totals from 2008 to 2013 and estimates the scrap used which is compared with external scrap purchases. For the years shown scrap purchased slightly exceeded use.

Table 5. World Crude Steel Production derived from [3] and [4]

Thousand Tonnes	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Crude Steel	1,343,269	1,238,285	1,432,761	1,537,206	1,559,472	1,649,303
BFI	949,582	933,625	1,035,120	1,104,651	1,124,263	1,168,397
DRI	67,907	64,253	70,505	73,250	73,433	74,718
External scrap by difference	325,780	240,407	327,136	359,305	361,776	406,188
Percentages	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
BFI	70.7%	75.4%	72.2%	71.9%	72.1%	70.8%
DRI	5.1%	5.2%	4.9%	4.8%	4.7%	4.5%
External scrap by difference	24.3%	19.4%	22.8%	23.4%	23.2%	24.6%
Compare	**2008**	**2009**	**2010**	**2011**	**2012**	
Scrap purchased by Steel Works	335,000	265,000	340,000	370,000	370,000	

5. Greenhouse Gas Emissions to produce Crude Steel

The emissions resulting from the manufacture of crude steel have been collected for the International Energy Agency (IEA) as the summaries of country averages for crude steel production. [4] Table 6 presents numbers drawn from this work which we should note reports CO_2 rather than CO_2 and equivalent gases (CO_2e).

Table 6. CO_2 Kg emissions per tonne crude steel (world averages)

	Low	High	Average
Scrap-EAF	210	540	384
DRI natural gas/EAF	660	1,260	1,080
Advanced BF/BOF	1,230	1,590	1,440
Average BF/BOF	1,500	1,860	1,635
DRI (Coal)/EAF	2,220	3,000	2,490

From Table 5, and assuming 25% of the DRI in Table 4 was produced using gases from coal as in 2008 [20], we can now estimate the global figures for the Low CO_2 scenario of Table 6 and present these in Table 7.

Table 7. Low CO_2 Scenario

2013 kilotonnes	Crude Steel	Average CO_2	Low CO_2
Crude Steel	1,649,303	2,173,339	1,600,882
BFI	1,168,397	1,910,329	1,437,128
DRI	74,718	107,034	78,454
External scrap	406,188	155,976	85,299

The “Low CO_2 scenario” would lead to a drop of annual emissions of 572 million tonnes CO_2 or CO_2e if the new natural gas displacing the carbon from coal were brought into play with no leakage.

The Stockholm Environment Institute study citing the IEA study suggested that the most direct way to reduce global steel industry GHG emissions would be to relocate EAF to locations that are rich in hydro or nuclear electricity, particularly where there is ready access to natural gas for DRI production and ocean access for ore. [23]

The Swedish study says that while there are individual countries with low GHG electricity and access to natural gas and ore, the world’s largest producer, China, does not have these factors. We should note that highest GHG emissions reported in Table 6 were from DRI coupled with coal.

6. Discussion

DRI averages around 6% of the fresh crude steel made from ore and averages 12% for all countries other than China. Following the relocation suggestion in the Swedish study, global crude steel GHG emissions could drop over half a billion tonnes per annum. [23] It would be a slow and difficult step to move half of the world’s total steel production out of China and the authors suggest that any relocation could take place only at the normal rate of industry expansion and equipment replacement. Key factors are the availability of electricity from low carbon resources and access to natural gas plus iron ore. Ore is easily brought in by sea, as exemplified in Trinidad by Nucor. [24]

Although Canada produces only 1% of the world's steel [3], it is well represented in the operation of DRI and EAF production processes. There are EAF facilities in Canada besides those coupled with the DRI equipment that the1980 report EPA had noted in Quebec. Iron ore pellets made to DRI specifications are produced in Labrador and exported from Quebec. [25] With iron ore close to the ocean, enough natural gas to consider exporting LNG, hydro and a safe nuclear record, Canada is clearly positioned to participate if there is agreement to cut coal use. Even minimal coal use constraint will tend to grow steel production in Canada. On the other hand there will be a trade-off as Canada is the world's third largest exporter of metallurgical coal (coking coal). [2]

Historically, though, besides the remarkable expansion of BFI/BOF in China, the steel industry changes slowly. For example the newest DRI facility in Quebec was started up 37 years ago.

In contrast, the world products of the automotive industry are changing rapidly as global efficiency standards come into play. The scope for a half billion tonne annual GHG reduction for the current vehicle volume is attainable within the replacement period of the vehicle fleet.

As the automotive transition continues apace, the steel industry will be aware that the amount of steel in recycled automobiles will reduce and thereby increase the demand for low impurity carrying DRI.

7. Conclusions

The scale of GHG reduction that can be attained by reducing road vehicle weight is of the same order as that of moving present steel and iron production to areas with low carbon power and natural gas. An automotive transition would be swifter.

When less automotive steel scrap becomes available, the demand for the low impurity levels of DRI would rise to dilute lower grade scrap.

Should there be an agreement to restrict coal use, iron and steel production will tend to rise in locations that have ore access, natural gas and low carbon electricity. There would be a tendency for steel and iron production to grow in Canada.

A coal limitation would more than proportionally slow the growth of steel production where there is reliance on BOF/BFI.

8. References

[1] McGlade C and Ekins, P., "The geographical distribution of fossil fuels unused when limiting global warming to 2 °C", Nature, 517, 08 January 2015, pp.187-190

[2] "Coal Facts", World Coal Association, 2014

[3] Steel Statistical Yearbook 2014, World Steel Association, Committee on Economic Studies – Brussels, 2014

[4] Baron, R., Reinaud. J and Philibert, C., "Sectoral Approaches to Greenhouse Gas Mitigation" International Energy Agency, November 2007

[5] Willeke, R and Rubach, C., editors “World Steel Recycling in Figures” 2008-2012, Bureau of International Recycling, Brussels, May 2013

[6] Van der Hoeven, M, ed. “CO_2 Emissions from Fuel Combustion- Highlights” (2013 Edition) IEA Statistics, Paris, 2013

[7] Kazunori Kojima and Lisa Ryan “TRANSPORT ENERGY EFFICIENCY, Implementation of IEA Recommendations since 2009 and next steps”, IEA September 2010

[8] Mohapatra, S. and Das, S., "Introduction of High Strength Steel for Commercial Vehicles - Light Weighting of Vehicles," SAE Technical Paper 2014-28-0002, 2014, doi:10.4271/2014-28-0002, 2014

[9] Scamans G., “Aluminium sheet in automotive applications” Aluminium International Today” March, April 2014

[10] Scheps, R., “Aluminum Sheet Outlook in Auto” Alcoa, Jan 14 2014

[11] Fitzpatrick, N., “Reducing greenhouse gas emissions with electricity and electrochemical products”, Canadian Nuclear Society Symposium on Climate Change and Energy Options, Ottawa, November 1999

[12] Bailey, A.R., “A Text-Book of Metallurgy’, 2nd Edition, MACMILLAN & Co. Ltd., London, St. Martin’s Press Inc., New York., 1961. p. 315

[13] Unglik, H., and Stewart, J.,Parks Canada, Analytical Section Services, Laboratory No. 92-2216, , "The Metallurgy of Norse Material from L'Anse aux Meadows, Newfoundland vol. 1," vi, viii., 1999

[14] Kibuta, T., “Method of manufacturing black-heart malleable cast iron from white cast iron”. US Patent 1692842A, Nov. 27, 1928

[15] Tetelman, A.S. and McEvily, Jr., A.J., “Fracture of Structural Materials”. Wiley, 1967 pp. 504-509

[16] Scaife, P., Nunn, J., Cottrell, A. and Wibberley, L., “Towards Sustainable Steelmaking-an LCA perspective.” ISIJ International, Vol 42, Supplement, 2002, pp. S5-S9

[17] Chatterjee, A, “Sponge Iron Production by Direct Reduction of Iron Ore” 2nd Edition PHI Learning, New Delhi, 2012

[18] Twidwell. L. G., “Direct Reduction: A Review of Commercial Processes”, EPA-600/2-80-036, January 1980

[19] Grobler, F., and Minnitt, R.C.A., “The increasing role of direct reduced iron in steelmaking.” Journal of the South African Institute of Mining and Metallurgy, March/April 1999

[20] Michishita. H and Tanaka, H, “Prospects for Coal-based Direct Reduction Process” Kobelco Technology Review # 29, December 2010

[21] Huerta, M., Patel, N., Cameron, I., Okrutny, M., Pereira, R., Gordon, Y., "Merits of Producing DRI in an Integrated Steel Works Using Coke Oven Gas," ABM 43rd Ironmaking and Raw Materials Seminar. Belo Horizonte, Brazil, Sept. 3, 2013

[22] Wang, Z., Liu, Z., Tang, J., Chu, M., Xue, X., "Analysis of Gas Thermodynamic Utilization and Reaction Kinetic Mechanism in Shaft Furnace" International Journal of Iron and Steel Research, 21(1), 2014, pp. 16-23

[23] Erickson, P., van Asselt, H., Kemp-Benedict, E. and Lazarus, M., "International Trade and Global Greenhouse Gas Emissions: Could Shifting the Location of Production Bring GHG benefits? ", Stockholm Environment Institute, Project Report 2013-02

[24] "Nucor Announces Start-Up of Production of DRI in Trinidad", Charlotte, N.C., Jan. 16 2007

[25] Yujnovich, Z., "Iron Ore Company of Canada", Rio Tinto Presentation, 14 Sept, 2012

9. Acknowledgements

The idea of this submission accelerated when staff at Parks Canada located and sent a report on iron made by Norse settlers at L'Anse aux Meadows, Newfoundland. Contacts in Canada, Australia, Japan and the UK made suggestions. E. Laurendeau-Fitzpatrick translated the abstract.

10. Biography

Nigel Fitzpatrick obtained his PhD in metallurgy at Imperial College's Royal School of Mines before joining an Alcan plant in Banbury, Oxon. Moving to Kingston. Ontario, he helped start a continuous casting plant in Jonquière. Joining Alcan's research team, he co-developed metal production processes before leading clean energy product projects. At BC Research Inc., Nigel worked on transportation projects and helped start a hybrid vehicle company.