

Original citation:

Sridhar, Seetharaman and Li, Zushu. (2016) Can there be a sunrise in steel town? Ironmaking & Steelmaking . 10.1080/03019233.2016.1211150

Permanent WRAP URL:

<http://wrap.warwick.ac.uk/80953>

Copyright and reuse:

The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:

"This is an Accepted Manuscript of an article published by Taylor & Francis in Ironmaking & Steelmaking on 9 August 2016 , available online:

<http://dx.doi.org/10.1080/03019233.2016.1211150> "

A note on versions:

The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP url' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

Can there be a sunrise in steel town?

Seetharaman Sridhar and Zushu Li

WMG, University of Warwick, Coventry

ABSTRACT

A sustainable UK steel industry is vitally important to the UK's future growth prospects. This article first analyses the grand trends and challenges that the UK steel industry is facing. Then alternative iron making processes are briefly reviewed with regard to its flexibility in raw material and energy and its reduction in CO₂ emissions. It is concluded that in the long-term, the scrap-based EAF route can be considered as a viable process route for the UK steel industry. For the current integrated process, its sustainability can be achieved by substantially improving its energy / material efficiency and by focusing on the creation of value-added steel products. It also points out that ensuring the sustainability of the UK steel industry requires a clear strategy, substantial capital expenses and support from the government and the industry itself. The UK has to invest in / re-shape steel-related research creating new competences for the viability of the industry.

Key words UK steel industry, ironmaking, steelmaking, CO₂, process and product innovation

INTRODUCTION

The last 12 months have been tumultuous if not cataclysmic for the UK steel industry. Key innovations in the integrated process for making steel were made in the UK but the industry is now struggling to survive amidst high raw-material prices, high energy costs and falling prices for commodity steel products amidst cheap foreign imports.

UK steel production is through two process routes, the integrated route (10.165 Mt in 2014) and EAF route (1.955 Mt in 2014) ^[1]. The integrated route (e.g. Scunthorpe and Port Talbot steelworks) is based on the production of iron from iron ore and coke, and steel from BOF (basic oxygen furnace) steelmaking, while the EAF (electric arc furnace) route (e.g. Tata Steel Speciality at Rotherham and Stockbridge, and Celsa Steel and Liberty in South Wales) uses scrap as the main raw material. The energy consumption through the integrated process was estimated to be 10.5 to 11.5 GJ/tls (tonne liquid steel), which is ~80% higher than that by EAF route (2.1 to 2.4 GJ/tls) ^[2]. Energy costs and materials costs account for 36% and 40% of the total production costs of hot rolled coils through the integrated route. Future demand for steel in the UK is estimated to be about 300 kg of steel per person per year; which is about 20 Mtpa for the whole UK ^[3].

Domestic production of steel is vitally important to the UK's future growth prospects, and to the UK's aspirations for the manufacturing and construction sectors - it is the critical part of UK materials supply chain. There is a clear case to protect steelmaking capacity in the UK. This article first analyses the trends and challenges that the UK steel industry is facing, and then examines possible solutions for the viability of this industry from a technical point of view.

TRENDS AND CHALLENGES AFFECTING THE UK STEEL INDUSTRY

Faced with little/no natural resources nor a national energy strategy the UK steel industry is being affected by grand trends and challenges, for example, in strict environmental regulation, new energy/materials sources, global over-capacity, and ever increasing customer requirements for high quality steel products. In other words, improvements in productivity to maximize yield, and reduce process costs are dwarfed by the changes in raw material prices and energy costs and fluctuations in the market for steel products (**Figures 1 to 3** ^[4,5]). Thus, it can be argued that when the steel industry 'does well' in modern times this is caused by a temporary trend in e.g. iron ore cost or some large infrastructural efforts in some part of the world (and not due to innovative

transformations in the steel plants). The question then becomes, how does one enable steel manufacturing to become resilient towards trends? Logically the solution would entail (I) flexibility in raw material and energy to manufacture iron at the front end, and (II) a viable strategy with regards to the products that are produced. The former may become ever more important as the UK exits the EU and, as a result of the fallout, economic imports of any kind may become challenging. The latter, i.e. a viable product strategy can be realised by new product development and more importantly flexibility of so called late stage differentiation in product (see the section “PRODUCT DIVERSIFICATION”). With the technology available today we are, in the UK, limited to strategically targeting products where we would have a competitive advantage due to local supply chain needs. This could be for example, strip for construction applications utilising advanced coating processes, products for the domestic automotive industry (electric steels for electric vehicles, light weight steels and steel/polymer hybrids etc) and specialty steel for aerospace and automotive drive train applications. A need for a domestic supply chain for such high value products may become essential for sustaining the sectors that depend on steel as UK exits the EU and imports may become more expensive.

Although the steel industry is pretty lean and efficient, steel production is still energy-intensive, consuming fuel (mainly coal and coke) and electricity and accounting for 6.7% of anthropogenic CO₂ emissions globally. In order to keep global warming to well below 2 °C by the middle of the 21st century compared to pre-industrial levels, the participating 195 countries in the ‘Paris Agreement’, by consensus, agreed to reduce emissions and carbon output as part of the method for reducing greenhouse gas ‘as soon as possible’. The EU Commission’s climate change target, summarised in their roadmap for Moving to a Low Carbon Economy in 2050 is a reduction in emissions of 80-95% by 2050 compared to 1990 for European industry. This is far beyond the reach of the steel sector as the actual energy consumption (and also the CO₂ emission) is only 25 to 30% higher than the theoretical minimum for the integrated process. This target of emission reduction can only be achieved by

transformative processes and in combination with Carbon Capture and Storage (CCS).

CCS is widely viewed as a crucial approach to meeting global and national climate change targets, although large-scale CCS is still in its infancy. It involves capturing CO₂ emitted from high-producing sources, transporting it and storing it in secure geological formations deep underground. While some of these have been operated successfully for decades, progress in applying large-scale CCS to carbon-intensive industry both in the UK and globally has been slow. Initial projects require large upfront investments, although the expectation is that costs will rapidly fall for second generation projects once the primary infrastructure is in place. CCS projects in the EU have been significantly delayed due to various reasons such as public awareness and acceptance, infrastructure, lack of business case, lack of a legal framework etc. There may be a long way for the CCS technology to be practically in use in the UK.

The reduction of carbon footprint can also be achieved by using clean/renewable energy to replace the fossil-based energy in the steel manufacturing. The clean/renewable energy can be wind power, hydropower, solar energy, geothermal energy, bioenergy, nuclear power, shale gas etc. US steelmakers have, in recent years, reaped the benefits of the shale gas revolution, which substantially reduced the gas price there. UK energy is becoming cleaner and greener with wind, solar and other renewables generating more electricity as UK energy from coal hit zero for several times in May 2016. Although it is early days for shale gas in the UK, work has started to extract abundant shale gas from previously unproductive rocks as the first fracking operation in the UK was just approved on 23rd May 2016. In the foreseeable future, cheap electricity from renewable energy or non-fossil energy (e.g. shale gas) is likely to be available, helping create a cleaner/brighter UK steel industry.

On average, steel goods last for 35-40 years. Apart from ~10% of steel used below the surface (for oil pipes or building foundations, for example) almost all end of life steel will be recycled. So, although the UK stock has nearly stabilised, only 10 million tonnes of steel are currently discarded. 90% of this is collected for recycling, of which around two thirds is exported. We can anticipate that over the next two decades, around 20 Mt of steel will be discarded annually. In particular, the rapid growth in demand for steel in construction which occurred in the UK during the 1970s will turn into a boom in demolition and steel recycling. ^[3]

In China, more than 90% of steel is currently produced by the integrated route with 772 Mt produced in 2014 ^[1]. This rapid growth in demand started roughly 15 years ago, so in 20 years' time there will be a huge scrap supply in China, which will completely change the supply of Fe-based raw materials in the UK and worldwide. Although UK domestic steel production is currently heavily reliant on iron ore-based integrated route, abundant scrap supply will favour the scrap-based EAF route for steel production in the future.

Customer requirements for steel products is ever increasing and drastically changing. The automotive sector is a typical example because of environmental regulation, cost, and public concern of safety. The numbers of people killed and injured in traffic accidents every year globally are staggering. Over the years the crash test requirements have become more severe leading to continuous efforts of OEM's to meet the goal of a drastic reduction of the number of fatalities and serious injuries in traffic in line with the visions of reaching zero, set up by the European Commission. Enhanced crash regulations will lead to tougher passive safety requirements favourable to steel. As energy evolves quadratically with speed, new high speed crash requirements will ask for innovative material and passive safety solutions exploiting the high strength and excellent deformation behaviour of steel. In the last decades, giant steps have been made in the development of steel grades for automotive. Whereas in the 1960s only very formable low carbon

grades were used for car production, a wide range of different grades has been developed over the years, mainly increased strength for better crash performance and enabling light weighting by down gauging. On top of that a range of coated steels have been developed, also increasing performance.

Another big trend in transportation under rapid development will be car sharing and on-demand mobility services like Uber and Lyft (every car a cab). This can be a genuine green transport alternative to compete with taxis and traditional public transport. Introduction of autonomous vehicles (estimated to completely implement by 2070) will give a huge boost to shared cars as, by then, a car will drive itself to the customer and the customer does not have to pick up the car somewhere. Shared cars will face a very high usage: from about 1% of time for a privately owned car to >50% of the time for a shared car, meaning an annual use of up to 300,000 km/year. This means there will be special requirements on durability such as fatigue performance. As the lifetime of these vehicles might be extremely short (~1 year) other requirements might change such as corrosion performance and appearance. With a short lifetime, recycling and (component) reuse will become far more important, of which steel can benefit. There may also be, with fewer personally owned cars, a lower need for coated steel sheets with impeccable surface finish which curiously is today the most competitive product line among steelmakers and occupies roughly 8% of the steel produced.

Therefore, a future sustainable UK steel industry would ideally be one that maximises the utilisation of abundant scrap supply and very cheap new/renewable energy (electricity) to ultimately produce differentiated high value-added products for critical industry sectors such as automotive sector. However, key technological challenges associated with Cu and Sn residuals stemming from automotive scrap (for the case of Cu) and tin cans (for Sn) currently restrict the grades that can be produced due to hot shortness. Hot shortness induced by scrap residuals, is caused whenever the surface of steel oxidises whilst in the austenite state, and the more noble Cu and Sn enrich to

the point where solubility limit is reached. If the temperature is above that of the melting temperature of Cu then a liquid forms which embrittles the underlying austenite grain boundaries. This may occur during cooling from the continuous caster and re-heating/hot rolling (or if direct hot-charge is practiced then during transfer in the tunnel furnace). To date, this restricts the grades that can be economically produced through low grade scrap to non-surface sensitive grades. Limitations may vary from plant to plant but generally are restricted to a maximum content in percent of Cu+Sn of 0.04 for IF sheet steels, while shredded car scrap contains nearly 0.3% of Cu+Sn. ^[6] Therefore, the recycling (without downgrading the steel grade) of high residual scrap requires innovation in terms of Cu and Sn removal and/or tighter control of thermo-mechanical processes to develop processing windows that ameliorate the harmful effects of the residuals. It should be pointed out that ~74 Mtpa of DRI are produced worldwide and 14% of the average EAF charge mix is DRI/HBI, which is used to reduce / dilute the residuals (e.g. Sn and Cu) in metal charge.

ALTERNATIVE IRON MAKING TECHNOLOGIES

Blast furnace is a dominant process to produce liquid iron with 1,183 Mt liquid iron produced worldwide in 2014 (cf. 73.2 Mt DRI produced). However, great efforts have been made by the global steel industry, academia and research institutes to explore possibilities to tackle the climate change issue. This includes making the process more energy efficient (process optimisation and process modification), changing to renewable energy sources and introducing completely new processes.

The importance of energy saving in the blast furnace ironmaking process is widely recognised, and various technologies have been developed such as blast furnace top gas pressure recovery turbine (TRT) and oxygen blast furnace (OBF). Modern blast furnaces in steel plants operate at a high top gas pressure (0.16 to 3.0 MPa at a waste gas temperature of ~200 °C). This gas, coming out at the top of a BF, is cleaned to remove dust and used in the steel

plant as a fuel for heating purpose at a relatively low pressure. The BF gas top pressure TRT utilises the gas heat and pressure energy to drive a turbine for generation of electric power and the gas is further used as a fuel in the steel manufacturing processes. This technology can recover about 33% of the pressure energy of the high pressure gas with no additional CO₂ pollution.

The oxygen blast furnace (OBF) is considered to be a promising process in terms of flexibility of energy use and advantages related to CO₂ mitigation. In the OBF oxygen is used instead of air as blast, and the top gas is recycled, after CO₂ removal, either to the lower tuyeres or to tuyeres in the shaft, or to both. If the removed CO₂ is not released to the atmosphere, this concept can significantly reduce the emissions. It was predicted to have an 33% increase in the production rate and savings of 100–200 kg/thm (tonne hot metal) of coke.

Apart from BF process modifications, various coal-based direct/smeltering reduction processes are currently either in commercial operation or under development, for example, Redsmelt, Corex, Finex, Hismelt, and Hlsarna. These coal-based processes can be grouped into four categories according to their reduction reactors – rotary kiln, shaft furnace, fluidised-bed and rotary hearth processes.

The **Redsmelt** process is based upon a rotary hearth furnace (RHF) which reduces green pellets made out of iron ore, reductant fines and binders to produce hot, metallised DRI that is charged to a submerged arc furnace (SAF) for smelting into hot metal and slag. The process operates at high temperature and atmospheric pressure.

Corex is an industrially and commercially proven smelting-reduction process. In the Corex process, all metallurgical work is carried out in two separate process reactors – the reduction shaft and the melter-gasifier. As the

coal is charged inside the melter gasifier, even non-coking coal can be used, making a coking plant unnecessary. The typical iron oxide mix for Corex is 30% lump ore (up to 80%) and 70% pellets. No sinter and therefore no sinter plant is necessary for optimal operation. In addition, Corex uses high purity oxygen, resulting in nearly nitrogen-free top gas with high calorific value. However, unable to use ore fines, requiring some coke to supplement coal, and its cost effectiveness compared to blast furnace are some of the limitations / concerns for the Corex technology.

FINEX, developed by POSCO and former Siemens VAI, is a promising technique that replaces blast furnaces for the production of hot-metal from direct use of fine ore and non-coking coal. In the FINEX process, fine iron ore is charged in a series of fluidised-bed reactors. A reactor gas made from gasified coal flows in the opposite direction over the ore, heating and reducing it to give DRI. The fine DRI is then smelted to make molten iron. The unique characteristics of the Finex process and its ability to use low-cost raw materials mean that both capital investment and production costs are much lower than in the blast furnace route. It is claimed that a 1.5 Mtpa Finex plant can produce hot metal more cost effectively than a modern 3 Mtpa blast furnace. There are currently only two operating Finex plants worldwide. Its benefits in productivity and cost efficiency will be more clear if more installations are operating.

Hismelt is a direct smelting process for making iron straight from the ore. Fine iron ores and non-coking coals are injected directly into a molten iron bath, contained within a smelting reduction vessel (SRV), to produce high quality molten pig iron. The excess gas produced during the process is used for power generation, production of direct reduced iron (an alternative iron input for scrap), or as fuel gas. The process can be considered as a potential replacement for the blast furnace and as a new source of low cost iron units for BOF or EAF steelmaking. The technology offers advantages such as lower operating costs; lower capital intensity, lower environmental impact, greater

raw material and operational flexibility. However, there is no commercial operating plant worldwide.

Hlsarna is currently the most actively developing smelting reduction process. It was created under the European Union ULCOS (Ultra-Low Carbon Dioxide Steelmaking) program and has captured the interest of steel- and policymakers. The process takes place in a special reactor that has a narrow cyclone furnace on top of a wider convertor. Pulverized iron ore, coal dust, and oxygen are injected into the cyclone furnace, where the ore partially reduces and melts, falling down to the convertor. Oxygen and coal introduced in the convertor form CO that finishes reducing the melted pre-reduced iron ore, creating hot gases that rise and provide heat for the reaction occurring in the cyclone furnace. The technology does not need coke, sinter, or pellets, making it 30% more energy efficient and 25% less CO₂-intensive than a conventional blast furnace. Plus, it can work with cheaper non-coking coal, which contains volatile matter and low-quality iron ore, enabling flexibility on raw materials. **(Figure 4)**^[7] So far four campaigns of pilot tests at a plant producing 8 tonnes of iron an hour have confirmed the researchers' predictions on Hlsarna's reduced energy use and CO₂ emissions. The 5th campaign (endure test) is under preparation.

For now, companies in the ULCOS consortium are interested in moving the technology forward to the next step of demonstration at the scale of ~1 Mtpa. The Hlsarna process is flexible in raw materials – fine iron ore, industry wastes (sludge), scrap, Ti-bearing magnetite etc. It can be used as iron producer as well as waste disposer. Higher energy saving can be achieved by the use of high percentage of scrap, high volatile coal, potentially cheap shale gas, and biomass. The target is to achieve more than 40% energy saving and reduction in CO₂ emissions. However, to achieve the target of 80% or more CO₂ emission reduction, it has to combine with the CCS process.

Although the alternative iron making processes are very promising, they are more or less based on fossil fuel. The most promising one, Hlsarna process is

estimated to reduce CO₂ emissions by 40%. In contrast, gas-based DRI, hydrogen reduction and biomass furnace can be considered as genuine decarbonising technologies.

EAF-DRI: In the USA, 60% of steel is produced from scrap steel recycled in an EAF (EAF route or mini-mill). Scrap reuse eliminates the energy needed to reduce iron ore and make coke. The mini-mills that employ EAFs have a fifth of the capital cost of traditional steel mills that start with iron ore. However, impurities in scrap such as copper and tin can cause cracking of the steel during casting, and this necessitates that the scrap is diluted with iron including DRI to lower the effects of the impurities. Because of impurities in scrap and possibly insufficient scrap supply, US-based recycled steel producer Nucor is taking advantage of the recent shale gas boom in the country to employ a new route at its upcoming steel plant in Louisiana. This plant converts natural gas in a reformer to hydrogen and CO, which together strip oxygen from iron oxide to give so-called direct-reduced iron (DRI). The DRI pellets are then mixed with scrap and fed into an EAF. **(Figure 5)** By eliminating coking coal, DRI reduces the energy use and carbon footprint of steelmaking.

Electrolysis: Electrolysis offers another option to make the steelmaking process greener. The method, in which an electric current is passed through molten ore, is commonly used to produce metals such as aluminium. ULCOS has led to two experimental electrolysis processes to produce iron, while researchers at the Massachusetts Institute of Technology are developing low cost electrolysis methods. Electrolysis is promising but it uses a lot of electricity so a sustainable energy source is needed. The process is also limited by the surface area of the electrode and impurities in the iron ore. Whether these innovative low-energy, low-carbon technologies make it to the market and gain widespread adoption is unknown.

Biomass in steelmaking: The history of industry is, in part, that of the search for energy resources, that started as biomass and then moved on to coal, oil and electricity with the nuclear power and renewables avatars. The CO₂ challenge might produce a comeback of biomass, as it holds the promise of carbon neutrality, if very strict conditions are met in producing it. A consortium, led by Corus (now Tata) steel producer, and incorporating the expertise of institutes and laboratories working on biomass, has explored the various opportunities in terms of dedicated crops (plantations) or of agricultural residues, produced in tropical countries (where the light efficiency is highest) or in Europe, and of conversion into a solid charcoal, a liquid bio-oil, or a gas (biogas or syngas).

The most obvious practical solution for producing biomass for the steel industry is charcoal, from plantations of eucalyptus trees grown in tropical countries (e.g. in Brazil or Angola) and converted there to be transported to Europe. PCI can be substituted fully by charcoal in large BF's (40% of the carbon input), while smelting reduction can accommodate up to 100%. Plantation technology is mature and has advanced to a remarkable level of excellence in Brazil. Progress has to be made on the conversion process, by designing continuous, high productivity furnaces, possibly working under pressure, to replace Missouri kilns. Small BF's running 100% with charcoal operate in Brazil (e.g. Acesita). Arcelor Brazil has been reporting its development of a biomass steel production route based on sustainable plantations of eucalyptus trees, production of charcoal and small charcoal blast furnaces, which is already used in Brazil but at a small scale (300,000 tpy BF) and is most probably a local solution.

HYBRIT (Hydrogen Breakthrough Ironmaking Technology): Big-emitting steel plants have steadily reduced their carbon intensity in recent decades but are viewed as unable to make much deeper reductions without changing the basic steelmaking process or burying the emissions underground. Swedish steelmaker SSAB has partnered with miner LKAB and utility Vattenfall to

develop a breakthrough technology to decarbonise its operations over the next 20-25 years without using CCS. It differs from those ideas of coal-based processes (such as FINEX, HIsarna etc) in that it foresees being able to fully decarbonise steelmaking without burying any emissions using CCS technology. The three firms aim to use hydrogen fuel in the steelmaking process to eliminate the use of fossil fuels, resulting in a waste product of pure water and no carbon dioxide emissions.

Since raw-material and energy flexibility is a key factor for an economically sustainable future, it is worth categorizing the alternative ways of producing iron based on the level of flexibility allowed which is shown in Table I.

Table I Comparison of alternative processes for producing iron in energy and raw materials flexibility

		TRT	OBf	Redsmelt	Corex	Finex	Hismelt	HIsarna	EAF-DRI	Electrolysis	Biomass BF	HYBRIT
Energy flexibility	Fossil-based	x	x	x	x	x	x	x		(x)**	x	
	New energy							(x)*	x	x		x
Fe-based raw materials	iron ore-based	x	x	x	x	x	x	x	x	x	x	x
	Scrap/DRI-based							(x)*	x			
Current status	new idea											x
	pilot plant							x		(x)**		
	demo						x					
	commercial	x	x	x	x	x			x		x	

*: HIsarna process can be (but not fully) flexible in energy and raw materials;

** : the electricity for electrolysis method can be from combustion of fossil fuel.

PRODUCT DIVERSIFICATION

Meeting the increasing customer requirements for high quality products at the lowest cost is the key for the survival of the UK steel industry. UK steel industry has to constantly invest in improving its capability and develop new steel grades for the ever changing steel market. A few examples are shown below.

Cold coating + CAPL:

The Continuous Annealing Processing Line (CAPL) is essential for ensuring precisely controlled metallurgical properties as required for high-end steel

applications and fast processing speeds. CAPL technology is best suited for the production of high-quality automotive skin panel steels and for the production of high-strength grades of cold rolled steels. The CAPL line at Port Talbot was built in 1999 (without cold coating line), aiming to improve the formability of steel products, increasing their value and market reach. Addition of cold coating to the existing CAPL at Port Talbot can provide surface properties and colours to meet very specific technical and aesthetic requirements. This will allow the adjustment of internal microstructure by the annealing process and surface quality by the coating layer(s). It will significantly diversify the product offerings to meet the requirements for a wide range of product applications. Currently POSCO and Arcelor Mittal have made significant advances towards realizing vapour deposition on steel strips.

New steel products for the automotive industry:

The UK automotive industry is an important part of the UK economy, which accounted for 4% of GDP and provided employment for more than 700,000 people in the UK (2013). Production and supply of new steel products to this sector are vital to the UK car manufacturers, to the UK economy, and to the viability of UK steel industry.

CO₂ emission reduction has become the prime driver for automotive developments. This generates huge opportunities for developing new business and technologies for the UK steel industry in light weight material solutions. The UK steel industry, in collaboration with leading universities and research institutes, has to continue its efforts to become, at least, at par with the industry leaders in high strength product mix in Europe. The UK steel industry should also work on the long-term (e.g. post 2030) steel solutions for further light weighting, for example, UHSS 2 GPa+ steels, tailor annealed/rolled/quenched products, low density steels (<7 g/cm³), high modulus steels (>250GPa) and ultra-thin structures (<0.4 mm, including laminate, sandwich and foam solutions).

Responding to the car sharing trend, durability solutions have to be sought for heavy used shared cars (e.g. 300,000 km/year vehicles), for example, new differentiated products with improved fatigue performance and different corrosion requirements. Recycling and re-use of materials and components can be another topic to consider for the heavy used shared cars.

Flash® Bainite:

The flash bainite process (<http://www.flashbainite.com/>) invented in the USA utilizes rapid heating and cooling of steel to introduce morphological heterogeneity and is a process that can be potentially utilized in conjuncture with high productivity direct hot charging in EAF lines.

Blue sky technologies:

The UK steel industry should also invest in blue sky ideas to develop differentiated process and products, for example, solid state steelmaking although its future is not certain. The solid state steelmaking process is the production of high carbon iron sheets from high carbon hot metal using a strip caster and a solid state decarburisation process to produce low carbon steel sheets. The S³ process ^[8] suggested the feasibility of decarburising of 4 wt% C cast iron in solid state during the continuous strip casting process using oxidising gases (such as CO₂ and H₂O), deemed. If such a process became feasible the chemistry of the steel strip can (at least in part) be engineered at the very end allowing for late stage differentiation. The process is also less raw material-intensive since the enormous amounts of oxygen used in the basic oxygen process is by-passed and also eliminates endogenous oxide inclusions, thereby enabling ultra clean steel to be produced. Fundamentally it is a promising environmentally conscious low cost steelmaking process.

INNOVATIVE RESEARCH

Steel metallurgy is the area where UK had, but is now seriously lacking competence since the demise of the large nationalised foundation industry laboratories e.g. BISRA (British Iron and Steel Research Association) and the

fading of research and education in metallurgy in UK universities. This is clearly evidenced by the absence of UK steel industry/research organisations in the development of any of the innovative steel production processes mentioned earlier. This lack of competencies has seriously affected the competitiveness of the UK steel industry in producing high quality/advanced steels and subsequently the downstream industries like automotive industries, and ultimately affected the manufacturing capability of the UK, and the UK economy. This is caused by the lack of investment from both the government and the industry itself.

On the other hand, the grand trends and challenges that the UK steel industry is facing provide a stimulus to transform the industry and this requires new approaches and new competences. It is the time to re-shape the way of conducting research, development and implementation, and to change the relationship of steelmakers with academia and customers.

High growth businesses like Apple or Google have intimate connections to their customers to seek every possible opportunity for adding value to their offerings. The UK steel industry can benefit from the experience from these high growth businesses while it is creating a customer-driven business model. Industry 4.0 can help establish the new sustainable, services and customer orientated business practices.

In the last decades there were no fundamental, only minor incremental changes in the UK steel manufacturing processes. The steelmakers pursued process optimisation or used late technologies to improve productivity and reduce costs. In order to achieve and maintain the sustainability of the UK steel industry, transformative research has to be done to create breakthrough technologies and to produce differentiated high value products. This requires substantial contribution from academia to create the fundamentals for new processes and new products. The typical examples are super bainite steel and the application of graphene on the steel surface. So the UK steel industry

must have strong ties with leading universities and research organisations to develop innovative processes and high value products.

As clearly identified the disconnection of steelmakers, steel end users and leading universities, WMG (Warwick Manufacturing Group) at University of Warwick, Tata Steel, and automotive industry have created a new model to accelerate fundamental research, process/product development, and its implementation in the industries. That is, Tata Steel R&D Centre, National Automotive Innovation Centre (NAIC), and the Advanced Steel Research Hub and Lightweight Technologies Centre for Excellence from University of Warwick are based in the same campus at the University of Warwick. This infrastructure creates a unique resource, with an environment to foster collaboration, cohesion and cross-fertilisation of knowledge. Academic, industrial R&D and end-users work together using state-of-the-art equipment and facilities to develop breakthrough designs, technologies and processes. This infrastructure also provides a critical mass of research excellence that positions the UK at the forefront of the international iron and steel research agenda; develops sustainable and competitive operations which can provide customers and supply chain partners with new value-added products and services. The infrastructure combines the disciplines of materials, physics, chemistry, mechanical and chemical engineering, manufacturing, mathematics, statistics and computer science to address hypothesis driven fundamental questions, enabling new generation value-added products for major steel application sectors including automotive, construction, energy & power, engineering and lifting & excavating. This new model for innovative research should be supported and further reinforced by the government and the UK steel industry.

The research paths should cover both transformative technologies such as alternative iron making technologies and new products as well as incremental improvements to process control, yield and product quality. Research project aimed at making transformative changes are best handled as large scale

multi-institution projects with significant investments from the government. Incremental improvements are best handled as projects with individual industries.

CONCLUDING REMARKS

Considering the availability of cheap/clean energy (electricity) in the near future, abundant scrap supply in 20 years' time, and the existence of a domestic steel market for high quality steel, the UK steel industry has great potential to become a sustainable business.

The ideal sustainable steelmaking process has to be a low energy, low carbon process for production of high value-added products in a cost-efficient way and in a flexible manner. It would be flexible in terms of raw materials and energy source. It would use low-quality, low-cost coal and iron ore, and scrap. It would allow a switch from coking coal to thermal coal, natural gas, biomass, or other clean electricity sources. For the current integrated process, this can be achieved by substantially improving its energy efficiency (process optimisation or adoption of alternative iron making process) and by focusing on the creation of value-added steel products. In the long-term, the scrap-based EAF route can be considered as a viable process route for the UK steel industry.

Ensuring the sustainability of the UK steel industry is not an easy task. First it requires the industry and the government to have a clear strategy. Then this would require substantial capital expenses and support from government and from the industry for the upgrading of the plants, adoption / implementation of any alternative steel manufacturing process, and for UK-based innovative research and development. The UK has to invest in/re-shape steel-related research creating new competences for the viability of the UK steel industry.

It does seem that there can be a sunrise in steel towns around the UK but the steel plants may need to be completely different than what we see today.

ACKNOWLEDGEMENT

The author ZL would like to sincerely thank the support from EPSRC under grant EP/011368/1.

References

1. Worldsteel Association: Steel Statistical Yearbook 2015. Brussels, 2015.
2. R. J. Fruehan, O. Fortini, H.W. Paxton, and R. Brindle: Theoretical minimum energies to produce steel for selected conditions. Carnegie Mellon University, Pittsburgh, PA, May 2000
3. Julian M Allwood: A bright future for UK steel – A strategy for innovation and leadership through up-recycling and integration. University of Cambridge, April 2016.
4. <http://www.eef.org.uk/uksteel/About-the-industry/Steel-facts/>
5. <http://www.indexmundi.com/commodities/?commodity=cold-rolled-steel&months=180>.
6. Markus Huellen, Christian Schrade, Uwe Wilhelm and Zulfiadi Zulhan: EAF-Based Flat-Steel Production Applying Secondary Metallurgical Processes, Secondary Steelmaking Session – Paper No. 7.1, IS'06, Linz/Austria, October 2006.
7. K. Meijer and C. Zeilstra: Development of the Hlsarna process – alternative ironmaking technology with CO₂ capture potential. Industry CCS workshop, VDEh, Dusseldorf. 8-9 November 2011.
8. W.-H. Lee, J.-O. Park, J.-S. Lee, J.A. de Castro, Y. Sasaki, Solid state steelmaking by decarburisation of rapidly solidified high carbon iron sheet, Ironmaking & Steelmaking. 39 (2012) 530–534.

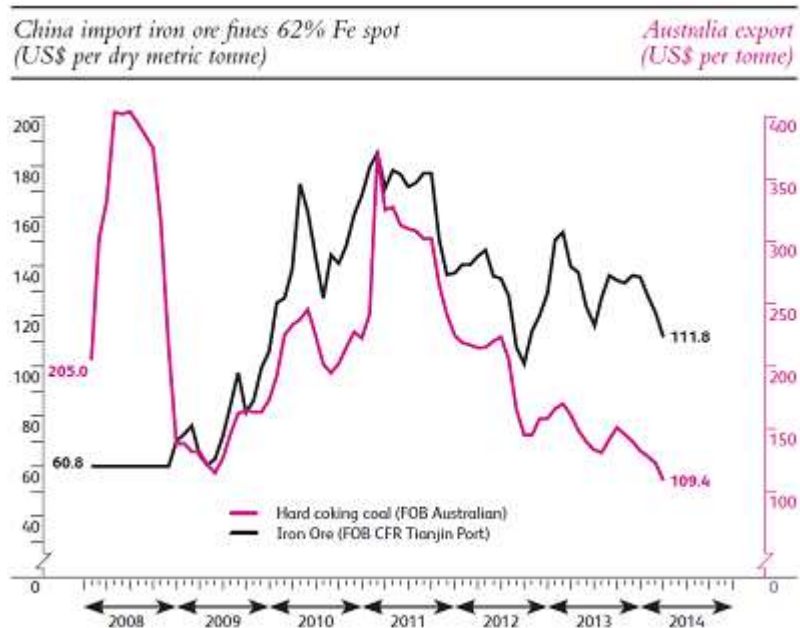


Figure 1: Raw material prices - iron ore and coking coal, January 2008 - March 2014. ^[4]

Pence/kWh excluding taxes

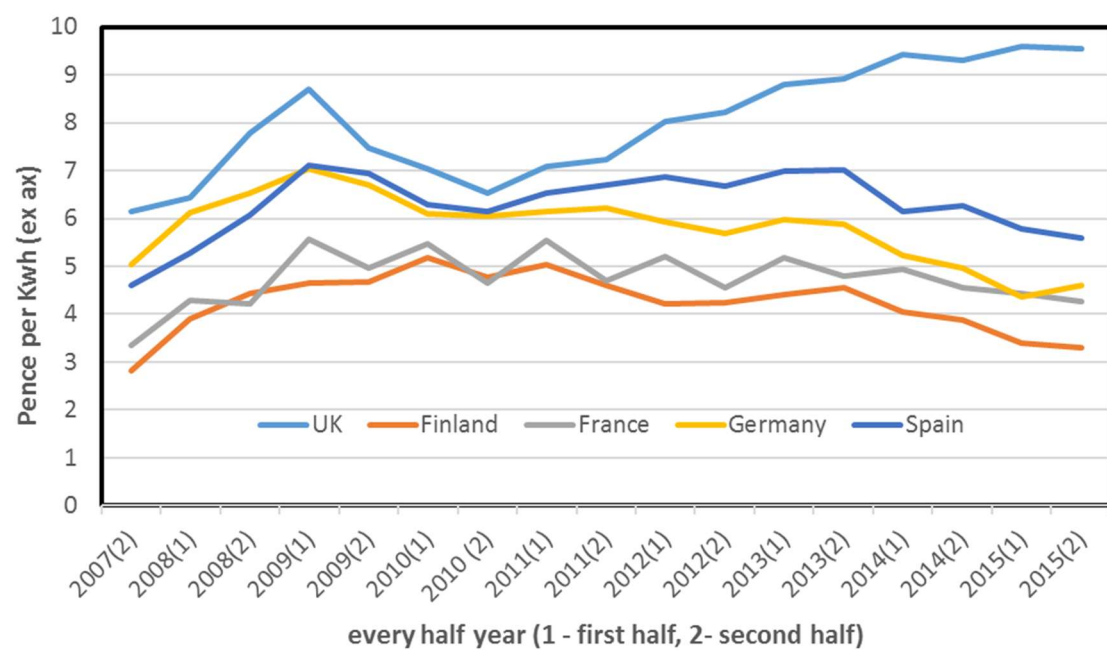
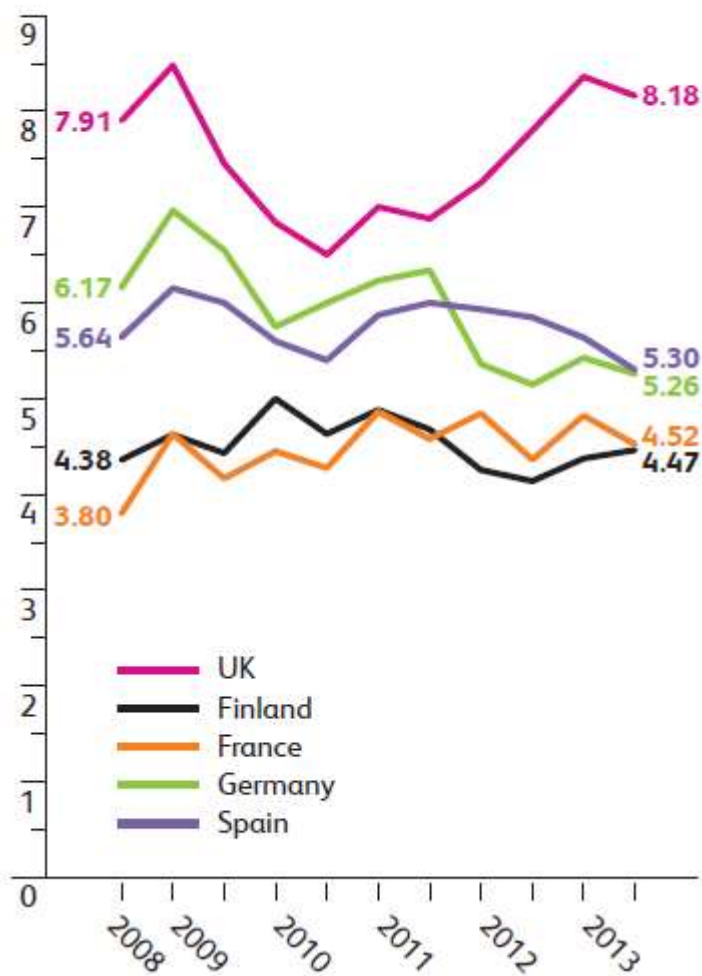


Figure 2: EU industrial electricity prices for extra-large users: July 2008 - December 2013. ^[4]

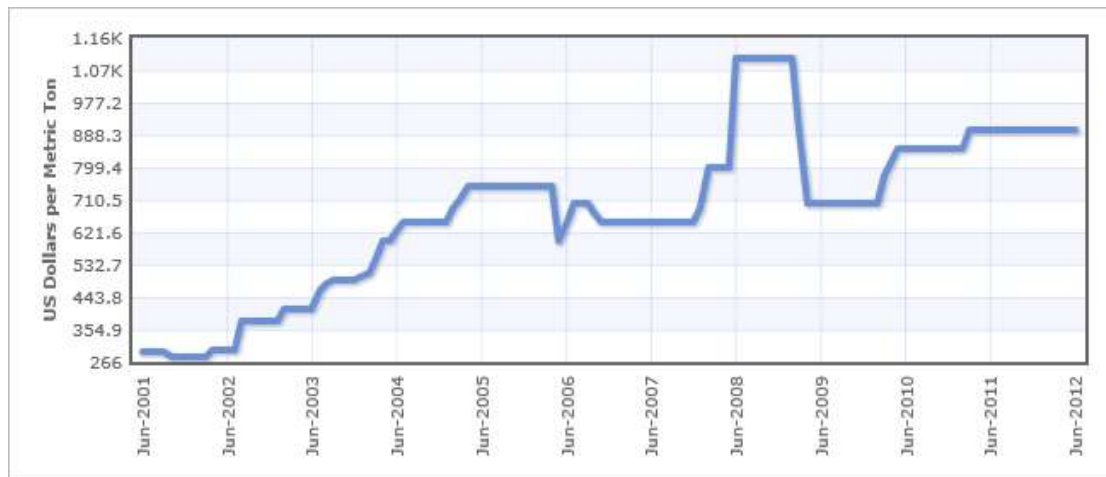
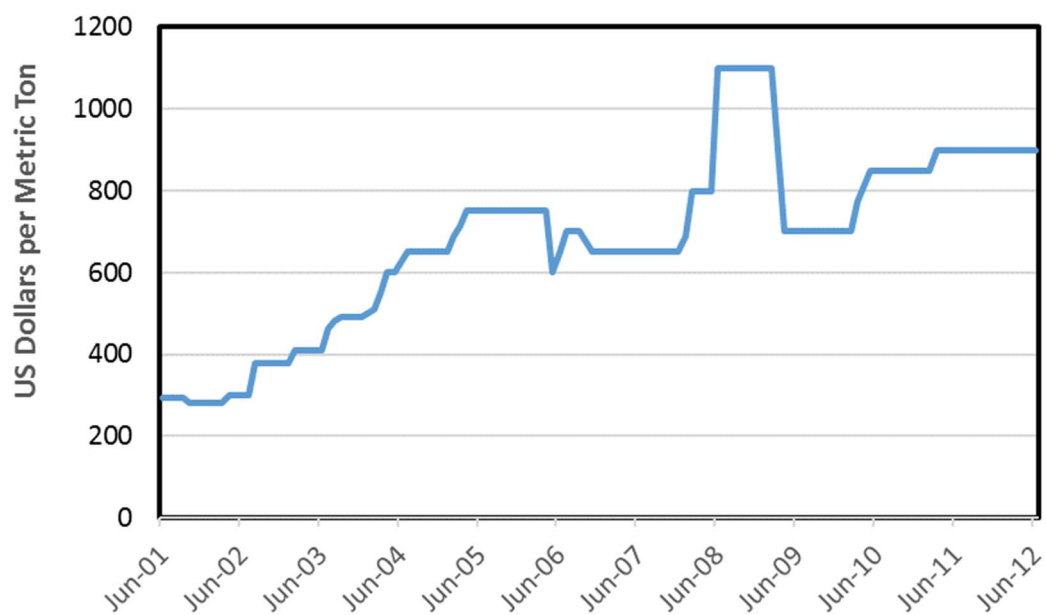


Figure 3: Cold-rolled steel Monthly Price - US Dollars per Metric Ton. ^[5] Note: Cold-rolled coil/sheet (Japan) producers' export contracts (3 to 12 months terms) fob mainly to Asia.



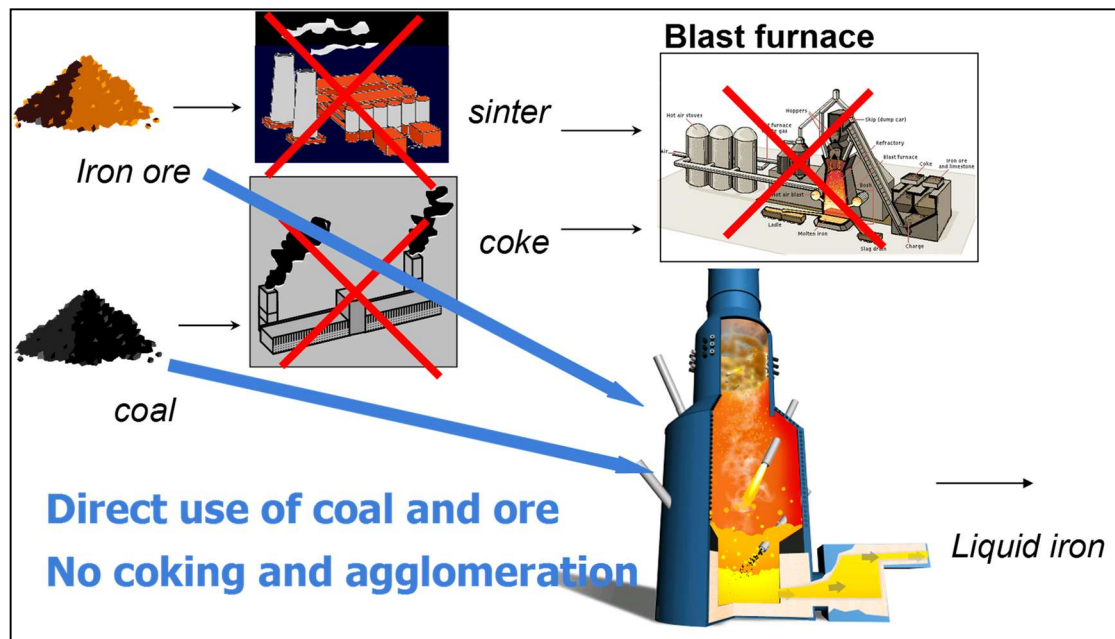


Figure 4: Comparison of HIsarna process and blast furnace for producing liquid iron. [7]

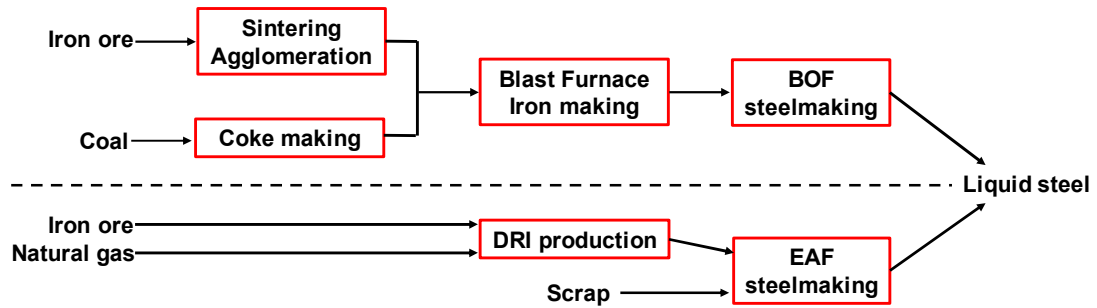


Figure 5: Schematic diagram showing the production of liquid steel by the integrated route (upper) and EAF-DRI/Scrap route (bottom).