Inaugural Bessemer Lecture

The relevance of Sir Henry Bessemer's ideas to the steel industry in the twenty-first century

Jean-Pierre Birat*

The inaugural Bessemer Lecture of the Steel Division of the Institute of Materials, Minerals and Mining was presented in London on 30 September 2003. In what will be an annual event, Dr Birat's lecture as the recipient of the 2003 Bessemer Gold Medal was followed by the Steel Division Dinner and preceded by the presentation of other Institute steel related awards (see I&S, 2003, 30, 419). The 2003 lecture was sponsored by BOC, Corus and VAI UK.

This Bessemer lecture provides a unique occasion for me to look at some of the issues I have been close to professionally, with a perspective spanning over three centuries, something that we do not often have the leisure to do in the steel industry.

I would like to speak first briefly about Sir Henry Bessemer and the dynamic nineteenth century in which he was such an active player, although much has already been said on the occasion of the Bessemer Centenary Conference that celebrated the centenary of his death.[1–3] There is certainly no need for another engineer to speak about him, after the Bessemer Memorial Lecture[4] given by Frank Fitzgerald, which provided a fascinating overview of his life and his accomplishments and can serve as a critical framework within which to read Sir Henry's autobiography with insight and profit.[5] Historians should now be given an opportunity to enrich the analysis of his life and put it into a broader perspective than that of scientists or engineers.

Then I will skip over 100 years to 1970 and recollect some of the endeavours and achievements of the steel industry of the late twentieth century, which I witnessed at first hand. There were deep changes of course, but also intriguing continuity with Bessemer's time.

Finally, I will indulge in a favourite pastime of mine, technological forecasting or rather *prospective*, to project what kind of path the steel industry might tread in the future and why.

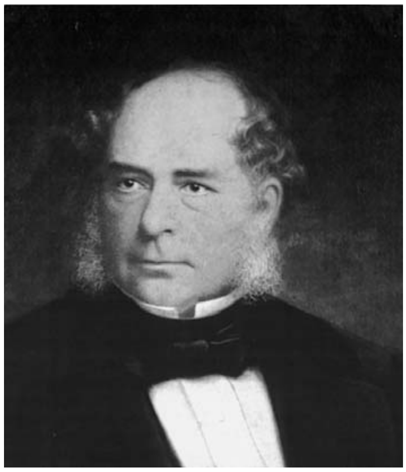
This will be done from the limited viewpoint of an engineer and based on the idea that the core of steel technology is the archetype of a cumulative technology rather than a mature, saturated and somewhat passé activity.

Bessemer and the nineteenth century

Bessemer is a man of the nineteenth century, a contemporary of Queen Victoria, Napoleon III, Lincoln or Emperor Meiji, but also of Beethoven, Rossini, Schubert, Weber, Bruckner, Tchaikovsky, Moussorgsky, Lalo, David, Géricault, Ingres, Goya, Turner, Constable, Degas, Whistler, Renoir, Monet, Gauguin, Cézanne, Stendhal, Mary Shelley, Schiller, Goethe, Kleist, Walter Scott, Karadjic, de Quincey, Maupassant, Victor Hugo, the French Romantics, Mallarmé, Henry James, Zola, Jules Verne, Eiffel, Rockefeller, to name but a few. This is fascinating material for historians, but a simple reminder to us that his world was very different from ours.

What can we therefore learn from his life that would be of interest for us and for our future? I want to stress six points.

First, Bessemer's most fascinating character trait was his almost manic compulsion to solve problems. It was probably a basic psychological need for him but also a way to 'advance in the world' and earn the money he needed to live – and to continue solving problems. Working to earn a living was still a new proposition in early nineteenth century England when



Sir Henry Bessemer (1813–98)

Bessemer started his professional life. This compulsion and his obvious talent at finding innovative and far-reaching solutions not only provided him with a comfortable income, it also brought about an amazing arrays of technologies, most of which have endured until today: from fake gold plating, false Utrecht velvet and sugar extraction from cane to use of reverberatory furnaces in glass manufacture, shells as a replacement for cannon balls, steelmaking by pneumatic conversion of pig iron (Fig. 1), ductile steels, steel guns, steel rails, steel plates for ship building, the basic concept of twin-roll strip casting (Fig. 2), etc. Of course people in this audience are more aware of his invention of the converter. His attempt at solving one of his personal problems, seasickness, by designing a boat that does not rock in the waves was also exemplary, even if it almost created an international incident when he attempted his first landing in Calais. Even during his retirement, or what passes for it in such an energy filled life, he worked on a telescope and on solar mirrors, with the vision of harnessing the energy that powers the Sun, a rather ambitious programme for someone who died the year when Marie Curie discovered radium. A talent still in great demand today!

*Scientific and Technical Director, IRSID, ARCELOR Innovation, Maizières-lès-Metz, France, e-mail jean-pierre.birat@irsid.arcelor.com

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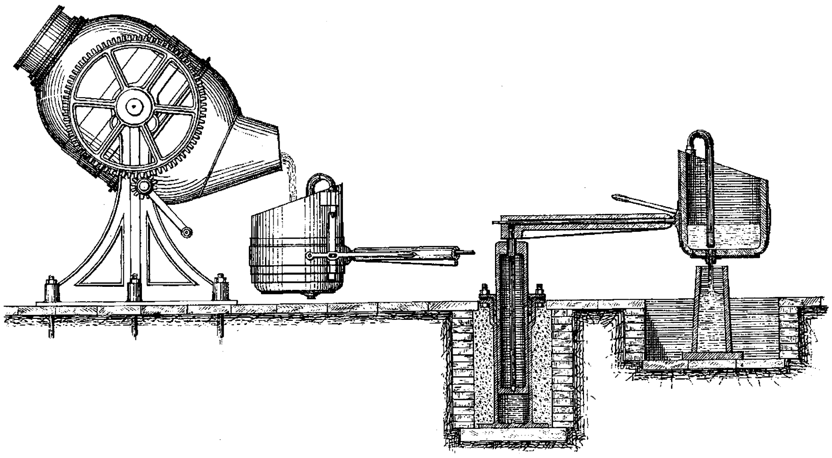
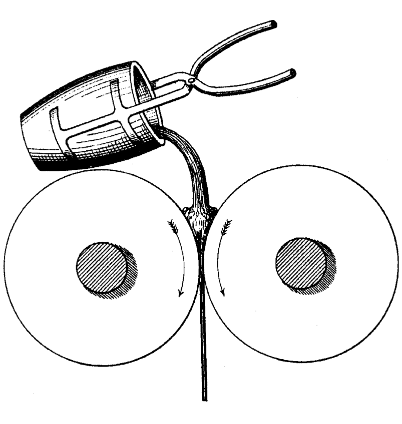


1 Bottom blown Bessemer converter for pneumatic conversion of pig iron

His second endearing character trait was his persistency, stubbornness, determination, obstinacy, doggedness and unrelentingness. Indeed, his ideas were always hitting at the core of the problem and therefore were deeply disruptive and perturbing. More often than not, they evoked rejection from entrenched vested interests, for example among the Sheffield steel producers, and Sir Henry knew exactly how to fight them, there again with a wide variety of strategies. This kind of difficulties facing innovators has not changed very much today either and the solutions to overcome them are the same as the ones he used.

A third interesting feature in Bessemer's life was his openness to the world and his many and frequent trips to the Continent. His father having lived in France until the middle of the French Revolution and being a member of the *Académie des Sciences* was probably formative in this respect. It is interesting to read in his autobiography that a conversation with the Emperor Napoleon was instrumental in his formulation of the need to produce steel having sufficient strength to make the guns required to shoot his new projectiles. His contacts with Sweden played a decisive role in his solving the initial problems met while producing steel in the converter, by providing him with low sulphur, low phosphorus, manganese bearing raw material that would avoid the hot shortness and the rimming of his steel. His trips were intended to give him access to solutions that were not available in England. He had understood that borders were there to protect him but not to keep him enclosed. This is a modern trait, although natural leaders throughout history have practised travel on a large scale, from Marco Polo to Christopher Columbus and the Roman politicians to the Neolithic merchants that brought tin to the Mediterranean world.



2 Bessemer's original continuous casting equipment using chilled rods

Bessemer's method for solving problems was deeply rooted in empiricism: he proceeded by trial and error and reasoned often by analogy. It is legitimate today to wonder if science could have helped him move faster towards solving the problems he met when trying to develop his steelmaking technology. It is true that Lavoisier had already formulated modern chemistry and that Réaumur had applied this to the metallurgy of steels. However, the relationship between science and technology at that time was not at all what it has become today. The value of science in solving technological problems was not obvious to most, nor were the findings of science acknowledged universally. Technologists or engineers were making their move first and science was coming along later on, rather than the contrary. This is not necessarily untrue today either …

Probably Bessemer's most brilliant trait was his ability to anticipate what was to become the norm by a few months, a few years – or a century. Had he not been there, the needs of society that he captured would probably have been met by someone else, but probably not quite as fast: this is the externalist viewpoint in history. Kelly in the USA might have become the inventor of the converter, or the open hearth process (OHP) of the Martin brothers would have brought the first practical answer to the need for mass production of steel – their process was indeed invented only five years after the converter.[6] What is also worth noting is that the OHP, not Bessemer's converter, rapidly became the main steelmaking technology: the conversion process took precedence over all other processes only in the second half of the twentieth century, after oxygen steelmaking was introduced. Bessemer was therefore not only a successful inventor but also a very long term precursor.

Bessemer's contribution to history should probably be analysed by an historian along the lines pioneered by Bruno Latour,[7] who analysed the work and life of the iconic French scientist Louis Pasteur, who is credited with discovering 'microbes'. For Latour, Pasteur's merits lie more in his 'selling' the concept of germs to the society of the late nineteenth century and doing it with a true sense of marketing science, rather than in demonstrating that spontaneous generation did not exist. I suspect that one could argue similarly that Bessemer sold the idea of steel to a society that needed it but was not yet fully aware of it: this goes beyond simple engineering innovation.

Fascinating also was his ability to mix an active engineering practice with that of a successful businessman and manager, probably without prioritising between the two faces of his activity. Can we find analogues of Bessemer in the nineteenth or twentieth century? The Martin brothers or Héroult, the inventor of both the aluminium electrolysis cell and of the electric arc furnace, might qualify. In the steel industry today, however, the practices of engineers and managers are too far apart for anyone like Bessemer to exist. In younger sectors like information technology, where great progress can still be accomplished over a short period of time, someone like Steve Jobs could perhaps be compared to Bessemer.

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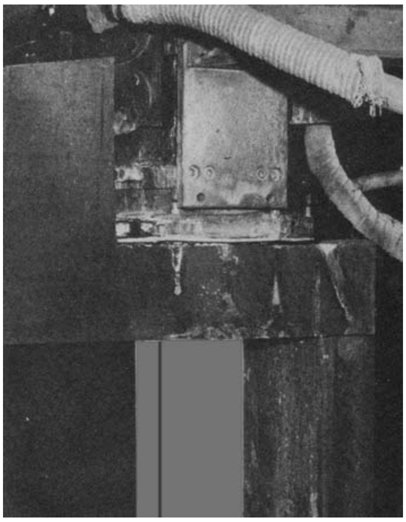
Our century, the twentieth

Let us jump in time now to 1970. The production of steel has grown by a factor of 1100 since a century ago, an extraordinary figure. Young engineering graduates still consider it an attractive proposition to join the steel industry, at a time when the strength of a nation is still measured by its consumption of steel per capita. Personally, I move from Berkeley, California to Metz, France and join IRSID in 1971.

The icons of steel technology are in Monroeville, Bethlehem, Sheffield, Lièges and Saint Germain-en-Laye, although Japan has already grasped leadership in this area, but nobody in the West is aware of it yet.

Some 150 years after Réaumur, physical chemistry has proved useful in sorting out ironmaking and steelmaking problems and large research centres are given leeway to mix science and technology and to innovate in all directions. The relationship between the two disciplines is still complex, though, since much innovation still stems from non-researchers, with obvious success if one considers the development of the LD process or the initial take-off of continuous casting, and researchers themselves are – already – watched very careful to monitor their degree of success.

The first metallurgical adventure I personally discovered, on joining IRSID, was continuous steelmaking (CS). Large scale experiments of the IRSID version of the concept were being run with great technical success in Hagondange on a pilot plant producing 30 t h^{-1} of steel that was run for 3 months.[8] Everyone was buoyant with expectations and full of the certainty that this was the modern equivalent of Bessemer's converter process. It took a while to realise that no such thing had happened and that technical success was not an automatic ticket to industrial and commercial implementation. Much later, the reasons of this un-success surfaced: the step forward was probably not large enough to warrant investing in the technology, especially at a time when oxygen steelmaking was becoming the mainstream technology and had already accomplished a quantum leap; moreover, CS was coming of age at about the time when the first energy crisis hit the West and brought the post-war high growth period to an abrupt stop. The timing for another innovation was not right.



3 Early electromagnetic stirrer

Continuous casting (CC) was still a minority technology: 23% of steel production in France in 1970, for example. But its potential was huge and this was starting to be understood by the visionaries, who built the first new steel mills based solely on this technology, Oita Works in Japan and Dunkerque in France. Interesting pilot plants were being debugged in Dillingen to make slab casting possible, a breakthrough from the standard technology, which was focused on high end billet and bloom casting for engineering steels.

One challenge for CC was quality in its broadest and most imprecise sense. Electromagnetic stirring (EMS),[9,10] which was a rather simple technology that 'just' needed to be put around a strand, was developed at IRSID and in Japan after the initial seminal ideas had been tested in Austria (Fig. 3). I enjoyed the brisk pace of the research work, which moved quickly from strand to in-mould stirring, from billet to slab casting, and explored rotary as well as linear stirring. Such diverse issues as surface quality, surface cracking and centreline segregation were touched upon and often improved, at a low cost. The format of a research centre like IRSID was well fitted to this type of development, both groundbreaking and modest, especially since skills from the electrical engineering community were incorporated into the project from the start. Today, among the roughly 6000 CC strands, 25% are equipped with one or more EMS units and the activity sustains a small industrial sector, particularly at Rotelec-Danieli, the offspring of the CEM laboratory which designed the first stirrer for IRSID in 1970.

Much work was done on the process engineering of continuous casting in the group I headed then, and even more elsewhere. These groups were the laboratories where science and technology were getting together to the point where the distinction between the two approaches was not easy to make. Both were running at the same pace to provide solutions to the problems that were being continuously raised, at a time when CC jumped to almost 100% of steel production. Research was closely associated with the growth of a technology, which provided pleasure to the researchers and money to fund their 'games'. There were also some incestuous forays into the twin approaches of process and product research, as we played at decreasing the level of deoxidation of liquid steel, to learn how to cast semi-killed steels and, once on the IRSID pilot CC simulator, fully rimming steel.

Not everything we tried at IRSID, was successful though. I spent some time working on a horizontal continuous casting (HCC) process, which we ran as a small pilot unit, from the mould of which a billet was eagerly coming out. The work was stopped abruptly when we put in a request to fund a larger pilot plant and I remember thinking of quitting the business then. The reason given by our top management was that pilot plants were no longer a good idea, after the demise of the CS dream: let specialised businesses develop these kinds of new process technologies! With hindsight, we know that the process was developed fully in Britain, Germany and Japan, but has remained extremely confidential, probably for the same reasons that CS did not fly either: the advantages of HCC over current technology were small relative to the risks of embarking into something so new.

My next real big adventure related to strip casting (SCC), which brings us back to Bessemer. The idea was latent in the minds of research people, eager to progress something new and sufficiently groundbreaking to avoid the pitfall into which CS or HCC had disappeared. Steel mills had grown very large, at least the integrated mills that were the norm then, and solutions were sought to shorten the production route and thus reduce both investment and operating cost. The needs of the production plants were not clearly expressed at the start, though, and equipment manufacturers were not yet

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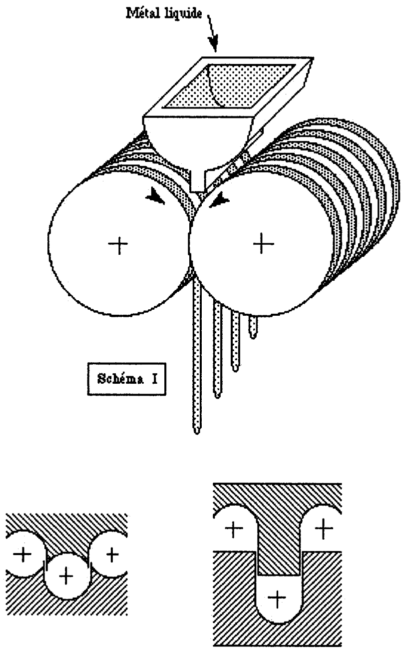
4 Pilot strip casting plant



6 Continuous wire casting process

in the game or had tried it and quickly moved out! But what a challenge to produce something that would compete directly with product from the hot strip mill!

We started working seriously on the concept at IRSID in 1982, in great secret. Within two years, it was obvious that many other groups had started to work on the same idea just as secretly at about the same time! Computer simulation was becoming popular and we could identify a design for the process fast enough, along with a long list of what we knew we did not know. The need to experiment was obvious but we had to get support from our own constituency before investing in any pilot line (Fig. 4). We had to 'invent' (or re-invent) the art of transforming a researcher's expensive dream into a funded research project, fully formulated, as is all R&D work carried out today – but not then! The difference with Bessemer's time was that we were involved in a large and fuzzy organization, not yet compacted into a big corporation such as Arcelor, and the money had to be identified in this nebula and continuing support generated for at least a few years. We obviously did not understood then that the time required for commercial implementation would be more than 20 years! But a couple of industry wide seminars generated the required interest and Ugine, the stainless steel component of the French steel industry, became our project sponsor and focused the work on clear technical targets related to their part of the steel business.

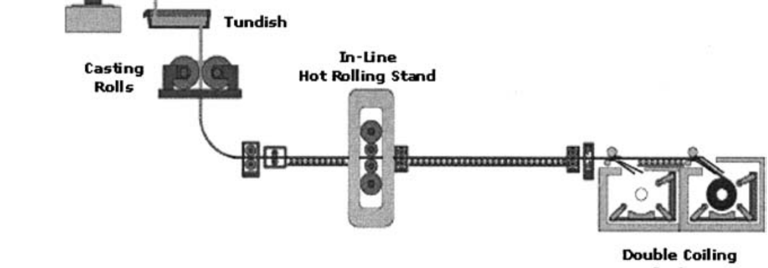
The lessons from that time are that empiricism was the key to success, since a trial and error approach based on intuition, sharp analysis of failures and computer simulation, was the only way to move forward. Modelling cannot (could not?) solve very complex problems *a priori*, but it is very useful in the next step, when solutions have to be optimised.

The first thing we understood, at a rather high price in terms of personal energy and anguish, was that a computer informed by several sensors was needed to run the pilot: the balance between mould level and casting speed was so delicate that no operator could be expected to discover the right settings empirically: we know, because we tried for almost a whole year without success. This is probably why Bessemer was a precursor and could not then have succeeded in making the process work for any length of time. The second 'secret' was that the surface of the casting rolls had to be textured to avoid cracking of the strip skin.

Of course, other issues related to the technological episteme of the twentieth century, which Bessemer would not have had at his disposal, were also essential: materials for the rolls and the side dams, sophisticated cooling technology to adsorb the gigantic heat flux from the mould, mechanical devices for holding the side dams and keeping them tight to the liquid steel, feeding designs for the liquid steel into the mould and prevention of pollution of the large meniscus by the atmosphere – to mention just a few.

Today, more than 20 years after the initiation of the research work on SCC, several large semi-commercial pilot units exist in Krefeld (Fig. 5), Terni, Hikari, Crawfordsville and Pohang. All seem to have solved the main technical problems related to casting the strip. When they will tip over into fully commercial use is, however, still a matter of conjecture.

To come back to the chapter of un-successes, I resented not being able to marshal enough support to develop a wire CC process on the basis of corrugated twin rolls, even though we could demonstrate feasibility with tin and small amounts of steel (Fig. 6).



5 Layout of semi-commercial pilot strip casting unit

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Again, the gains in terms of operating costs did not seem enough compared with the risk and cost of developing such a concept. Or were we not pugnacious enough to gain the support that we needed?

But there is life outside SCC, including for myself. I was relieved to move to something else, less groundbreaking but wider in scope: recycling and, more generally, environmental and sustainability issues. It has indeed been interesting to fathom how far the kind of process R&D the steel industry was used to doing for its core business could benefit this field. The Cycle of Iron project[11] brought forth a number of ideas which today are widely accepted, all the more so as it was run in parallel with similar projects in Europe (Scrap Megaproject[12]) and in Japan (Shinseiko[13]). Scrap has been accepted as a raw material on an equal footing with iron ore, especially as far as its definition in terms of quality is concerned. It has the potential to be used for making high end steel products, long and flat. And steel is commonly acknowledged as being sustainably recyclable and recycled.

Moreover, the potential of recycling to solve present and future problems has been widely recognised. Two figures can exemplify this. At the present level of recycling (roughly 80%), 1 t of steel from virgin iron will generate 5 t of steel, which is a peculiar benefit due to the fact that steel is indefinitely recyclable – contrary to most of its competing materials. If we look at Greenhouse gas (GHG) emissions, assuming roughly that the blast furnace generates 2 t of CO_2 per tonne of steel, then 1 t of virgin steel will eventually create a credit of 6 t of CO_2 due to its recycling: calculating this figure is somewhat of a mind twister and does not quite conform with the accept methodology for estimating GHG emissions, but it shows exemplarily the potential of recycling for steel or for any other material.[14]

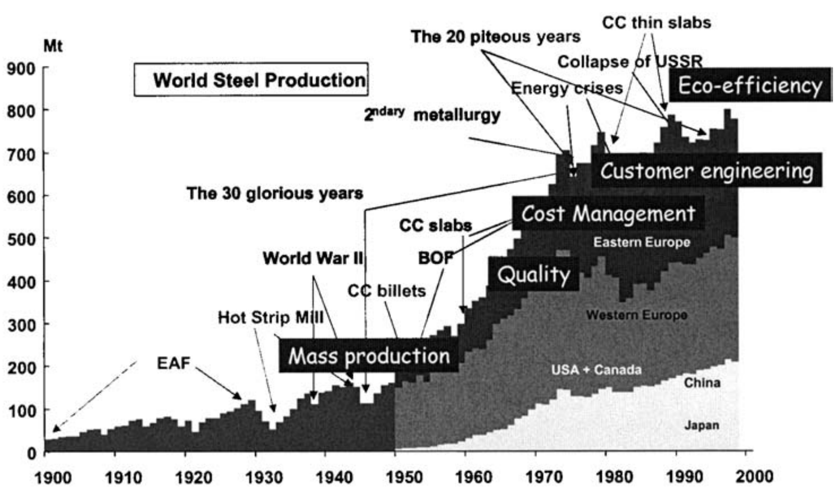
Another interesting idea that surfaced in these studies, where life cycle methodologies such as LCI, LCA and LCC are used to a large extent, is that the most practical way to collect the environmental benefits of weight reduction on consumer vehicles is by reducing weight with steels, high strength steels for example, rather than with lower density, higher energy intensive materials.[15]

Our other century, the twenty-first

There is a large pool of innovations awaiting the chance to emerge in the steel industry on the supply side of technology. A few examples:

- powerpack supplies for high speed trains have been developed, which have the potential to power an electric arc furnace (EAF), with an expected increase in efficiency in the use of both active and reactive power from the electrical grid, and, ultimately, probably tap-to-tap times and vessel size of the same order as is common in oxygen steelshops. A European project called SAFES (Smart Arc Furnace Electrical Supply) has been proposed to the 6th Framework Programme on this theme[16]
- more generally, the EAF still has great potential to change technologically, for example by becoming even more airtight[17] and thus improving its energy efficiency further
- an interesting analytical tool is now routinely used by the cement industry to monitor the composition of the feed to the cement kiln continuously and online, based on the principle of neutron interrogation.[18] This is potentially the tool that the steel and the scrap industry have been looking for to measure the composition of scrap before it is used and melted
- potential technologies related to continuous casting, which are being explored in various RTD programmes: meniscus-free casting and electromagnetic casting, for example
- information technology is becoming integrated in the very fabric of the steel mill by linking sensors, operation control computers, product stream management, quality online assessment and, eventually, global production management and scheduling. In this area, Arcelor is using and further developing a system called product line management (PLM),[19] which is an interesting example of this promising holistic approach.

On the demand side for technology, there is also much to say. The economic and business drivers for development of the steel industry in the late twentieth century were mass production, the drive for quality, cost management, product development and customer engineering (Fig. 7). Technology has been able to respond with solutions that have proven robust and capable of changing to accommodate this evolution of needs. Two parallel worlds, business and technology, could and did develop in parallel, one changing slightly to respond to the other's requirements and vice versa. It is interesting to note that some of the technological concepts exhibiting this robustness can be traced back to Bessemer: the converter with fast cycle times and therefore high productivity, continuous production and continuous casting, for example. This is both a demonstration of the brilliance of Sir Henry and of the fact that we are lucky that robust technologies exist – or that the complexity of our times can rely on a limited set of simple technologies that are enduringly at our disposal. This also explains why the technology of the steel industry is a cumulative technology.[20]



7 Evolution of steel production and drivers for change in the steel industry during the twentieth century

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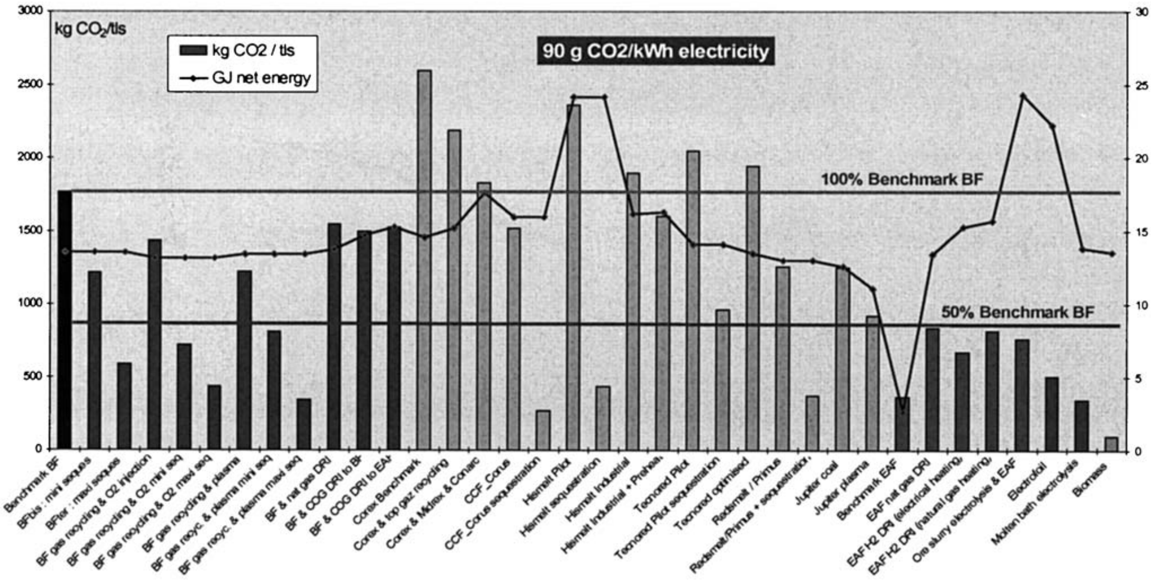

8 Comparison of CO_2 emission and energy consumption of reduction and steelmaking routes

We have stressed the continuity of technological development, but there are clearly limits and discontinuities are necessary every so often. The giant integrated steel mills invented in the late twentieth century are clearly a discontinuity with respect with the small mills that preceded them. The discontinuity is in the global steel mill concept, rather than in the step-by-step technologies that are put together smoothly in such a plant. Similarly, continuous casting is a breakthrough, even though its grammar of elementary technological concepts can in some cases be traced back to Bessemer.

What will be the next driver for change in the steel industry and the next discontinuities?

My guess is that the environment is the next driver. It has actually been in play for decades, but has remained in the background as a business driver, hidden behind the rhetoric of value, for the shareholder and for the customer. Environment friendliness is value for society, nature, the earth, etc. – and, therefore, the popular word 'sustainability' probably conveys its most important connotations.

Probably again, global environmental issues, the foremost of which is global warming, will usher in the need for deep changes in the future. In the post-Kyoto world, reductions in GHG emissions of much more than 50% will probably become mandatory, because of regulations or simply of business ethics. This will require deep changes in habits, from individuals and businesses, to a degree that one can only imagine with difficulty today.

The steel industry, being based on a cumulative technology, cannot change its level of emissions overnight, especially since it has become very resource-lean. Engineering the changes at the level that is likely to be required will take much time, creativity – and money (Fig. 8).

What will be needed are deep paradigm changes in the core technologies that steel mills are based on. The only certainty is that these new mills will continue to produce steel, as there is no other basic material that is likely to demonstrate a similar potential to ensure the wellbeing of a large portion of the world's population during the present century. Moreover, if one projects the expected world population increase in terms of modest steel production increases, i.e. with a lower per capita steel consumption than in developed countries today, then the overall production of steel will probably increase dramatically. I thus have made a projection of 3000 Mt/year by 2100.[14] This is more than unknown territory, but the reason for giving a figure is to show that a business as usual scenario is unlikely. What is just as certain is that this future steel will be as different from today's steel as today's steel is from Bessemer's. Steel is a robust and enduring word, because the level of complexity embedded in metallurgy and material science, being multi-parametric and combinational, has something in common with that of biology. If steel were invented today, it would most certainly be called a nanotech material.

Several programmes have been launched to search for these future technologies for steel production; IISI is running a coordinating program.

In Europe the program is ULCOS (Ultra Low CO_2 Steelmaking). Among the paths under investigation are:

- carbon based reduction of iron ore, with full exhaustion of the reducing power of carbon by removing and later sequestering CO_2, and recycling of the top gas
- utilisation of short cycle-time carbon, i.e. of plant biomass
- utilisation of carbon-lean energy and carbon-lean reducing agents, with electricity or hydrogen as vectors
- greater use of natural gas in more innovative ways
- combinations of the above.

Of course, recycling is also part of the solution.

The steel mill emerging from such programmes will both show deep changes with respect to the steel industry that we know today and much continuity with today's and yesterday's practice. Among the probable invariants: the need to produce liquid metal in the intermediate process, the conversion process based on pure oxygen, continuous casting – most probably near-net shape, continuous processes.

Conclusions?

The world that lies ahead will probably turn out to be as foreign as Bessemer's world would look to us. But we are lucky to be walking along the timeline with the help of the robust concepts

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that visionaries like Bessemer have endowed us with.

What may be comforting is that both iron, our favourite basic material, and hydrogen, an interesting fuel and reducing agents, are the most common elements on earth and in the universe respectively.

Of course, digging for the superconducting, hexagonal iron that forms the core of our planet is still clearly a science fiction programme as is the collection of interstellar hydrogen using material or immaterial sails … But that leaves some leeway for imagining even more alien and disruptive steel technologies!

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