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The ‘Industrial Enlightenment’ and technological paradigms of the modern steel industry

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ABSTRACT

Scientific knowledge is crucial to opening up new possibilities for major technological advances. When did science become important for economic development? The steam engine was the earliest major science-based invention. Conversely, the role of science has not been regarded as important in the innovations leading to modern steelmaking. In addition, how did science begin to play an important role? Mokyr focuses on the ‘Industrial Enlightenment’, which has its origins in the Baconian program of the seventeenth century. However, the role of science is often not regarded as important in the emergence of modern steelmaking technology. This paper examines the process through which modern steelmaking emerged and clarifies the role of science and ‘Industrial Enlightenment’. This discussion is also important in determining how to view the role of science in economic development and in considering ‘the Great Divergence’ and ‘the Great Knowledge Transcendence’. In addition, the examination of this paper will show how to create radical innovations that are completely different from existing paradigms, and how to create new technological paradigms to overcome difficulties such as the recent Covid-19 pandemic and environmental problems. When much time elapses between scientific and technological advances, the role of science is often not regarded as important and sensational innovations such as the Bessemer process are emphasized. However, this is not a proper evaluation. The role of ‘Industrial Enlightenment’ on the supply side must also be recognized as significant in the emergence of modern steelmaking technology.

1. Introduction

Science’s influence on economic development has long been discussed (e.g. Ref. [20,31,35,37,56,60]). [19] points out that scientific knowledge is crucial to opening up new possibilities for major technological advances, and that in the 20th century the emergence of major new technological paradigms has often been directly dependent on, and associated with, major scientific breakthroughs. ‘It is nowadays apparent that the development of science provides much of the basis for future industrial development. These connections, however, have been present from the creation of science as an organized activity in the 17th century’ ([21]; p.117).

When did science become important for economic development? According to Ref. [31] (p.10), the steam engine was the earliest major science-based invention. It dominated much of the first century of modern economic growth. As [16] states, ‘an important step leading to the invention of the steam-engine was the discovery of the pressure of the atmosphere …. The discovery suggested the possibility of using …’. The discovery suggested the possibility of using ….

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atmospheric pressure to do work on a piston beneath which a vacuum could be created ... [and this] culminated in the invention of the steam-engine’ (pp. 168–170). Cardwell also observes that, ‘combining the expansive properties of steam with the recently discovered pressure of the atmosphere’ (12); p.56] made the steam engine feasible. [32] also describe its emergence and insist that ‘clearly, science played an important role in the development of the steam engine’ (p. 253). (See also [66] on steam (heat) engines.) Conversely, the role of science has not been regarded as important in the innovations leading to modern steelmaking, including the development of Bessemer’s converter, Siemens’s open hearth and Thomas’s basic lining. For example, [57] insists that ‘[t]he innovations which marked the discontinuous stages of growth of the iron and steel industry – the introduction of the blast furnace and finery, of puddling, and of the Bessemer and open-hearth steel-making processes – all owed almost nothing to the direct influence of science’ (p.363). [39] agree, saying that ‘Bessemer had developed his process without the benefit of any training in the chemistry of his day. Neither he nor his contemporaries had a very precise idea of the chemical transformations that occurred inside the converter ... None of the three great technological innovations in ferrous metallurgy in the second half of the nineteenth century ... drew on anything but elementary chemical knowledge that had already been available for a long time. Indeed, only Siemens had had the benefit of a university education’ (pp.28–31). In the same vein, [8] states the following: ‘In considering these three contributions to the nineteenth-century revolution in metallurgy, the first striking point is their independence of any organized scientific movement. Of the three inventors only Siemens had a university education, and none of them received any material assistance or more than a little advice from academic, scientific or governmental sources’ (p. 109). [26] even insists that ‘[t]he real scientific breakthrough of Monge, Vandermonde and Berthollet in 1786 may itself have been a misleading incentive to make industrial progress depend on more scientific investigation, for it had no useful technological spin-off’ (pp.219–220).

How did science begin to play an important role? [36,37] focuses on the ‘Industrial Enlightenment’, which has its origins in the Baconian program of the seventeenth century. [22] state that ‘[t]he Industrial Enlightenment, we contend, cannot account for technological change in the steel trades. There is little evidence that the circulation and codification of “useful knowledge” among artisans (a key feature in Mokyr’s formulation) had a discernible effect on the ways in which steel goods were made ... The nature of demand, in other words, was the key determinant, not the cognitive conditions of supply ... In this sense, there was an enlightenment in steel, but it manifested itself in the design and marketing of goods rather than their manufacture’ (p.534). Furthermore, [1] insists that ‘metals were striking for the absence of much connection to the Enlightenment’ (p.250).

On the contrary, [34,35,37,38] emphasizes the importance of scientific knowledge on the invention of the Bessemer process, and insists ‘the growth of the epistemic base in the preceding half-century was pivotal to the development of the process’ (2002: p.86). However, although he focuses on some of the key factors, he has does not analyse the relationships between science and technology in detail.

This paper examines the process through which modern steelmaking emerged and clarifies the role of science and ‘Industrial Enlightenment’. This discussion is also important in determining how to view the role of science in economic development and in considering ‘the Great Divergence’ [48] and ‘the Great Knowledge Transcendence’ [30]. In addition, the examination of this paper will show how to create radical innovations that are completely different from existing paradigms, and how to create new technological paradigms to overcome difficulties such as the recent Covid-19 pandemic and environmental problems. In the process of emergence of these new paradigms, new combinations of scientific and technology, and the ‘fields’ that create such new connections play a very significant role.2 The composition of this paper is as follows. Section 2 examines the history of steelmaking, focusing on advances in science and technology. Section 3 highlights some steelmaking issues and examines the role of science and ‘Industrial Enlightenment’. Finally, Section 4 concludes the article and raises some theoretical and strategic implications.

2. Relationship between the science and technology of steelmaking

It is said that the production of iron began in western Asia. After that, the technology diffused to other regions and steel production became widespread. Although the origin of steelmaking is ambiguous, steel was probably produced by the bloomery process by 1200 B.C. and carburizing and quenching were practiced in the Near East by 800 B.C. ([6] (p. 13). [5] (p.43 and 142) states that in China, carburizing began in the late Western Zhou era (about 8th century B.C.) and de-carburizing began in the early Warring States era (about 4th century B.C.). Although it is still not known when Indian wootz steel was developed, it is said to be at least a few centuries before the 3rd century A.D. ([23]; p. 49).

Although there are various views on steel’s technological diffusion between Asia and Europe (e.g. Ref. [43,69], natural steels were made in the Weald by fining cast iron in 1509, and the cementation process was recorded in Nuremberg in 1601 and patented in England in 1613 ([6]; p. 13). René Réaumur tried to introduce carburizing to France and used tensile tests and microscopy to analyse the process. Although he used the term ‘sulphur and salt’ instead of ‘carbon’, he clarified how wrought iron, steel and cast iron differ and clarified carburizing methods [51]. Because the quality of steel made by carburization was not stable, Benjamin Huntsman, who was a clockmaker, developed a crucible process to stabilize its quality by smelting carburizing steel in about 1735.

While these steels were also produced in India, Torbern Olof Bergman in Sweden was interested in Indian wootz. Referring to Réaumur’s studies, Bergman used wet chemical analysis with acid and balances for quantitative analysis and was able to extract the source of the differences among wrought iron, steel and cast iron [7], although he based his work on phlegiston theory.3 Carl Wilhelm Scheele in Sweden, who studied with Bergman, discovered oxygen using wet chemical analysis. Joseph Priestley in England also found the same element independently. Antoine Lavoisier in France denied the theory of phlegiston and built the basis of modern chemistry on such studies about various elements. In these processes, the chemical analysis of steel and the development of modern chemistry were closely intertwined.4 Vandermonde, Berthollet and Monge, who studied with Lavoisier in the Parisian Science Academy, stated that ‘the theory of phlegiston is no longer tenable after the latest discoveries on the calcination of metals and on the decomposition and reconstitution of water’ ([68]; p. 307) and identified carbon as the most important element based on the modern chemistry of Lavoisier instead of the phlegiston theory.

Wootz, which had an effect on Bergman’s studies, also came to be of interest in England. Joseph Banks, the president of the Royal Society of London, ordered some cakes of Indian wootz and let James Stodart and George Pearson investigate them. Pearson identified manganese’s

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1 See also [24,33] and [63–66].
2 See also [11] for steel in the Muslim medieval world.
3 Réaumur also acquired and verified wootz ([51]; p. 176), and Heath (1839, pp. 391–393) also described in detail the manufacturing method (the crucible process) of wootz. [50] states the following: ‘Modern metallurgy and materials science rest on the foundation built by the study of this steel during the past three centuries’ (p.67).
4 Smith also insists that ‘[t]his knowledge arose out of and contributed to the Chemical Revolution in an intimate way’ ([58]; p. 150).
significant role in the production of wootz ‘as the fine experiments of Professor Gadolin, made under the direction of Bergman, have demonstrated’ ([45]; p.342). (Scheele and Johan Gottlieb Gahn, who studied with Bergman, discovered manganese in 1774). Pearson had been influenced by the scientific knowledge of Bergman and Berthollet, and Stodart was an ingenious artist [45]. In addition, Stodart was the first to measure the temperatures corresponding to colours associated with the tempering of steel ([59]; p.53). William Reynolds, who worked iron works with the Darby family, was a pupil of Dr. Joseph Black, Professor of Chemistry at the University of Edinburgh. He was, as were James Watt, Josiah Wedgewood, and James Keir, adept in both the laboratory and the workshop as [4] (p.16) states. He gained a patent for steelmaking using manganese in 1799. ‘This patent of Mr. Reynolds’ started a host of imitators, who all laid claim to improve iron for steel making, or to improve steel when made by alloying it with manganese’ ([10]; p.258).

Wootz further influenced scientists and technologists. David Mushet, who took out a patent for combining iron with carbon for steelmaking through a direct process in 1800,6 received cakes of wootz from Sir Joseph Banks and also showed that wootz involved a large amount of carbon [40]. D. Mushet had a profound knowledge of the works of French chemists of the Lavoisierian ‘oxidation’ school and of the works of mineralogists such as Bergman and Kirwan, as pointed out by Ref. [42] (p.185). He also published a paper about steel and manganese in 1816 [41]. Moreover, the above-mentioned Stodart studied wootz and alloys of steel with Michael Faraday of the Royal Institution of London [61,62].

Josiah Marshall Heath, who served in the East India Company, imported a considerable quantity of wootz and had it assayed by D. Mushet. Heath, being affected by the experiments of Faraday and Stodart, got a patent for steelmaking using manganese 1839.8 [27] states the following about D. Mushet: ‘That iron could be converted into cast-steel by fusing it in a close vessel in contact with carbon, was a discovery made by Mr. D. Mushet about the year 1800. This was undoubtedly the original idea of a man of talent, following the light thrown on the theory of steel-making by the discoveries of modern chemistry’ (p.396). As [14] (p.352) insist, D. Mushet’s work led directly to Heath’s Process.

Bessemer made a presentation for a revolutionary steelmaking method in 1856. In his process, molten cast iron changes to steel by only blasting air into it. Moreover, Robert Mushet, a son of D. Mushet, played a role in improving the Bessemer process using manganese (see also [44] for the personal relationship between the Mushet family and Heath). Although the Bessemer process was only applied to ores containing little phosphorus, Sidney Gilchrist Thomas invented a new process (the Thomas process) using basic lime instead of a study by Professor Louis Emmanuel Gruner. (In addition, Scheele, who is mentioned above, identified phosphorus as a factor causing cold-shortness in 1785). Thus, the Bessemer process came to be applied to a variety of ores and has been a mainstream process in steelmaking since the invention of the Linz-Donawitz (LD) process in 1951, although Siemens’s open-hearth process was also used in many countries.10

3. The influence of science and ‘Industrial Enlightenment’ on steelmaking

In the previous section, we considered the relationships between science and technology of steelmaking. In this section, we discuss some issues in modern chemistry and steelmaking technology, and deepen our understanding.

First, even if scientific and technological knowledge was not transcendent from 1790 to 1850, a variety of advances in knowledge were underway. D. Mushet advanced scientific and technological knowledge about steel and carbon. Pearson, Reynolds, Mushet and Heath published many papers and took out many patents related to steel and manganese, and greatly contributed to the evolution of steelmaking (see Section 2).

The important thing is how to understand the time lag between advances in scientific knowledge such as those clarified in Ref. [68] and advances in technological knowledge like the development of the Bessemer process (1856). Sometimes there is almost no lag between scientific discovery and technological application, while in other cases it takes a long time (decades or more) ([65]; p. 221). Even if scientific knowledge is potentially useful, it may not be possible to apply it as technology due to the lack of other technologies.11 In the case of steelmaking, the technology for achieving high temperatures and for making furnaces capable of working at these temperatures had become an obstacle, and the mechanism for financing such development had also been premature. Just because there is a long lag between advances in science and technology, we should not regard the science as unimportant.

Next, we revisit the insistence of [22] recounted in Section 1, but taking the science-to-technology time lag into consideration. Because no one was able to fully develop modern steelmaking technology right after the chemical revolution, it might seem that the demand for ‘enlightened practitioners’ such as physicians and anatomists influenced the incremental improvement of pre-modern steelmaking technology as Evans and Withey insist. However, if we allow for an indeterminate time lag, the ‘Industrial Enlightenment’ and science of Lavoisier, Stodart, Pearson, Banks and Mushet can be seen as having gradually contributed to modern steelmaking technology over an extended period of time. That is, the ‘Industrial Enlightenment’, on the supply side, played a significant role in modern steel industry. In this process, as discussed by Ref. [28]; the prevalence of ‘scientific culture’ in society had a significant impact.12

In addition, [1] put together a database of seventy-nine important inventors in the seventeenth and eighteenth centuries. Concentration on this time period reflects my view of technological development as a path-dependent process (pp. 242–243) and insisted that ‘[i]n the cases when ‘science and technology were separate spheres with little interaction’ (p. 251). Furthermore, he defined macro-inventions as follows: ‘Macro-inventions are characterized by a radical change in factor proportions’ (p. 151). However, it is important when considering the role of science and the ‘Industrial Enlightenment’ is not the important inventors that influenced radical changes in factor proportions, nor the path-dependent process of technological development (technological trajectory), but the relationship between science and technology in the process of emergence of the technology paradigm. Although Allen

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6 See Ref. [3, 46] (p.48) and [23].
7 See also [40] for the influences of Bergman and Reynolds on D. Mushet.
8 ‘With this view, he returned to England, and placed himself in the chemical school of Dr. E. Turner, of the University of London, one of the most accomplished professors of that day, here he was permitted to erect a furnace of his own, and assisted by Dr Ure and by the late David Mushett, the most distinguished of modern British authors and workers in this class of subjects, he became familiar with the most approved means of chemical analysis and manipulation’ ([70]; p.vii). See also [25] for further information about Heath.
9 Furthermore, [71] describes that ‘[p]ractical students of cementation and cast steel quickly learned that the carbide-forming qualities of manganese made it an ideal “regulator” in iron (however not in quantities to produce brittleness); and this knowledge was made the basis of important improvements in English cast-steel manufacture by William Reynolds and Josiah Heath’ (p.279).
10 See Ref. [49] for the rise and fall of each technology.
11 See also [66] on the time-lag from Huygens’ invention of the internal combustion engine to its commercialization in forms such as Newcomen’s engine.
12 [29] (p.63) insist that ‘The scientific revolution thus entered a distinctly new phase characterized by the public disputations of the eighteenth century Enlightenment’. In addition, [26] (p.113) emphasizes that ‘English science in the form of Newtonian mechanics directly fostered industrialization’. 
insisted that ‘elaboration [of the macro-inventions of the eighteenth century] drove the British economy forward through much of the nineteenth century’ (p. 243), it goes without saying that inventions such as the Bessemer process in the nineteenth century were not merely elaboration of the inventions in the eighteenth century.

According to Mowery and Rosenberg, ‘Bessemer had developed his process without the benefit of any training in the chemistry of his day’ (1989, pp.28–29). Bernal adds that he had not ‘received any material assistance or more than a little advice from academic, scientific or governmental sources’ (1953, p.109). However, it is not important whether he directly benefitted from a university education and academic sources. Whether he used the knowledge that had accumulated regarding steelmaking, however, is significant. From the text of a presentation Bessemer gave at the British Association for the Advancement of Science in 1856, it is clear that he benefitted from modern chemistry.13 [5] said the following:

‘On this new field of inquiry I set out with the assumption that crude iron contains about 5% of carbon; that carbon cannot exist at a white heat in the presence of oxygen without uniting therewith and producing combustion; that such combustion would proceed with a rapidity dependent on the amount of surface of carbon exposed; and, lastly, that the temperature which the metal would acquire would be also dependent on the rapidity with which the oxygen and carbon were made to combine, and consequently that it was only necessary to bring the oxygen and carbon together in such a manner that a vast surface should be exposed to their mutual action, in order to produce a temperature hitherto unattainable in our largest furnaces’.

Bessemer’s father was a member of the Parisian Royal Academy of Sciences, and Bessemer himself received advice from Andrew Ure, a fellow of the Royal Society of London and author of The Dictionary of Mining and Technology [10].14 As [54] says, Bessemer was well acquainted with chemical processes, for example through his reading of specialized literature.

Bessemer’s invention came about following a long accumulation of scientific and technological knowledge since the chemical revolution, rather than being triggered by scientific knowledge in a linear manner as in the Bush model depicted in Ref. [65]. [57] insisted that ‘[a]lthough Bessemer remarked in his 1856 paper that he built his first converter with a view of testing practically a theory involving the reaction of carbon and oxygen, from his autobiography it is clear that his work was precipitated simply because he happened to note an unmelted shell on a pig of iron that had been superficially oxidized’ (p.363). However, we need to pay attention to the ‘chain of science and technology’ rather than discussing whether science precedes technology or not.15 There was a chain of science and technology tying the endless endeavours of scientists and technologists to the completion of the Bessemer process. Thus, as the functions of elements such as oxygen, carbon, manganese and phosphorus were clarified based on Lavoisier’s modern chemistry, a new technological paradigm, the modern blasting process (the Bessemer process), was approaching completion. Although the announcement of the Bessemer process in 1856 received sensational attention, we should not regard the preceding chain of evolution in science and technology as unimportant. Furthermore, the accumulation of scientific and technological knowledge made the improvements by R. Mushet and Thomas Heath possible. Thus, in the analysis of the modern blasting process, we should emphasize the chained evolution of science and technology over a long time rather than one technologist, Bessemer.

4. Conclusions and implications16

Many of the advances in science and technology in the period from Lavoisier’s chemical revolution to Bessemer’s steelmaking revolution were described in Section 2. Section 3 touched on how our view of the role of science in the emergence of modern steelmaking technology can change depending on how a 70-year time lag between scientific discovery and technological development is regarded. It is more useful to frame the emergence of technological paradigms as a chained process of science and technology than to discuss whether science precedes technology or not. When much time elapses between scientific and technological advances, the role of science is often not regarded as important and sensational innovations such as the Bessemer process are emphasized. However, this is not a proper evaluation. The role of ‘Industrial Enlightenment’ on the supply side must also be recognized as significant in the emergence of modern steelmaking technology.

[31] stresses that the application of science to economic production is the main characteristic of modern economic growth. However, almost all theories of economic development, like that of [53], treat science as an exogenous factor. Nevertheless, a proper theory of economic development can be constructed by endogenising advances in science. The hierarchical evolution of a chain of scientific and technological knowledge generates economic development. This is evident in the development of steelmaking. Chained evolution is also observed in the cases of heat engines [66] and semiconductors [64].17

Another factor that should be recognized is that, organisations like the Parisian Science Academy and the Royal Society of London, which pursue both science and technology, played an important role in the emergence of modern steelmaking. This is similar to the case of heat engines and even semiconductors where Bell Laboratories played a significant role. Organisations that focus on technological development can be important in promoting advances along a technological trajectory. However, there can also be significant differences between the advances along a technological trajectory and changes in technological paradigms, irrespective of whether scientific knowledge or technological knowhow comes first. A field that straddles science and technology often plays a significant role in the emergence of technological paradigms.18

On the emergence of technological paradigms, demand plays a certain role, but the role of ‘Industrial Enlightenment’ and attitudes in trying to apply science to technology is significant (this is also applicable to recent cases, such as semiconductors).19 Factors such as these are the reason why technological leaders, such as China and India 500 years ago, could not develop modern steelmaking technologies.20

CRediT authorship contribution statement

Keiichiro Suenaga: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - original draft.

See also [65,66] about theoretical, political and strategical implications in this paper.

Needless to say, science’s degree of importance differs depending on the characteristics of the industry in question.

See also [21,47,55].

See also [67] regarding to the role of demand on the emergence of technological paradigms.

The discussions of [2,13,48] are interesting, but the discussion in this paper is similar to that of [35,36]. However, [35], emphasizes the reduction of the cost of access to knowledge as a result of the ICT revolution, while [64] analyses the chained evolution of science and technology as generating the ICT revolution as in this paper. In addition, [36] emphasizes the existence of ‘artificial skepticism’ as a factor that prevented China and India from developing modern steelmaking technology.

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13 [35] also insists that ‘Bessemer knew enough chemistry to realize that his process had succeeded and similar experiments by others had failed’ (p. 86).

14 See also footnote 9 of this paper for the relationship between Ure and Heath.

15 The term, ‘chain of science and technology’, is not just synonymous with ‘co-evolution’. Science and technology are not a unified evolutionary system, but a chain of their actions forms an evolutionary system. See also [65,72] for discussion.

16 See also [65,66] about theoretical, political and strategical implications in this paper.

17 Needless to say, science’s degree of importance differs depending on the characteristics of the industry in question.

18 See also [21,47,55].

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Declaration of competing interest

The author declares that I have no conflict of interest.

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