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The iron industry energy transition

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ABSTRACT

This article examines the energy transition in the iron industry and studies the consequence of this switch to coal-fueling technology upon forests: what happens to long-lived energy carriers when a new source of heat and power makes significant inroads into their own markets? What factors underpin the substitution of older raw materials by new ones? The major lesson to be drawn from the iron industry energy transition points to the fact that within the "transitional" time-frame one may expect either the effective substitution of the older energy carrier or incentives to its actual expansion.

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1. Introduction

In its broader sense, "energy transition" describes a structural change in the relationship between men and natural resources. It was mostly in the nineteenth century that mankind systematically began to tap into the legacy of carbon and carbon and hydrogen compounds accumulated beneath the earth over the course of 360 million years. Courtesy of the practice of drawing assets from this stored energy bank, developed nations were each year able to add fresh inputs to their renewable resources of muscular force, biomass, wind and water power. What is more, large scale usage of fossil fuels did not simply mean additional 'raw' inputs for productive activity but was historically associated with a far-reaching technological–economic shift characterized by a continued increase in the useful work (technically called exergy) extracted from each unit of input, a change in the composition of economic activities, a change in the distribution of population and enhanced flexibility in energy supplies.

Revealingly, the recent literature on the transition towards the fossil fuel age has proven that the usage of coal diffused across the world economy in a rather protracted and asynchronous process. Among leading nations, coal attained a 50% share of the overall energy balance by the middle of the eighteenth century in Britain (Warde, 2007; Fouquet, 2008, 2010), before the turn of the twentieth century in the United States (Grubler, 2004, 2003) and in the 1930s in Western Europe (Gales et al., 2007). On the other hand, according to Smil, "all of the world's major economies—the United States, Germany, France, Russia, Japan, China and India have followed the classical sequence from biofuels to coal" (Smil, 2010, p. 28). We know, furthermore, that Netherlands with its abundant peat and Portugal with its minor coal consumption levels constitute exceptions to the classical scheme of energy transition (Gales et al., 2007; Henriques, 2009). Much more is certainly to be learned from applied research in this area in the forthcoming years.

Another conclusion points to complex and often indirect causal relationship between coal's diffusion and adoption of the steam-engine. In fact, British mining extraction was driven by the growth in population and incomes, by the demand from coal-fueled blast furnaces and puddling ironworks, and by price decreases arising from improvements in transport (Church, 1986; Clark and Jacks, 2007). Only after steam engines witnessed breakthrough improvements with the incorporation of high-pressures and upgraded boilers supplemented by minor complementary improvements like the redesign of line-shafts in textile mills did coal consumption shoot up heightened by this general purpose technology (Hills, 1993, pp. 59–90 and 112–114; Report of the Commissioners, 1871). From a macro-economic perspective, the 1840s were a key turning point in the application of mechanical power to consumer goods industries and transportation (Fouquet, 2008). One may therefore conclude that, in Britain—the pioneering nation—the steam-engine benefited from preceding market dynamics rather than being the exclusive driver of demand for coal.

This article examines this energy transition in the forerunner sector of the iron and steel industry. Besides its major impacts on expanding coal markets across Europe and North America, the iron and steel manufacturers supplied the ultimate structural material of the industrial revolution and experienced a technological change which was independent, even though interconnected, of the technological improvements in steam engines (steam engines came to substitute water wheels for running blowing devices and blast engines). In other words, they were a self-sufficient stream of the nineteenth century energy transition

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and the most important quantitative stream in Britain (Report of the Commissioners, 1871).

The particular point herewith under examination is the consequence of this switch to coal-fueling technology in ironworks upon forests: what happens to long-lived energy carriers when a new source of heat and power makes significant inroads into their own market? What factors underpin the substitution of older raw materials by new ones? It is important to note that the resilience of traditional energy sources has large implications for the pace of energy transitions, which means that the advance of coal is to some extent dependent upon the competitive edge attained by wood.

The first author that provided a theoretical framework for the analysis of the fossil fuel transition was the British economist William Stanley Jevons in his much acclaimed book "The Coal Question" (1865). Jevons believed that coal-based technologies would soon wipe out and actually replace the traditional non-fuel-intensive sectors of windmills, animal and water power, making Britain, ever more dependent on coal reserves. This phenomenon was described as an indirect "rebound" effect. Rebound, because the continuous improvement of steam engines prompted macro-economic savings in coal and a reduction in the price of useful energy, with this very same mechanism also generating the side effect of compelling non-steam producers to switch to coal. What was momentarily saved via gains in macro-efficiency was later offset by shifts in the composition of production. In the end, more coal would always be needed and dangerously hastening the pace of mining extraction and threatening the conservation of British underground reserves (Jevons, 1866). Implicit to this analysis is the idea of a relentless pace of techno-economic obsolescence forcing traditional energy carriers into marginal market niches as they cannot withstand the price competition from the useful energy delivered by "king coal".

Some decades later, this interpretation appeared, at most, an incomplete and benign account of the process of technical and economic change. For the Austrian-American economist Joseph Schumpeter, the consequences of innovation went far beyond the narrow mechanisms of relative price changes. Aware of the role ascribed to multifunctional and multinational enterprises in modern capitalism, Schumpeter extolled the new type of competition that was looming everywhere: "the competition from the new commodity, the new technology, the new source of supply, the new type of organization (the largest-scale unit of control for instance)—competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundations and their very lives" (Schumpeter, 1975, p. 85). To an ever increasing extent, entrepreneurship and innovation were creating dynamic imbalances in the course of capitalist development, from which resulted the creative destruction of the old economy and not just its substitution. Inasmuch as technical change was broadly defined as a cluster of quality improvements on a given array of products, bearing the dimension of a "vertical innovation" process, its repercussions could only be devastating. Whilst Jevons had envisaged a retreat of traditional producers into market niches, Schumpeter foreclosed on any possibility other than their almost immediate obsolescence and extinction. Industrial mutation unleashed a selective evolution in which uncompetitive economic actors were condemned (see Grossman and Helpman, 1991). Also of significance is the fact that the cases the Austrian economist held in mind as glaring examples of creative destruction were all related to the history of coal-steam technologies, specifically the disappearance of iron and steel charcoal, of water-well motive power, mail coaches and horse-drawn carriages (Schumpeter, 1975, p. 84).

Even though Schumpeter's agenda sparked fruitful research on innovation, some empirical studies have nonetheless called into question his core assumptions. In a 1976 book, Nathan Rosenberg, found evidence of vigorous and imaginative responses from older industries whenever their profits margins were threatened by competition from replacement technologies (Rosenberg, 1976, pp. 205–206). Other authors have also noted this same pattern of "fight back" in economic activities as diverse as sailing ships, typesetters, ice harvesting and carburetors. Building on these sectorial histories, they proposed the concept of a "last gasp" or "fight back" to describe the process of "extraordinary efficiency growth in threatened technologies" taking place just before they enter into abrupt decline (Snow, 2003; Snow and Ron Adner 2010; Tripsas, 1997, 2001). Furthermore, they have suggested causal mechanisms by which the benefits from innovations might be captured by industries supposedly due for replacement: to begin with, components from entrant technologies might "spill over" to incumbent technologies, and improve the incumbent; a second likely possibility is that the market split between entrant and incumbent spurs the application of each technology in the applications to which they were best suited thus increasing efficiency by dint of specialization. Ultimately, these complex and mutual reinforcing dynamics between old and new industries would prompt clear-cut market segmentation.

Drawing on the "last gasp" perspective, Alwyn Young envisioned a formal model for situations in which production is undertaken in stage by stage cycles, such as the iron and steel industries. In his model, the traditional producers are beset by a shift in producer demand towards new inputs and away from the old ones. However, this tendency is largely offset by the gains accrued with new applications that come to the fore for the existing inputs (Young, 1993). Innovation is viewed as pushing through an overhaul in demand from which both traditional producers and ground-breaking entrepreneurs have much to benefit. This means that the Schumpeterian destructive effect is matched by a creative or complementarity effect that extends the market for "obsolete" technologies ("new applications for existing inputs") deferring their "last gasp". However hard the competition, however hard the cutbacks in costs, there are further incentives for survival.

At first sight, we have a full palette of theoretical explanations to assess the substitution of wood-fueling by coal-fueling technologies. Within this framework, one may expect a shorter time-span in the energy switch when the destructive forces prevail, either through demand side mechanisms (Jevons's enhanced price competition) or through supply side mechanisms (Schumpeter's overall shift in business). Contrariwise, a longer time span should be expected whenever creative market incentives prevail through supply side mechanisms (The Snow–Tripsas pattern of technological imitation and specialization) or through demand side mechanisms (new markets for "obsolete" technologies, according to Young's view).

The ensuing pages sketch out the battle between these destructive and creative forces throughout the energy transition of the nineteenth century, testing the adequacy of the aforementioned theoretical models in the larger iron producing nations: Sweden, Britain, Belgium, France, Germany, the United States, Russia and Canada.

2. Charcoal and coke: an overview

The claim that coal represents a "higher quality energy form" than wood is grounded both on the capacity of solid fossil fuels to perform more useful work and on their larger contribution to the productivity of non-energy inputs. Basically, these two traits meant that coal has more chemical energy per unit of weight, and permits greater efficiencies in storage, transportation, maintenance and repair, economies of scale and ease of handling and usage. Whereas the first aspect stems from the physical properties of the raw material, all the others have involved some kind of purposeful human action throughout history. In truth, the very idea of civilizational progression from simple energy carriers towards more sophisticated ones, up what was termed the ‘‘energy ladder’’ (Hosier and Dowd, 1987), tends to reflect a long history of successful achievements in entrepreneurship and science. It is also useful to keep in mind that before the turnaround brought about by the British industrial revolution historical actors were utterly convinced that wood rather than coal was the superior fuel and especially so for feeding furnaces and forges.

This industrial wood was, in effect, charcoal, a secondary energy source. Charcoal was obtained from air drying green wood for a period lasting from one to four months after which the dry-wood is moved into a traditional hearth or pitsead in the form of dome-shaped stacks, generally located in the woods, where it is burned slowly and without oxygen for one to six weeks. When properly executed, wood drying removes as much as 15% to 30% of the wood’s original water with the remaining moisture being further reduced by means of the pyrolysis process (Svedelius, 1875, pp. 6–26 and 200–201). In the end, the chemical transformation underwent by wood yielded a carbon-rich material, physically very similar to coal and with a similar calorific power. This means that despite the simplicity and low cost of this rural-industrial transformation, pyrolysis in kilns returned a twofold increase in the thermal content of dry-wood (from 14.4–17.4 MJ/kg to 29.5 MJ/kg), raising the potential heat per unit of weight. However, since charcoal was an extremely bulky fuel whereas coke is much denser, the former required two and a half times the storage space normally reserved for fossil fuels (175 cubic feet by metric ton as against 69 cubic feet occupied by coke) and about one and a half times the furnace cubic space, consequently a loss in the energy contained per unit volume of space (Space occupied by fuel, 1882, pp. 160–161; Bell, 1884, p. 133). Moreover, the friability of charcoal capped the potential height of furnaces.

Equality of energy by weight, imbalance of energy by volume and the relative fragility of the billets made the vegetable fuel more difficult to handle, to transport and to process. However, this apparent inferiority was largely offset by the smoothness of operations and the good results in terms of the average final product quality. Charcoal furnaces, bloomeries and forges could easily control undesired chemical reactions, the contamination of heated metal with impurities from the fuel and the volume of gases. These were precisely the kind of problems that appeared technically insurmountable whenever coal was experimentally used. For these reasons, European ironworkers of the modern period tended to view wood’s ‘‘superiority’’ in terms of charcoal’s chemical purity, namely its low sulfur and phosphorus content and the high porosity of the carbon-rich material. Defined in this way, the iron quality became an attribute of craftsmanship as the better the raw-materials, the less the workforce effort required in processing it (for instance high-quality charcoal produced less slag and demanded less hammering). Ultimately, this vision lended itself to moral analogies. As a nineteenth century iron puddler put it: ‘‘Man’s nature is like iron, never born in a pure state but always mixed with elements that weaken it’’ (Davis, 1922, p. 31).

In terms of drawbacks, the intensive use of woodland resources constrained the scale of production, where not the sustainability, of charcoal manufacturers largely because it took at least 4–6 t of wood to produce 1 t of charcoal. Measured in energy units this implies that 60–90 MJ/kg of primary energy was needed to obtain a secondary raw-material which delivered 29.5 MJ/kg on entry into the furnaces or the forges. Under the pressure of wood shortages and compelling scientific approaches to and results from the pyrolysis process, European practices began to display some signs of convergence around best practice conversion ratios of 4 t of wood to 1 t of charcoal during the first decades of the nineteenth century (Svedelius, 1875; Hammersley, 1973; Benoit, 1990; Blanchard, 2005). Further improvements in energy saving in this preliminary productive stage afterwards came to a standstill revealing that the meiler and kiln technology had possibly reached its technological limits. The adoption of a new system of wood distillation in apparatuses with retorts in the second half of the nineteenth century, gave another new push to economic productivity and to the profitability of wood carbonization. With the diffusion of this technology, the conversion ratio dropped to 3.3 t of wood for 1 charcoal ton while by-products such as tar, wood alcohol, and turpentine began to be recovered and sold in markets (Forsythe, 1913, pp. 82–85). Throughout this evolution, the most significant strides towards wood saving practices were attained by producers in the Urals, in Russia, whose brick–earth system equipped with iron retorts was able to deliver yields of 2.7:1 in birch-charcoal output (Blanchard, 2005, pp. 134–136).

Fashioned by the well-to-do who could afford the smokeless heat of charcoal, domestic consumption of this vegetable fuel had shot up in European capitals by the early nineteenth century (Boissiere, 1990; Henriques, 2009, pp. 40–43). Aside from this domestic consumption located within major cities, charcoal fed the of malt-beer and iron production sectors in modern Europe, in the U.S. and in Canada. Within the iron industry, fuel consumption weighted approximately the same in the first cycle of the ‘‘trade’’, the making of pig iron from ores in blast furnaces, and in the second phase, the refining of the metal and its shaping into bars. This was achieved by reheating the pig iron in a finery so as to reduce the carbon content in the molten iron from 4% to around 0.05% and finally by forging and consolidating the throughput in a chafery (Tylecote, 1991, pp. 233–240). Once the iron was rendered malleable, it was accordingly sold to blacksmiths who transformed the bars into an array of final products—horseshoes, locks, nails, hinges, knives, scythes, and other agricultural implements. Here, charcoal was of lesser importance as the fabrication of hardware and tools could be performed with the aid of pit coal. In any case, each step in the production cycle added further fuel costs to the material produced. To single out the thermal efficiency attained in each respective productive phase of iron production, the ensuing pages present most data in terms of secondary energy consumption, that is, in terms of the calorific value of charcoal, regardless of the progress attained in the primary conversion of wood into charcoal. This methodology ensures a basis for comparison between nations and between periods of time.

Sweden with its bountiful forest areas and rich deposits of non-phosphoric ores emerged as the leading exporting nation in the seventeenth century, carving an unbeatable reputation for its combination of iron bar resistance, malleability and chemical purity. Ranked above any possible European competitor, Swedish oregrounds iron and Swedish iron set a quality standard difficult to attain, seizing premium prices for forging purposes and for steelmaking. So overwhelming was its reputation that the many technical experiments pursued at length by British ironmasters in the domain of coal-heating methods were not intended to directly challenge Swedish competition, nor even Russian imports, which grew in importance from the 1760s onwards. Rather, their best endeavors were directed towards making cheap iron for the supply of low-quality goods, in the interim securing the benefits of lower fuel costs and an abundant fuel supply (King, 2005; Evans et al., 2002).

Recurrently attempted, the adaptation of mineral fuel to iron-smelting was achieved in the context of substituting cast iron for the traditional brass and copper in the manufacture of small commodities, requiring the heating techniques deep-rooted in non-ferrous metallurgy be transposed to this metal (King, 2011). Abraham Darby, a former iron and brass manufacturer, who had already taken out a patent for an improved method of casting pots, succeeded where many others had failed thanks to the use of sand-castings to make small cast iron items. Coke pig iron was probably used for the first time to make cannon balls at Coalbrookdale in the West Midlands region of England, near the Severn River, in one of the years in the 1690s. It was certainly used to make pots and other cast iron goods as from 1709 (King, 2011). These pots and cannon balls were particularly brittle breaking when struck hard and weak in extension. However, cannon balls and pots were precisely the kind of goods that brushed aside the attributes of malleability and strength characteristic of charcoal wrought iron. In the wake of Abraham Darby's discovery, in 1709, coke smelting remained a minority pursuit. By 1750, only four furnaces out of the sixty-eight existing had adopted coal for iron smelting. Such a stalemate, extending over forty years, has been a puzzling problem to British economic history. Whilst the classical explanation hinged upon the secrecy of the innovation, historians have recently placed much greater emphasis on the adversity of market conditions, specifically the growing competition from imports; the reduced efficiency of pioneering coke-ironworks; the low level of demand for cast iron and its limited usage; the technological constraints of using too little blast, as well as the price disadvantage of coke-smelted iron (Ashton, 1924, pp. 24–59; Riden, 1977; Hyde, 1977; King, 2005).

In conjunction, these factors hampered the diffusion of coal technology. Only in the second half of the century did some of the aforementioned factors (productivity, technology demand and costs) begin to change heightening the incentives for a new wave of innovations. This period was marked by increasing pressures on charcoal ironwork profit margins, pinched between mounting costs and greater competition from imported iron staples (Hyde, 1977, pp. 34–35; see also Evans, 2005, pp. 19–21). Consequently, up to the 1770s, aggregate British output of charcoal pig iron declined by an amount that was exactly offset by the rise in the coke sector, with furnaces often only one being used one year in two or two in three or even one in three. In order to ensure their survival, traditional sectors responded by cutting back on fuel consumption, which accounted for the largest share of their overall cost structure (Hammersley, 1973, p. 610), fighting hard to hold onto their markets and so counteract the new competition.

Following the erection of new coke furnaces in Shropshire, West Midlands, coke pig iron became a normal feedstock for finery forges. Coal usage henceforth became a self-reinforcing process that is, grounded in direct smelting for the production of cast-iron (augmenting the production of final goods) but also in feeding the fining sector of the forges with coke-pig iron and seizing at least one-fifth of the demand from charcoal fineries (Hyde, 1974, p. 199). These developments come to characterize the second phase in coal diffusion and rested on the discovery of a new technique to remove the carbon from pig iron and convert it into malleable bar iron (decarburization), while overcoming the drawbacks from the relatively high share of silicon in coke-smelted pig iron plus the contamination of the heated metal by another undesirable impurity, the sulfur contained in the coke. Both the stamping and potting process, invented in the early 1760s by the Wood brothers and Henry's Cort's puddling and rolling technology patented in 1783–84, drew upon the same solution: avoiding direct contact between the coke and the molten pig thereby halting the transmission of chemical impurities. The widespread diffusion that ensued, particularly of the puddling and rolling technologies, led to the closure of most traditional charcoal forges, mostly by 1815.

The changeover to coal brought about an increase in the amount of energy per unit of output when compared to the traditional methods of charcoal fueling. By the end of the eighteenth century, the overall consumption of coke-ironworks amounted to 225–255 MJ/t (8 to 9 t of coke) per ton of bar iron produced. This figure comprised the fuel supplied at the furnaces and the subsequent feeding of the stamping and potting process or, alternatively, of the puddling process (based on Needham, 1831, pp. 27–28; Truran et al., 1865, pp. 80–96 and 205–240; de Beer et al., 1998; Hyde, 1977). On the other hand, the corresponding charcoal yield was 127–163 MJ/t (4.3–5.5 t of charcoal) per ton of bar iron, which means that traditional ironmasters almost halved their own secondary fuel consumption throughout the eighteenth century (Hyde, 1977; Hammersley, 1973).[2] Nevertheless, the accomplishments in charcoal fuelling were not sufficient to reverse the tide or even to countervail the lower coke-iron prices. Conversion to coal proceeded apace spearheading the drive in society's demand for more energy in the early years of industrialization. Per capita secondary energy consumption grew relatively steadfastly because there was a sudden increase in the secondary energy intensity of final goods (MJ/lb of bar iron or wrought iron); an upward shift in the demand of goods with high energy intensity (mounting consumption of cheaper iron in construction, naval ironware and agricultural implements); and also a spurt in new manufactures that demanded higher energy intensity equipment goods (iron plates, cast iron, larger steam engines for blast, special machinery such as grooved rolls for puddling or steam-powered tilt hammers). All in all, it took about a hundred years for the English coke-iron industry to reach the level of heat efficiency at the entry of furnace and forge entrance, attained by the old charcoal industry, a threshold in any case only achieved by the most efficient plants (Allen, 1979).

It would seem to follow from these considerations that the history of coal adoption by the British iron industry unveils the course of action predicted by Jevons, in which the creation of innovative opportunities thrives alongside the destruction of the old business and substitution mechanisms rule out complementary mechanisms. In reality, destruction prevailed over creativity. The course of events came to be entirely dominated by price-switching effects in which not only did consumers of final goods shift their demand to coal-iron products but also producers of traditional final goods shifted over to the new intermediate inputs (charcoal forges began working on coke produced pig-iron). Further invention stepped up these switching effects, creating a path-dependent trajectory in the substitution of the older technology. The striking point, however, is the absence of any countervailing mechanisms that might have led to an expansion in the charcoal-based iron goods market. Since overall market growth was insufficient to create new applications for older inputs, charcoal fueled ironworks witnessed the substitution of their products as they were boxed into ever-narrower market niches and basically ousted beyond the production of high-quality metal for wire manufacturing (Hayman, 2008). Broadly in line with the Jevons position, decline proved irreversible and the fight back inconsequential. By the dawn of the nineteenth century, wood substitution had been fully accomplished with charcoal fueling representing less than 10% of iron production.

[2] Estimates based on the British Sussex cord, which later became a standard, of 128 cubic feet, containing approximately 1089 kg of wood, (see Hammersley, 1973, pp. 604–605). For the low level of influence caused by net transportation losses, (see Smil, 2010, pp. 62–63).

Underpinned by its technical efficiency and lower raw material and transport prices, British iron industry entered upon its great era as the major supplier of iron and steel to the world market. For over seventy years (1800–1870), its cost-quality performance outflanked top-quality producers, such as Sweden and Russia, but also emerging industrial powers, such as Germany and the United States (Allen, 1979).

3. The fight back from traditional industries

It was only after the end of the Napoleonic Wars, when trade resumed its course, that continental iron producers noticed how the competitive gap had in the meantime widened. Charcoal-based manufacturing hubs located near the ocean were the first to feel the destructive power of this new competition. Swedish and Russian charcoal–iron exports were also hard hit. As events played out, there proved to be only one region in the world capable of sustaining the speed of innovation necessary to catch up with British technology. That region was the Walloon hinterland of Liège and Charleroi, in Belgium.

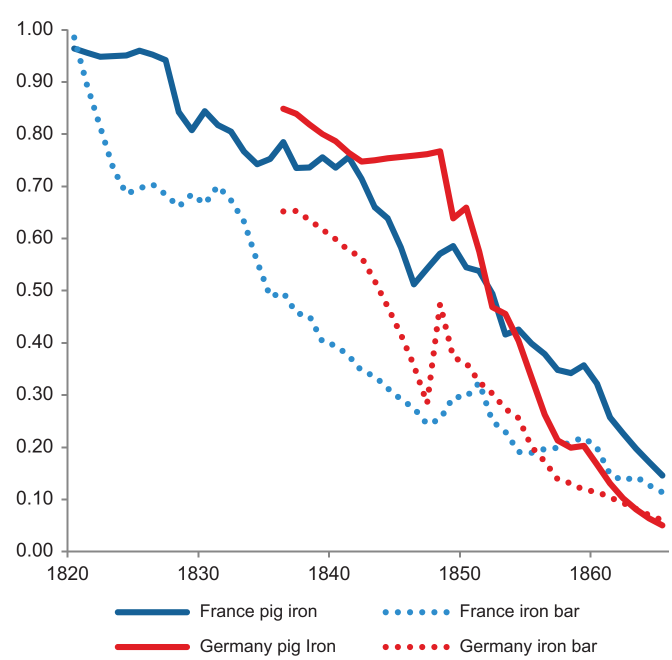
Drawing on a long tradition and renowned expertise in the processing of malleable iron for armaments and nails, Belgium entrepreneurs and British immigrants like William Cockerill erected the first puddling-furnaces and coke blast-furnaces there, in 1821–1823 and 1827–1829 respectively. Almost immediately, other coal-fired plants mushroomed across the region with ravaging consequences upon the traditional charcoal iron industry, which was plunged into irrelevance and basically restricted to a handful of charcoal hearths. By as early as 1835, the throughput of new technology had already surpassed the old (Fremdling, 2005, pp. 49–50). With this short time-span there also came a compression and intensification of the destructive effects driven by metallurgical innovation. So swift and successful was this changeover that Belgium stood out in the years ahead as the pivotal nation in spreading coal-technology throughout Europe (Pollard, 1981, pp. 87–94). Some factors have been pointed out to explain this singular path which closely resembles the theoretical model of traditional industry instantaneous obsolescence developed by Schumpeter: to begin with, the Walloon area enjoyed an array of fortunate geographical conditions, with ore and coal in close proximity, low transportation costs and an interface position between the British Isles and the continent. It is important to add that nowhere else did these common British–Belgium factors stand out as clearly. A second advantage lay in the significant transference of British capital and British expertise involving not only managerial and engineering skills but also "ground-floor" worker skills (Pollard, 1981). Less commonly mentioned is the fact that Belgium had already depleted what represented one of the smallest forested areas of Europe therefore hampering the development of its traditional charcoal industry (see Table 1 below). Given the opportunity costs for change, industrial restructuring quickly prompted an overall raw-material substitution reaping in the meantime the benefits of 'fast-second' innovation.

Unlike this near Schumpeterian pattern, France and Germany experienced a much more protracted process. The technological transference was intense in the final phase of pig iron fining with coal but less so in the current charcoal based methods for ore smelting. David Landes was the first author to identify this development stating that it was as if continental Europe had reversed the "natural" order of British innovation because the adoption of puddling and rolling technology entailed lower capital costs, lower technical difficulties and uncomplicated learning (Landes, 1969, pp. 175–176). Thus, the French and German entrepreneurial attitudes tend to reflect a risk adverse adaptation sprinkled across those industrial structures that faced harder geographical conditions and a more backward level of technological development.

Recent research has, however, shown that this was not just a faulty emulation but an original pattern of specialization that endured for over forty years and successfully withstood competition. Dubbed the "Champagne model", after its place of origin in north-eastern France, the continental pattern efficaciously combined charcoal blast furnaces with the *méthode à l'Anglaise* of puddling and rolling (Fremdling, 1991, 2005). The ensuing hybrid economy spluttered and struggled to take root and survive not only throughout central and north-eastern France, but also in western Germany along the banks of the River Rhine, in the Ruhr Valley, Westphalia and Saar in addition to the eastern band of Upper Silesia.

Graph 1 depicts an estimate of the energy transition dynamics. The wider gap between the lines represents charcoal usage in blast furnaces and in forges, in France, as compared to Germany, indicating that the split in the iron industry in a dual-sector economy was more sweeping than in the former nation. Additionally, it is clear that the "fight back" by traditional sectors in the terms defined by Snow–Tripsas hinged upon specialization in ore smelting and lasted only up to the 1850s, dwindling afterwards to residual market shares. In technological terms, this "fight back" entailed a new cycle of investment that hastened the pace of charcoal blast furnace along the tracks already opened up by their British and Belgian coke competitors. Particularly important was the swift adoption of Scottish hot-blast technology amid the charcoal milieu, which involved a redesign of furnace shapes and an increase in their height and internal cubic capacity (Benoit, 1990; Fremdling, 2005). This, in turn, led to the augmentation of average furnace temperatures with an immediate consequent decrease in the amount of charcoal required to smelt a ton of iron.

Altogether, the "Champagne model" sparked a full sequence of changes whose ultimate result was the maximization and valuation of forest resources. Wood was saved because hearths and forges were substituted by coal fueled rolling mills and furthermore because the new hot-blast furnaces reduced energy consumption by between 12 and 27% (Benoit, 1990, pp. 98–99).

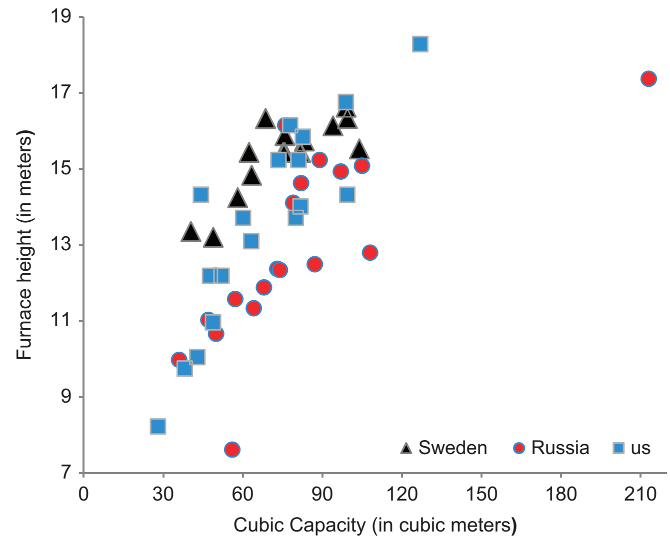


Graph 1. Share of charcoal in the fuel consumption of the French and German iron industries (in percentages) 1820–1865. Sources and methods: Appendix 1.

Part of the wood thereby released could henceforth be diverted to feed the growing economies of scale in blast-furnaces, fostering the gains resulting from specialization. In fact, saving traditional energy sources so as to guarantee a regular fuel supply and end forced interruptions had been a key issue for industry in north-eastern France, plagued with shortages and price hikes ever since the times of revolutionary period turbulence and destruction. The adoption of the hot blast was just one more step in long standing efforts to improve in whichever way possible the consumption of biomass energy and reduce the pressure on forests. From this perspective, there is ample continuity between several eighteenth century French innovations and nineteenth century technological adaptations of foreign technology (Woronoff, 1984, pp. 245–250; Benoit, 1990).

There were, however, other regions where the charcoal industry proved more resilient. Judging from the historical evidence, it is hard not to notice that all these regions were endowed with large ore-mining resources and, most importantly, ore-mining resources embedded in outstanding areas of forests. Sweden, Canada, Russia and the United States in this respect stood far ahead of any other nation, with their vast, unexplored and bountiful timber reserves (Zon, 1910). A brief overview of the path taken by the charcoal-iron industry in these regions shows that the traditional ironworks witnessed a push for modernization strong enough to extend their competitiveness into the second half of the nineteenth century: displaying the criteria of absolute trend reversal, charcoal iron throughput continued to increase until it reached an all-time peak in the 1890s (Russia, the United States) or in the 1900–1910s (Sweden, Canada). However, this second wave of innovation bore little resemblance to the continental European "fight back-last gasp" situation, which rested upon continuity of both ownership and investment, furthering traditional production through specialization, geographical inertia and participation in local markets. On the contrary, the second wave involved development in leaps and bounds, industrial concentration and the destruction of the old traditional industry, territorial displacement of the frontier of charcoal-ironworks, specialized commercial markets and a broader environmental span. Briefly, a brand new version of the traditional industry cropped up and detached from its historical moorings.

In spite of these differences, the rebirth of the charcoal iron industry proceeded, as ever, on the heels of coke and coal technologies. The first burst of successful imitation and adaption embraced the lesser branch of finery forges, whose obsolescence threatened the competitiveness of final products like bars, plates, rails and nails. After several failed attempts, Swedish ironworks succeeded in carrying forward to the productive stage ideas arising out of the field of British techniques. In the 1840s, puddling and rolling methods were transposed to old charcoal-forges through an adaptation of two separate hearths, the refining hearth and the welding furnace, along with a shingling hammer for shaping the blooms, a welding hammer and a fine hammer for shaping the bars (Rydén, 1998, 2005). A similar change took place concurrently in Russia by means of establishing an indigenous technological base for the production of malleable charcoal iron. This mostly affected the traditional charcoal iron industry of the Urals, which witnessed the installation of *svarochnik*-puddling hearths with lower fuel consumption but larger average capacity (Blanchard, 2005). More in line with the last-gasp specialization pattern, US charcoal-producers hedged their backward development by raising the share of direct casting production from blast furnaces, thus avoiding the incorporation of fining costs. Accordingly, Swedish innovations in charcoal-puddling were only very slowly adopted by American producers (Temin, 1964, pp. 25–29, 214–215; Gordon, 1996, pp. 129–132).



Graph 2. 18 topmost charcoal furnaces in Russia, Sweden and the US, 1880–82. Sources: C. Kirschhoff, Jr. (1881) The manufacture of charcoal pig-iron in Russia. Journal of the United States Association of Charcoal Ironworkers 2, 200–206; Swedish Blast Furnace Practice (1882); Narrative of the Third Annual Meeting of the USACIW (1882); Some Remarkable Furnace Work, 1881; U.S. Census Bureau (1880).

After the turn of the century, a second selective push was set in motion by the building of "monster-coal blast furnaces", a technological development that had begun in Cleveland, Britain in around 1855–60, and quickly sprang up in and across other producing nations. Aimed at increasing output by raising the height and at saving fuel by raising the blast temperature and pressure, the new style furnaces unleashed a new cycle of productivity gains coupled with industrial concentration. Its effects were far-reaching upon the industrial landscape: whilst some coke pioneers in the early nineteenth century could make over 1000 t of pig iron in a full year, the largest blast-furnaces could produce the same amount in a single week by the 1890s (Davies and Pollard, 1988, pp. 78–79; Temin, 1964, pp. 158–159). In what appears to have been a handy "tip for tap" reply, Swedish, Russian, US and, later, Canadian charcoal furnaces followed in the footsteps and increased height, erecting larger and taller units with powerful blast machinery. As Graph 2 shows, this tendency was fully exploited in Sweden, which achieved regularity in height and design that contrasts with the wider-ranging dimension/capacity of US blast furnaces. At the bottom of scale, Russian plants displayed a smaller height profile situated around 9–13 m which is explainable by the chronic prevalence of cold-blast technology. In the light of this evidence, there is little wonder that the Swedish attained the greatest efficiencies in energy saving methods with average charcoal consumption per ton of final manufactured rolled iron of 98.8 MJ/t (3.3 t in 1860), improved to 59 MJ/t (an average of 2 t of charcoal in 1900) and reaching the highest saving of 41.4 MJ/t (1.4 t of charcoal in 1900) through the utilization of a charcoal blast furnace with Bessemer decarburization and rolling equipment (Harpi, 1953; metric unit conversion based on Jüptner, 1908, p. 198). This conveys how the newly resurgent Swedish charcoal iron industry was capable of outstripping its counterparts. Nevertheless, its tallest heights of 17–18 m were still dwarfed by the 22–27 m that could then be found in a few "monster" coke blast-furnaces.

This point becomes even more striking if we account for the fact that the largest contribution to total factor productivity in the nineteenth century came from technological change in terms of fuel and metal input savings (Houpt, 2007). Matters proved rather different among the competing coal–coke furnaces as in this case the trend towards increasing heights triggered a broader process of productivity growth based not only on fuel and metal input savings but also other interrelated factors less relevant to charcoal ironworks, namely the diffusion of hard driving and improvements in ore selection (Temin, 1964, pp. 196–206; Allen, 1977; Inwood, 1985; Houpt, 2007). Minor benefits obtained from minor economies of scale help explain, at least partially,[3] why the charcoal iron industry floundered later in the twentieth century.

Economies of scale became further interlinked with mounting industrial concentration and efficiency gains through mergers and takeovers. Judging by the empirical evidence, it seems the later the innovation occurred, the quicker and stronger came the push towards industrial concentration. The intensity of the movement towards integration and amalgamation into groups among the businesses of late-comer Canada supports this view (Donald, 1915; Inwood, 1986).

Having undergone a complete overhaul, the charcoal industry overturned a possible trend towards obsolescence. Like the mythical phoenix, ironworks fueled by biomass proved their ability to rise reborn from the ashes. And while these furnaces and hearths continued to be dependent upon their use of pre-industrial energy inputs, their relationships with their surrounding forests nevertheless changed profoundly.

In modern times, the wood supply was assured by a 7–15 km radius of woodland area around the major plant (Sieferle, 2001, p. 63; Harpi, 1953, p. 12), and over much wider areas around populated towns (Sans, 2004, p. 699; Ortego et al., 2011). Subsequently, when average production reached the ceiling of 800–1000 t a year, a good yardstick for the first half of the nineteenth century, the furnaces were compelled to haul their charcoal over distances of up to 17 or 20 km, something that was achieved "with great expense and vexation" (Warren, 1973, p. 29). In this context, even when the geographic conditions allowed for locating plants near navigable watercourses ironworks still had to maintain some distance from the water so as to favor the establishment near woodlands, in addition to having to be far enough apart from each other to ensure a ready fuel supply (Knowles and Healey, 2006, p. 620).

It was only during the "Phoenix era", spearheaded by giant charcoal furnaces, that the very idea of drawing resources from the hinterlands became outdated. Henceforth, the natural milieu from which the industry could draw on raw materials was the geographic scope served by the railways. This was certainly an environmental change brought about by technological modernization. A whole new ecology of needs and wants began to surface with several devices invented for long haulage: special packaging procedures for lessening the waste from crushed charcoal; the construction of specialized railroad cars for conveying sacks or baskets with minimal damage; the adoption of mechanical equipment for loading and unloading; the invention of special cage systems to facilitate transfers as well as improvements in the design of horse and sleigh (Risks in transporting charcoal by railroad, 1883; Lilienberg, 1884; Transportation of charcoal, 1885). Still more importantly, the railroad not only provided a market for the new charcoal industry but it also enabled its displacement into new areas. These new areas were basically regions with plentiful ore, like Michigan, Alabama, and Wisconsin in the US, Ontario and Nova Scotia in Canada, and the central region of Sweden closer to the northern forests. In the same vein as the coal trade, wood was disembodied from the nearby community of forest users and turned into a long distance tradable resource.

Having sketched in very abridged terms the major trends and factors in the iron industry's energy transition, it is now the moment to test some of its consequences. Most generally, economic analysis resorts to the statistical criteria of the market share held by competing technologies to determine the scope of destructive and creative effects (for instance, see Graph 1). However, this point of view does not fully account for the environmental impact upon forests of the switchover to coal-fueled iron technologies. From the perspective of resource endowment, what matters mostly are the ups and downs in the amount of woodland that had to be felled and reforested so as to satisfy charcoal production needs. This becomes especially the case when the consequences of technological change were not single-sided, but yielded contradictory results upon traditional energy sources.

To highlight the various historical paths, Table 1 depicts the amount of forested area that was used to feed the ironworks in four nation-types: Belgium (charcoal's competitive destruction), France (charcoal's fight-back), the US (charcoal's rebirth with internal coal competition), and Sweden (charcoal's rebirth without internal coal competition). For the sake of comparison, for each benchmark period, the table also shows the virtual forested area that would have been necessary for producing the iron actually made with coal. The third column provides the percentage of forested area reserved for feeding the iron industry and the fourth and final column the proportion of forested area necessary for manufacturing the coal produced iron.

The figures from continental Europe reassert the view of the increasing release of forested areas from iron's dependence. The significant exception is the thirty-five-year period of charcoal "fight-back" spearheaded by the French industry in the first half of the nineteenth century that swelled wood consumption. As previously mentioned, this drift took advantage of recent technological innovations in blast furnaces to specialize part of the charcoal industry in the capital intensive branch of ore smelting. Looking at the data displayed in Table 1, it is possible to conclude that the French fight-back prompted a 50% increase in the forested area felled for the iron industry (1820 to 1840 and 1860). However, due to enhanced coke-competition, by the second half of the nineteenth century, iron producers had turned their back on the forests, exploiting only a minor portion of the ongoing available resources. Comparatively, the energy transition in neighboring Belgium was significantly more straightforward and faster. In just a few decades, Belgium iron entrepreneurs, aided by their newly independent government, embarked on the complete transformation of their extraordinary dependence upon scarce forests. Furthermore, in no other country did the iron industry encroach upon half of the national area of woodland (Table 1 Belgium, 1820). The strains provoked by this particular situation spanned entire regions and the speedy pace of depletion left most contemporaries alarmed (Alviella, 1927). However, high dependency also meant that the nation could hardly rely on their internal forestry resources to boost the scale of the industry. This was all the more so as the transportation costs of foreign factors of input still made a difference in the allocation of resources. Under the Belgium banner, the switchover to coal was to shortly mean a release from the constraints of the biomass–solar energy system. Consequently, by the end of the century, using coal, the iron industry was consuming eight times as much energy as could possibly have been obtained from wood in the country's forests

[3] Three factors account for the final demise of the charcoal iron industry: the destructive effects of "manufacturing iron without fuel" introduced by Bessemer and open-hearth steel upon charcoal-iron products, particularly wrought-iron plants; the tighter limits on productivity gains from charcoal blast furnace economies of scale; and new opportunity costs for industrial timber (wood chemicals obtained from the charcoaling process, wood pulp and sawn timber). On this issue, see Eriksson (1957), Schallenberg (1975), Wengenroth (1994), Rogers (2009).

Table 1
The impact of ironwork fuel consumption on forests. Selected countries, 1820; 1840; 1860; 1880.
Sources and methods: Appendix 2.

Year	Belgium: Forest used to fuel the charcoal iron industry (thousand ha)	Belgium: Forest equivalent to coal consumption in the iron industry (thousand ha)	Belgium: Forest used to fuel the charcoal iron industry/total forest area in 1880	Belgium: Forest equivalent to coal consumption/total forest area in 1880	France: Forest used to fuel the charcoal iron industry (thousand ha)	France: Forest equivalent to coal consumption in the iron industry (thousand ha)	France: Forest used to fuel the charcoal iron industry/total forest area in 1882	France: Forest equivalent to coal consumption/total forest area in 1882
1820	253.8	0	52%	0%	848.0	97.8	9%	1%
1840	182.5	441.8	37%	90%	1272.2	892.7	14%	10%
1860	106.5	1642.3	21%	336%	1120.9	3378.8	12%	36%
1882	0	3824.4	0%	782%	319.6	8189.0	3%	88%

Year	Sweden: Forest used to fuel the charcoal iron industry (thousand ha)	Sweden: Forest equivalent to coal consumption in the iron industry (thousand ha)	Sweden: Forest used to fuel the charcoal iron industry/total forest area in 1890	Sweden: Forest equivalent to coal consumption/total forest area in 1890	U.S.A.: Forest used to fuel the charcoal iron industry (thousand ha)	U.S.A.: Forest equivalent to coal consumption in the iron industry (thousand ha)	U.S.A.: Forest used to fuel the charcoal iron industry/total forest area in 1908	U.S.A.: Forest equivalent to coal consumption/total forest area in 1908
1820	1942.3	0	11%	0	125.8	42.3	0.1%	0.0%
1840	2541.8	0	14%	0	2067.5	315.8	0.9%	0.1%
1860	2764.7	0	15%	0	1125.5	3862.2	0.5%	1.8%
1880	4144.7	0	23%	0	1902.7	15961.0	0.9%	7.2%

(column "forest equivalent to coal demand/total forest area in 1880").

Unlike mainland Europe, Swedish and US manufacturers were able to continue drawing on their forest supplies throughout the nineteenth century. This long survival of charcoal energy sources should not obscure the booms and busts experienced by both countries as well as their respective aftermaths: the persistence of the traditional industry side by side with the "modernized" traditional industry. Moreover, whilst the industrial forested area grew steadily in the Scandinavian nation, there was stabilization in US demand, with the plateau reached in the 1840s. Several factors appear to have had contradictory effects. On the one hand, successful imitation of coal-blast furnaces and puddling and rolling technologies pushed fuel consumption downwards; the specialization in ore smelting with the progressive retreating of wood demanded by charcoal-based refineries in the final quarter of the nineteenth century also contributed to shrinking charcoal consumption; on the other hand, markets for the final goods produced pushed the industry in the opposite direction.

Turning premium-quality prices to good effect, charcoal producers were able to take advantage of the dislocation of the coal-fueled iron supply curve to the right, seizing market niches that became enlarged by the dynamics of lower prices and widespread usage. These comprised temporary niche market opportunities like iron rails and pig-iron for Bessemer plants and long-standing quality goods like railroad wheels, plows, scythes, sickles, knives, nails, steam engine boilers and tubes, crank shafts, axles, gears and even telegraph wire. Globally, the action of opposite factors resulted in increased throughput, more specialized goods and less fuel consumption per unit of product. Price comparisons between the two competing technologies show that charcoal fueled iron still retained a premium over coke fueled iron up to the dawn of the twentieth century (Hammersley, 1973, pp. 354–355; Blanchard, 2000, pp. 112–113; Olsson, 2007, pp. 48–52).

One must nonetheless add that notwithstanding the rising trend for charcoal production in the United States, its development lagged far behind the outstanding boom in coal-fueled iron and steel production. Additionally, the forested area devoted to this type of manufacturing activity was completely irrelevant and occupying at most 1% of the available surface area (Table 1, US. See also assessments made by Sargent, 1884, pp. 485–490 and Williams, 1987, p. 16). Seemingly, the limitlessness of American riches offset the impact of charcoal growth throughout the nineteenth century. However, on another scale, the micro-scale of the region, the abundance of woodland had the perverse consequence of forest conservation mismanagement. Particularly after the Civil War, the negligence in preserving coppices allied to muddled intrusions by cattle breeders curtailed the chances of the tree cover regenerating over entire areas. Ultimately, this would lead to the exhaustion of woodlands around the furnaces and the squeezing of the industry (Williams, 1987; Schallenberg, 1975). For public opinion, the emerging conservationist movement and the charcoal manufacturers, the blame for such environmental disasters was pinned on the reckless behavior of agricultural settlers with their wild agricultural clearing methods. The settler rather than the industrialist henceforth became the main enemy of environmental conservation. Precisely at this juncture, charcoal-iron manufacturers felt that the moment was ripe to forthrightly fashion themselves as the true "protectors" and the true "restorers" of the forest (On the importance of giving timely attention to the growth of charcoal for metallurgical uses, 1880).

4. Final remarks

The iron industry was a powerful engine in the switch to coal that took effect in the nineteenth century. Political economists such as Stanley Jevons and Joseph Schumpeter extolled the superiority of blast furnaces in terms of technological advance, progress and modernization, underpinning the positive effects of substitution of obsolete bio-mass fueled ironworks. Similarly, the energy transition was portrayed like a snowballing process which destroyed traditional wood carriers either immediately (Schumpeter) or gradually (Jevons). Although the basic premises of coal ascendancy remained sound, some authors called into question the historical pattern of linear evolution. For Rosenberg, Tripsas, Snow, Young and others the mechanisms that triggered the destruction of older technologies might also promote their rise. Hence, one could expect to find a complex mix whereupon market creation and market destruction interact together to produce a new equilibrium, that makes the transition a period of hybridization, complementary and technological maturation rather than straightforward substitution.

Overall, three distinct patterns of energy transition have emerged. A first case in point was the swift release of forested areas due to coal substitution in the iron industry as happened in Belgium. This case quite closely resembled the Schumpeterian blueprint of creative destruction. A second situation found in France and Germany featured a lingering substitution process with initial stimulus to forest exploration embracing solely the branch of blast-furnaces followed by competitive destruction. The fight-back model chronicled by Snow, Tripsas and others captures the main traits of this evolution. A third pattern entailed market substitution but with concurrent incentives to forest exploration and the rebuilding of the traditional charcoal industry in accordance with the technical–organizational parameters set by their coal–coke competitors. Sweden, US, Canada and, to a lesser extent, Russia experienced this type of phoenix-like rebirth. Judging from the historical evidence, two conditions stand out as requirements for phoenix-entrepreneurship success: first, the competing technology must be mature enough to amplify the overall market so as to create product segmentations with sizable dimensions. Note that unlike Young's model what matters here is the market for final goods as much as the market for intermediate goods. In this respect, it is worth noticing that charcoal's rebirth took place simultaneous to coal-fueled iron and iron seizing the broader market of structural construction materials and a fully new technological approach to steel production, developed by Bessemer and Siemens-Martin, deeply changed the market configuration (Misa, 1999, pp. 45–8). This means the rebirth occurred under tough competitive pressures. Secondly, resource endowment must have a positive effect upon prices and upon the choice of technology. As several authors have pointed out (Harpi, 1953; Hammersley, 1973; Inwood, 1985), the vastness of woodlands with huge virgin forests enabled a large charcoal iron industry to persist in countries with moving frontiers long after it had disappeared from continental European nations.

The most important lessons to take away from the energy transition in the iron industry points to the fact that within the time-frame for "transition" one might expect either the effective substitution of the older energy carrier, or an incentive to its expansion. The same is to say that the course of action that leads to destruction through innovation and cost decreases also unleashes creative market mechanisms. These basically act upon the supply side (technological imitation and specialization) and upon the demand side (new markets for the "obsolete" product) for the industries due for replacement.

As aforementioned, one must not forget that coal supremacy remained undisputed throughout the nineteenth century. In terms of the market share for coal-fueled iron, more than half of the world's production was obtained using coal by as early as 1840. And, in the ensuing decades, this market share could not but expand. One must therefore recognize the prevalence of destructive mechanisms over creative ones in the macro-economic domain and the fact that the new coal-fueling technology enjoyed undisputed leadership in price, output, investment and scientific research. Likewise, countries that completed a relatively fast energy transition, wiping wood consumption off the map, won a competitive edge over all others.

The general conclusion deduced from the foregoing analysis is that energy transitions are not just driven by the competitive edge attained by new fuel technologies over incumbent ones, nor by mechanisms of destructive substitution. If the lessons from the past are to be taken seriously, energy transitions represent first and foremost critical leaps forward in secondary energy consumption, and significant changes in the map of applications, usages and markets. As the new energy technology challenger reaches maturity, new opportunities for the rebirth, the fight back or the last gasp of older industries are found to occur.

Appendix 1

Graph 1 Share of charcoal in the fuel consumption of the French and German iron industry (in percentage form). 1820–1865.

Methods: This estimate applies fuel ratios to pig iron and malleable iron output to assess the amount of coke and charcoal used. Owing to the lack of precise information concerning each country, an array of four time series of fuel ratios was built resorting to the linear interpolation between benchmark years: fuel ratios of French charcoal ore smelting; French charcoal pig-iron refining; Belgium coke ore smelting; British coke pig-iron refining. The application of these ratios to French and German outputs relies on the assumption that in moments of technological transference continental Europe has adopted the best practices of the social–technological system of Britain or Belgian improvement of the British social–technological system.

Sources

(1) Production time series: (Fremdling, 1991; Fremdling, 2005).
(2) Fuel ratios: (Benoit, 1990; Woronoff, 1984; Pluymers, 1992; Allen, 1977; Isard, 1948; de Beer, 1998; Needham, 1831; Mushet, 1840; Proceedings of scientific and technical societies, 1872).

Appendix 2

Graph 2: Methods and sources: To estimate how much wood could be cut from a given area of woodland, one must first start by choosing a historical-normative rule that posits how much *should* be cut. In practical terms, the normative dimension of "should" can be made operational by considering the annual yield of wood produced from coppicing systems. According to Peter Sieferle (2001, p. 55), the European method of sustained forest management used in the early modern period to maintain a constant consumption over time and a regular cycle of regrowth of the total forested area, yields an average return of 5 m^3 of wood per hectare. Applying the Food and Agricultural Organization factor of 1:0.65 to convert stacked wood into solid wood, Food and Agricultural Organization—FAO (2004), leaves an amount of 3.25 m^3 of solid wood per forest hectare (ha).

All things being equal (species of trees, grazing regimes, institutional and social rules of forest access), one should expect that whenever a nation cuts more than this average annual growth value of 3.25 m^3 of solid wood per hectare its forests will face the impending threat of depletion. Inversely, countries which manage their resources under a coppicing system and adjust the cut yield to average annual growth of 3.25 m^3/ha are perhaps able to keep a safety margin for production increases while allowing for the regular cycle of regrowth. Nineteenth century estimates, as reported by Warde (2006), further confirm this represents a good average value.

The table below represents the value of wood cutting in the four nations under study: Belgium and France, Sweden and the US. Figures from the early twentieth century were taken from Zon (1910, p. 70), while figures from the nineteenth century were based on contemporary estimates and monographic research as reported by Warde (2006) for France, by Bahre and Hutchinson (1985, p. 181), Warren (2001, p. 9) and "Economy of fuel in iron" (1882) for the US and by Hedström (2005) for southern Sweden. The average of these two benchmark periods is further calculated to serve as reference for the yield of one hectare of forestland (column c). The next step consisted in devising the specific weight of this yield given the industrial traditions and the forest resources in effect for the charcoal industry in each country. For this purpose, a mixed meiler of hardwood and softwood was calculated for France, whilst an average basket embracing hardwood species (maple, beach, elm, birch), common in eastern US and coniferous species, more available in the scarce forest areas of the western US (pine, spruce, hemlock), was furthermore constructed to account for American diversity. The Swedish charcoal mix, in turn, draws on the proportion of 1 weight unit of spruce to 4 weight units of pine (See Wilber, 1872; Svedelius, 1875; Some Remarkable Furnace Work, 1881; Lilienberg, 1884; Zon, 1910).

Finally, the yield of wood per hectare was converted into charcoal to feed the furnaces, forges and rolling mills, by adopting the best practice conversion ratio of 1 kg of charcoal to 3.3 kg of wood (see article).

The data series on the production of pig-iron and wrought iron are based on Fremdling (2005), Annuaire statistique de la France (1883–85), Olsson (2007), U.S. Census Bureau (1880), Swank (1881), Temin (1964) and Davis and Irwin (2008). The forested surface area in 1880–1908 is taken from the data presented in Zon (1910).

	Country		
	Belgium and France	Sweden	United States
(a) Annual cut per hectare. XIX century (cubic meters of solid wood)	3.5	1.6	3.4
(b) Annual cut per hectare. 1910. (cubic meters of solid wood)	2.7	1.3	2.9
(c) Average annual cut per hectare (cubic meters of solid wood) (a+b)/2	3.1	1.45	3.1
(d) Weight in kg of one cubic meter of solid wood	490	450	541
(e) Yield from 1 ha of forest land (in kg of solid wood) (c × d)	1519	625.5	1677

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