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"Historical Responsibility" for Climate Change in Historical Perspective

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Abstract

International climate negotiations have been hamstrung by a dispute over whether a handful of developed countries have "historical responsibility" for climate change. The thesis rests on the presumed fact that a small number of early-industrializing nations (the "accused" countries) emitted an excess of greenhouse gases ("historical emissions") through their use of coal for energy over a period of at least a century, before mineral-based economic development was adopted universally. Advocates of historical responsibility deduce from this that the accused countries have a moral responsibility to reduce their greenhouse gas emissions faster than they are required to through their treaty-based obligations. The position has been a negotiating weapon, entrenching differences and retarding progress. I argue that industrialization's early emissions should be attributed to their actual sources, namely the foundational technologies of the Industrial Revolution. In a historical sense, these belong, not to the accused countries, but to modern civilization. More than a century was required to develop the core technological cluster. During that time, the inventions were largely confined, for practical reasons, to the loci of invention. Their universal adoption beginning around 1850 undermines the argument that the countries whose distinct economic circumstances gave birth to industrialization are to be penalized in the present.

JEL Classifications: N50, O3, Q54.

Keywords: Climate change; biological old regime; coal as an energy source; Industrial Revolution; history of carbon-based technologies; greenhouse gas emissions c. 1750-1850; moral responsibility for "historical greenhouse gas emissions".

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Introduction

This article responds to a popular thesis that developed countries of today have a "historical responsibility" for their greenhouse gas emissions. The thesis is, for example, vociferously defended at the international climate change negotiations by states seeking "compensation" for climate change damage resulting, they say, from the age-old self-enriching emissions of today's wealthy countries.

Historical responsibility is a thesis that distinguishes the responsibility of states for greenhouse gas emissions during a "historical" period from those emitted during what is labeled the "current" period. The current period has indisputably engendered state legal responsibility for greenhouse gas emissions. It plausibly begins in 1990, with the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[1] The report spelt out for the first time the scientific consensus on climate change, under the aegis of the IPCC, which is a state-approved international organization. The IPCC's report was followed, in 1992, by the United Nations Framework Convention on Climate Change (UNFCCC).[2] The UNFCCC is the foundation of state legal responsibility for climate change in the "current" period.

The international legal regime now boasts three climate treaties.[3] Its evolution is ongoing, with the latest treaty, the 2015 Paris Agreement on Climate Change, deepening the legal responsibility of states and spreading it widely within the community of states. According to the historical responsibility thesis, in addition to treaty-based state responsibility in the current period, certain developed countries, which I will refer to as the "accused" countries, have a moral responsibility for an excess of historical emissions in the course of an approximately 240-year period, namely 1750-1989.[4] This is the "historical" period that precedes the current period of international awareness and treaty-based regulation of climate change.

In this article, I will focus on the first one hundred or so years of the historical period, whose significance, I believe, is most misunderstood by advocates of historical responsibility. I will show that the historical record does not support their thesis.

The Argument from Historical Responsibility

The wrongful act that the historical responsibility thesis attributes to the accused countries is described in two different ways. The first alleges physical damage: the uninterruptedly strong growth in the historical greenhouse gas emissions of that group of countries significantly and disproportionately changed the climate, compared with the (modest, business-as-usual) growth in emissions of other countries during the historical period, causing global warming and consequent damage to the developing countries of today.[5] The second version alleges that the accused countries' historical emissions "appropriated atmospheric space" beyond their fair share, denying such space to today's developing countries for their own economic development, today and in the future. On this view, fossil-fuel-powered industrialization is a story about a few "winner" countries that took all, as fast as they could:

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[1] See J. T. Houghton, G. J. Jenkins, and J. J. Ephraums (1990), xv.

[2] The UNFCCC was adopted on May 9, 1992 and entered into force on March 21, 1994.

[3] The two other climate treaties are the 1997 Kyoto Protocol to the UNFCCC (adopted on December 10, 1997; went into force on February 16, 2005) and the 2015 Paris Agreement on Climate Change (consented to on December 12, 2015; went into effect on November 4, 2016).

[4] Conventionally, in the narrative of climate science, the Industrial era begins in 1750, when the atmospheric carbon dioxide (CO_2) concentration was 280 parts per million (ppm), following which it began to rise; see Intergovernmental Panel on Climate Change (2013), 10.

[5] For example, Simon P. James (2015), x; Marcia R. Rocha, Mario Krapp, Johannes Götschow, and M. Louise Jeffrey (2015).

> the industrialized countries have the main historical and causal responsibility for climate change and have realized large benefits from emission-generating activities, whereas the developing countries have contributed far less to the problem of climate change and have derived comparatively small benefits from emission-generating activities.[6]

Often a "cake" metaphor is used (eating more of your fair share of a cake) to conceptualize the alleged injustice in the appropriation version of the thesis:

> the past and present pollution of the atmosphere by the industrialized countries ha[s] been at the expense of the under-developed countries. ... what is left of this resource [i.e. the atmosphere's absorptive capacity] must be justly distributed and the historical fact that some specific countries have directly [limited it to an intolerably low level] becomes highly relevant. ... [T]his redistributive obligation is not derived from some fault on their part but from the stupendous benefits they have amassed.[7]

An extreme version of the appropriation narrative alleges criminal plunder: "The culprits [who used up the atmospheric global commons] are not hard to identify. It is as if wealthier nations such as Britain and Germany had used up all the world's breathable air, leaving none for poorer ones such as Rwanda and Nepal".[8]

Whether the first indictment is laid (damage) or the second (unjust appropriation of an economic resource), the same conclusion is said to follow: the countries that perpetrated those wrongs should bear a cost in the present, taking the form of extraordinarily ambitious curbs in their greenhouse gas emissions, or, amounting to the same thing, extraordinarily generous climate finance contributed by them to developing countries to underwrite the latter's adaptation to climate change. This would be in addition to their legally-obligated vanguard role under the climate treaties to lower their own emissions.[9] The benefit which the accused countries gained through their historical injustice is thus to be dealt with through a form of reparation in the present.

Historical responsibility is an important thesis, because, if accepted, it turns the responsibility of certain states for climate change into a compound responsibility consisting of that which they acceded to in the current period through their acceptance of treaty obligations and that which they generated for themselves by their actions in the historical period, which has moral consequences in the present. This heightened responsibility entails, for example, that the accused countries must set their greenhouse gas mitigation ambition *higher* in their "nationally determined contributions" under the Paris Agreement[10] than they would have if it were not for historical responsibility; whereas developing countries engaged in the same exercise of setting themselves targets are entitled to set their mitigation ambition lower than they might have done, taking into account the collective historical responsibility of the accused countries. The correctness of the historical responsibility thesis is taken for granted by many academics.[11] Of greater concern is the rift that the thesis has created at the international

[6] Lukas H. Meyer and Pranay Sanklecha (2017), 2-3.

[7] David Heyd (2017), 25-26. The cake metaphor is also used by Rudolf Schuessler (2017), 149.

[8] James (2015), x.

[9] Sarah Mason-Case and Julia Dehm (2021), 175-183.

[10] See Article 4 of the Paris Agreement, in UN Doc. FCCC/CP/2015/L.9/Rev.1, 12 December 2015. The Nationally Determined Contributions are the core mechanism of emission reduction under the treaty.

[11] For example, John H. Knox (2019), 173; Annalisa Savaresi and Juan Auz (2019), 248.

negotiations on climate change since the very beginning of the process. Many developing countries continue to level the accusation encapsulated in the thesis.[12]

Counterarguments

Two lines of argument are most effectively deployed against the historical responsibility thesis. One I have already presented elsewhere.[13] It goes to the question of historical emissions, which is a foundation of historical responsibility. In fact, we know very little about how much each country emitted during the historical period 1750-1989. In particular, we do not know the growth rate in emissions at the country level, on which the historical responsibility thesis depends. Country borders changed and some countries came into, and others went out of, existence during the historical period, further bedeviling any attempt to calculate historical emissions. I showed in that other work that it is as likely as not that certain countries or regions now in the non-accused group grew their emissions at least as quickly as the accused countries during the historical period, consequent upon their expansion of deforestation, land-clearing, agriculture, and population growth—not to mention their own fossil-fuel-based industrial development after, say, 1914. The high uncertainty about pre-1990 historical emissions exists despite the presumed fact that greenhouse gas emissions from coal must have been high in the first century of the historical period in the accused countries.

Considering that country-level greenhouse gas emission data prior to 1990 are largely unknowable for most countries, and equally unknowable for all of them in the first century of the period, the dearth of comparable data denies any dependable factual basis to the claim that the accused countries' historical emissions caused disproportional damage through climate change or appropriated an unfair share of atmospheric space.

The second key argument against the historical responsibility thesis is the one I develop here. Early industrialization began in Britain, with coal mining paired to the steam engine. From this beginning grew other carbon-reliant inventions, some of which served as a springboard for yet others, in a line that can be traced to the technological ecology of today. This history quickly becomes complicated as technological links multiply, but what is beyond doubt is the foundational importance of coal mining and the linked emergence of the steam engine in Britain. The two technologies were rapidly transplanted and adopted elsewhere around the world during the nineteenth century, to create a global industrial civilization.

The gist of this second argument is that every state without exception benefited from the innovative industrializing explorations that contributed to the accused countries' early emissions from coal. Those emissions supported the technological leap from the Boulton & Watt steam engine to the railroad; and they supported the subsequent leaps, to agricultural machinery, nitrogen fertilizers, and the internal combustion engine. The early emissions enabled the realization, unprecedented in world history, of uninterrupted economic development and progress. The lives and livelihoods of people in every country have relied on those early inventions in Britain, Western Europe, and the United States, which required

[12] For example, Brazil (2022), 1 ("This NDC ... largely exceeds the level of ambition expected of a country with a small historical responsibility"); China (2016), 1 ("especially the accumulated carbon dioxide emissions from the intensive fossil fuels consumption [sic] of developed countries, have resulted in significantly increasing the atmospheric concentration of greenhouse gases, [and have] exacerbated climate change"); Egypt (2022), 8 ("the country's negligible responsibility for the world's historical GHG emissions"); India (2016), 2 ("By enhancing their efforts in keeping with historical responsibility, the developed and resource rich countries could reduce the burden of their action from being borne by developing countries"); and Kenya (2020), 17 ("Kenya believes that the key factors in determining the fairness of a contribution should include historical responsibility. ... Kenya's historical emission contribution is negligible").

[13] Zahar (2021).

those early emissions from coal. History reveals no alternative pathway to the benefits of modern civilization. There was no road not taken.[14]

Once the logic of the inventions that enabled the Industrial Revolution is appreciated, no-one can consistently raise historical responsibility against the accused countries for their early historical emissions. All states were complicit in embracing those technologies, as fast as their local circumstances permitted. In the language of the present, industrialization's early greenhouse gas emissions were "exported" to non-inventor countries, embodied in the new machines and processes perfected in the accused countries, which the receiving countries (including the developing countries of today) eagerly adopted for their developmental benefit. That benefit was, of course, not unqualified, as is now understood. It had environmental costs, only one of which (the most inconspicuous of all) was climate change. But universal adoption cannot have happened in the absence of a perceived balance of benefit, and the line of argument I develop here turns on adoption having happened on the basis of a balance of benefit.

My argument is not just factual but also normative. The non-accused countries are no less at fault than the accused countries for climate change, because they benefited no less than the accused countries from the technologies they adopted. Adoption entails complicity in a chain of linked events. The act of adoption precludes laying blame on the accused countries for their emissions of invention.

History is almost non-existent in legal debates on historical responsibility. Space here permits only an outline of that history, which has received extensive treatment by historians. I will trace the links from coal mining and the steam engine to the mechanization of cotton spinning, the invention of the railroad, the mass production of iron and steel, the "fertilization" and mechanization of agriculture, and the invention of the internal combustion engine and the automobile. In this chain, fossil fuels and emissions from their utilization are the golden thread. Private inventors and investors bore the burden of improving the carbon-based technologies. All countries welcomed these revolutionary products, which they applied to their own industrialization. By doing so, they implicitly abandoned any basis for complaining later about product "defects", in particular those climatic consequences which very few people were aware of before the very end of the twentieth century.

It hardly needs to be remarked upon that the coal-assisted escape from the material limits of the biological old regime, which I come to immediately below, was but a "temporary reprieve" for humanity.[15] It was a path dependency leading in one direction only, with characteristics of a drug dependency. Everything might yet be undone by climate change. At the same time, very little of what we now value would exist without coal. My argument, therefore, is the very opposite of historicist. We have collectively dived into an abyss out of whose depths we might never be able to climb. The fault transcends time and space and is genuinely collective.

From the Biological Old Regime to Coal and Steam Power

Historians identify two industrial revolutions: a limited, British one, starting around 1750, which affected only a few sectors of Britain's economy; and a broader one, which by 1850 was transforming the economies of Western European countries and the United States and was beginning to spread outside those regions.[16]

Why "revolution"? Up until the beginnings of industrialization in Britain, the productive potential of human beings everywhere was limited by the so-called biological old regime,

[14] Coal consumption continues to rise today: Jan Steckel and Michael Jakob (2022).
[15] Fredrik Albritton Jonsson (2012), 681.
[16] Iván T. Berend (2013), 214.

whose energy source was essentially solar.[17] Solar energy supplied the necessities of life, including crops and wood fuel. The material constraints on pre-industrialized people were severe.[18]

The biological old regime allowed for some population growth, as well as for some productivity growth. Deforestation and destruction of other natural habitats (for instance, peatlands) facilitated the expansion of agriculture and fulfilled the increasing demand for biomass energy resources. The creeping expansion supported a larger population, domesticated animals substituted for some human labor, and flowing water and wind-power helped with milling and pumping.

Nevertheless, the solar constraints could not be overcome by pre-industrial people, some of whom were, by the seventeenth century, beginning to exhaust the natural resources in the places in which they had settled—in particular, forest and land.[19] The curse of poverty was until then the universal experience of humanity.

With Britain hard up against the limits of the biological old regime at the end of the seventeenth century,[20] the country shifted its reliance to an exceptionally accessible and transportable non-biomass energy resource: coal.[21] No other country with an economy as developed as Britain's enjoyed such advantageous access to coal.[22] David S. Landes calls it "the special bounty of an uneven Providence".[23] Prior to that time, coal mining had been a small operation in the country. Firewood use along with other biomass was always dominant. But already by the early eighteenth century, half of total heat energy in England came from coal.[24]

The increased demand for coal for heat-energy and the attendant extraction challenges at collieries stimulated thinking about how to derive mechanical energy from coal. A basic coal-powered steam engine, whose one large piston was filled with steam by suction and was returned to its starting position by the weight of the air column above it once the steam was condensed to create a vacuum, was invented by Thomas Newcomen in 1712 to serve the upsurge in coal production.[25] This hulky machine was used for the sole purpose of pumping the accumulating water out of mining shafts, which at the time was the main constraint on production.[26]

More than sixty years of redesigns of that first steam engine were required to make it small and efficient enough in terms of coal use to free it from the collieries and put it to other applications. Most of the credit for the first economical, versatile steam engine goes to James Watt (1736-1819) and the company he co-founded with Matthew Boulton.[27] Watt's first major

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[17] Robert B. Marks (2012), 58.

[18] Paolo Malanima (2006), 103-104; Edward Anthony Wrigley (2010), 13-17.

[19] Marks (2012), 58; Greg Woolf (2020), 28-30, 120.

[20] Marks (2012), 65; H. J. Habakkuk (1967), 157-159. See also Vincent Geloso and Vadim Kufenko (2015).

[21] Berend (2013), 73; Rolf Peter Sieferle (2001), 81; Wrigley (2010), 106.

[22] Robert C. Allen (2009), 163.

[23] Landes (1969), 24. Spain, for example, wealthy and, like Britain, in possession of many colonies in the second half of the eighteenth century, lacked coal, so it was never a candidate to originate the Industrial Revolution: Berend and György Ránki (1982), 154. France did not have the right kind of coal for coking, and Germany's deposits in the Ruhr were as yet unknown. France's use of (non-mineral) charcoal in iron smelting was significant as late as 1875: Allen (2009), 231; Landes (1969), 139, 217. Belgium was the only continental European country to dig up coal on a substantial scale (still at around only 13 percent of Britain's output) during the period to 1850: Wrigley (2010), 98.

[24] Wrigley (2010), 38, 41. For the earlier history of coal-use in England, see Sieferle (2001), 82ff.

[25] Landes (1969), 101.

[26] Marks (2012), 65; Wrigley (2010), 44-45.

[27] Allen (2009), 171; Berend (2013), 73; Landes (1969), 102.

improvement (1769) was to condense the steam outside the piston chamber, saving the energy that went into reheating the piston upon each reinjection of steam.[28]

At the end of the eighteenth century, when Watt's patent on the separate condenser expired, Boulton & Watt Co. was responsible for manufacturing every steam engine in Britain (321 engines were in operation in 1800).[29] Watt's machine was at that point using 7.5 pounds of coal per horsepower hour, much less than the 30 pounds of the mine-bound Newcomen engine. By the mid-nineteenth century, the steam engine's coal consumption had fallen to 2.5 pounds per horsepower hour.[30] Boulton & Watt's invention went on to power industry and transportation around the world for more than a century.[31] As late as 1925, "England still derived 90% of its primary power from steam engines".[32]

The spread of Watt's engine turned heretofore modest-scale coal mining into a major industry. Up until 1800, most of Britain's coal production, at around 10 million tons per year (approximately 90 percent of world output), was used to heat homes and to light stoves in London.[33] Fifty years later, annual production in Britain had jumped to 44 million tons, representing around 80 percent of world production.[34] At that point, most of it was being converted into mechanical energy. The coal industry was taking off across Europe and beyond.[35] By 1880, for example, thousands of small coal mines were operating in Japan.[36] This was the energy revolution that set people free from the constraints of the biological old regime. Our way of life—not Britain's, but everyone's—is defined by this historical period, and by coal. Coal power caused "the greatest discontinuity in modern history".[37]

Private enterprise produced the steam engine and its applications, not the state. The government in London was supportive of private enterprise—but that was the extent of its involvement.[38] The proto-steam engine could not have left the coal mine before its dependence on huge amounts of essentially free coal had been broken. Entrepreneurial coal and steam-engine development reinforced each other, in a rising crescendo of individual initiative, which was necessarily place-bound. "Technical progress has a logic of its own",[39] and this is especially true of the place-bound path dependencies seen in the first century of the Industrial Revolution. In a world with a different practice of invention, the primitive Newcomen engine might have been transferred unmodified to every country with accessible coal reserves and left there to develop in different directions.

But this was not the way of the Industrial Revolution. "The full effects of technological change were often delayed by the need for gradual adjustments until a machine was properly fitted to a specific manufacturing process".[40] Allen calls this a "tipping point".[41] The Newcomen engine remained largely native to Britain, where it was studied by local engineers, including Watt.[42] It was methodically improved in the course of decades. After the tipping point, aspiring

[28] Habakkuk (1967), 158; Landes (1969), 102.
[29] Berend (2013), 69.
[30] Landes (1969), 103.
[31] Berend (2013), 69.
[32] Vaclav Smil (2005), 20.
[33] Marks (2012), 65.
[34] Berend (2013), 73. Higher production figures are given by Wrigley (2010), 37.
[35] For Belgium, France, and Germany, see Landes (1969), 194.
[36] Thomas C. Smith (1955), 46.
[37] Berend (2013), 62.
[38] Jonsson (2012), 681. See also Terence Kealey (1996).
[39] Habakkuk (1967), 181.
[40] Jonsson (2012), 682.
[41] Allen (2009), 149, 217.
[42] Allen (2009), 166-167. In fact, a Newcomen engine was installed in Liège in 1720-1, and by 1750 local ironworks had made copies of it. Through to 1790, 39 Newcomens or Newcomen "knock-

countries imported the finished technology, along with experts from Britain and the other core countries of the Industrial Revolution to guide its installation and operation.[43] By 1800, almost all steam engines in Continental Europe had come from Britain.[44]

From our perspective today, Boulton & Watt's genius—the speed at which the company improved the energy efficiency of its models—*prevented* unnecessary greenhouse gas emissions in the rest of the world resulting from widespread use of, or experimentation with, inefficient engines.

Automation in Textile Production

Once the steam engine was improved enough to be moved out of the mines, other private initiatives extended its use. It was adopted by Britain's textile industry. A torrent of inventions, originating both in Britain and soon in other parts of Western Europe, hastened the textile industry's coal-powered automation.[45] In 1783, the time taken to produce cotton yarn in Britain was already only six percent of what hand-spinning took in India. By 1830, British productivity in spinning cotton had further skyrocketed: "while it had previously taken 50,000 hours to spin 100 pounds of cotton, this was now reduced by the self-acting mule to 135 hours".[46] In 1845, Britain's textile industry was operating 17.5 million spindles and 250,000 power looms on steam engines.[47] It was this industry that, along with coal mining and the engineering of steam engines, defined the early (pre-railroad) Industrial Revolution.

Mechanization dramatically cut the price of textiles worldwide. Between 1784 and 1832, the price of one pound of cotton yarn dropped to one-twentieth of the price before mechanization.[48] Many more people would henceforth have access to convenient clothing. "Britain supplied the entire world with cotton products, and the volume of its exports was one-and-a-third times greater than its home consumption".[49] In the short term, Britain's advantage wrecked indigenous industries, notably in India.[50] But the advantage was short-lived.[51] A flood of imports from the mills of Lancashire was the stimulus for other countries to modernize.[52] They could do so without having to invent home-grown technologies to free themselves from the biological old regime. "The irony is that ... [t]he genius of British engineering undid Britain's comparative advantage".[53]

Efficiency gains from mechanization achieved in Britain were thus transmitted to the rest of the world. The London government was not above restricting access to the components of its advanced technology; however, industrial spies, smugglers, and copyists rendered such efforts futile. British technician-entrepreneurs were free to travel—and did so, for profit.[54] It was finally more profitable for Britain to allow the sale of the steam-powered machines abroad, while they were being constantly improved at home, than to expend resources on trying to hide them from sight.[55]

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offs" had been installed at mines in France. But this was the exception. The first Watt engine reached France in the late 1780s, when the model was already well advanced: Landes (1969), 141.

[43] Smith (1955), 46-47, 61.

[44] Landes (1969), 182. By 1800, France had 25 Watt engines: Allen (2009), 163.

[45] Berend (2013), 72.

[46] Berend (2013), 63.

[47] Berend (2013), 71.

[48] Ibid.

[49] Ibid.

[50] Landes (1969), 42; Prasannan Parthasarathi (2011).

[51] Tirthankar Roy (2011), 209-210.

[52] Landes (1969), 240.

[53] Allen (2009), 275.

[54] Allen (2009), 163.

[55] Landes (1969), 148 ff.

Mechanization's first triumph in Japan was in textiles. By 1899, 63 percent of all factory workers in Japan were employed in steam-powered textile mills.[56] For countries on the "periphery" of Europe during the age of industrial revolution, economic development was varied.[57] The Scandinavian countries quickly caught up with those of Europe's industrial core. By contrast, Balkan countries were still bogged down in the biological old regime at the end of the nineteenth century.[58] Of the sugar-producing countries across the Atlantic, Brazil was still an old-regime country in 1860 (only 1 percent of its sugar mills were steam-driven), in contrast with Cuba, whose relative proximity to markets enabled it to modernize quickly (70 percent of its sugar mills were steam-powered in 1860).[59]

Transmission was constrained not by any interest of the countries now blamed for historical responsibility, but by the demands of technological development. First, the early breakthrough inventions took decades to escape the local conditions favoring their local use and parallel development in their imperfect state; and, second, less-developed countries imported the core technologies (steam power, blast furnaces, etc.) as complete assemblies, not in fragments and not in an outdated form.[60] The timing of importation depended on an importing country's own local conditions. In the case of China, provincial rivalries, corrupt strongmen, and difficulties with raising risk capital, among other domestic obstructions, delayed the arrival of steam-powered spinning and weaving machines from Britain and the United States until 1883.[61] The Industrial Revolution created the potential for change for the better, which was open to all. Yet, extraneous factors—disincentivizing economic structures, totalitarian ideology, political ineptitude, and the destruction wrought by war (those glaringly obvious subjects of true historical responsibility)—deprived whole populations of industrialization's benefits for decades on end.[62]

The time of passing of the biological old regime in different regions was another important variable. Ongoing deforestation in India and China was one of the reasons these countries did not industrialize earlier. Their reliance on plentiful (for a while yet) biomass carbon energy delayed their exploitation of their own coal deposits.[63] Brazil, with seemingly unlimited forest to cut down, but with no coal to speak of, simply kept cutting down trees as the model of its economic development for a very long time, extending cane fields and coffee plantations into virgin land instead of fertilizing the old.[64] It is a model that Brazil has never fully disowned.

Despite these constraints and the many other challenges of the pre-modern world, elements of Britain's early Industrial Revolution had already been internationalized by 1800. The rise of the modern textile industry and the ongoing development of the steam engine and its applications beyond it had already taken on the character of a Western European achievement, influenced by numerous contributions by French and other Continental inventors.[65] As the Industrial Revolution matured, the time it took for technologies in the chain of coal-powered mechanization to escape local conditions and spread was reduced considerably. By the last quarter of the nineteenth century, for example, lightbulbs would be

[56] Smith (1955), 54.

[57] Landes (1969), 126 ff.

[58] Berend and Ránki (1982), 159-160.

[59] Richard Graham (1985), 748, 768.

[60] Allen (2009), 149, 164, 177, 217, 273; Alexander Gerschenkron (1966), 139; Habakkuk (1967), 141, 172-173, 181-182.

[61] Albert Feuerwerker (1958), 208-218.

[62] Wrigley (2010), 208-9. See also Deirdre Nansen McCloskey (2016) and Joel Mokyr (2002).

[63] Landes (1969), 126.

[64] Graham (1985), 748 ff.

[65] Berend (2013), 64, 77.

patented, commercialized, and diffused in just a matter of months after their experimental demonstration.[66]

Invention of the Railroad

The second phase of the Industrial Revolution began when the steam engine was freed from its stationary role in British mines and textile factories and put on wheels on iron tracks.[67] A locomotive version of Watt's engine was developed in the 1810s, replacing horses on colliery railroads.[68] The steam-powered railroad stimulated mechanized heavy industry. Britain again led the way.[69] In 1830 there was less than 60 miles of railroad track in the country; by 1840 it had grown to more than 4,470 miles, and by 1850 it had surpassed 23,000 miles.[70] The invention of mechanized coal-powered transport spread from Britain to the rest of the world as fast as local conditions allowed.[71] Egypt built its first railroad in 1851.[72] Each kilometer of track used around 190 tons of iron.[73] It took about two tons of coal to make a ton of iron. The growth of the iron-and-steel industry, which further deepened dependence on coal mining, created the backbone of modern economies everywhere.

Iron production had had a long history prior to the eighteenth century, of course, but the wood-fueled technology of the past did not allow for the production of pure metal. In 1709, in Britain, coal substituted for charcoal in furnaces for the first time. The cast-iron blowing cylinder for blast furnaces was invented in the 1760s. In 1776 it was combined with the steam engine, in one of the earliest experimental applications of the engine to a task other than pumping water. A Scottish inventor (J. B. Neilson) integrated the whole system with preheated air in 1829, decreasing coal (and, by then, coke) consumption by up to two-thirds.[74] "Between 1830 and 1850, the output of iron in Britain rose from 680,000 to 2,250,000 tons".[75] The country was still manufacturing half the world's pig iron in 1870.[76]

Greenhouse gas emissions from coal in Britain multiplied, we must presume, as industrialization reinvented metallurgy, but so did efficiency gains—gains that led to low prices for formerly prohibitively expensive necessities, such as iron, which were heavily polluting and environmentally destructive in their own right prior to their improvement through coal-based technology. During the 1830s alone, British innovations decreased the cost of iron production by two-thirds.[77] A century later (1940), India had around 38,000 people directly employed in the steel industry.[78]

To summarize the invention pathway so far: the passing of the biological old regime in Britain forced a reliance on coal in the country, which gave birth to the modern steam engine which was improved while modernizing the textile industry, which went on to create the railroad, which gave rise to the modern iron-and-steel industry—all on the back of spectacular increases in coal production and, from our perspective, the greenhouse gas emissions from

[66] Smil (2005), 9.
[67] Marks (2012), 65.
[68] Wrigley (2010), 105.
[69] Berend (2013), 76.
[70] Marks (2012), 66.
[71] Railway engines at first used wood fuel in some countries (for example Russia), but switched to coal once the railway system, and fuel demand, grew.
[72] Charles Philip Issawi (1982), 6.
[73] Marks (2012), 66.
[74] Berend (2013), 72.
[75] Marks (2012), 66.
[76] Landes (1969), 219.
[77] Berend (2013), 72.
[78] G. D. Birla (1944), 122.

its mining and use. It was a time as historically transformative as any to accompany an invention, before or since.[79]

The Railroad's Challenge to Under-Development

Let us consider the railroad's arrival in Russia, China, and India as examples both of the speed at which the revolutionary technologies spread around the world and the general improvement to living standards they brought with them.

In the mid-nineteenth century, Russia was still, by the standards of Britain and Western Europe, a backward country.[80] Agriculture was primitive; the chemical industry lagged behind the advanced countries by a generation; and the machine industry was in an infant stage. A legacy of serfdom had left the country without craftsmen or technical training.[81] Traditional ways dominated:

> The horse, the sail, the hand loom, the water wheel, and the human barge hauler were the rule, and the intrusion of the new machines and processes were more often than not the work of foreigners come to Russia or, even more frequently, imported products of factories and laboratories in Europe and America.[82]

Russia was government-heavy and light on entrepreneurship—the very opposite of the political economy in Britain.[83] Its conditions of backwardness began to recede around 1850. The railroad's influence was significant. Private enterprise in the United States brought the materials and know-how for railroad construction to Russia.[84] The St Petersburg-Moscow line, at a length of 404 miles, was the first major railroad built in the country.[85] It was officially opened by the emperor Nicholas I in 1850. A civilian passenger service on the line began a year later. American engineers built the locomotives and the rolling stock; and they came in person to Russia to introduce and oversee the management practices that would complete the project on time.[86] Production of railroad equipment in Russia itself would not be achieved before 1866.[87]

The country was lifted by its imperial railroad project. Until 1862, when another line was completed (the St Petersburg-Warsaw), "the Nicholas railway remained the largest in the world and the best equipped".[88] Railroad construction created a general demand for industrial products.[89] The government decided that this would be its track to industrialization, for the country was plentifully endowed with the two basic materials of the Industrial Revolution—coal and iron ore.[90] Within a few years, more major lines (including the Moscow-Kursk and the Moscow-Ryazan) were completed. Freight and passengers from the interior of Russia flowed west across the country's enormous expanses to trading and educational centers.[91] Large-

[79] Landes (1969), 42.

[80] Berend and Ránki (1982), 145.

[81] William L. Blackwell (1968), 393; Gerschenkron (1966), 119-124; Reginald E. Zelnik (1971), 292 ff.

[82] Blackwell (1968), 393.

[83] Gerschenkron (1966), 126; Landes (1969), 130 ff.

[84] Gerschenkron (1966), 125. As late as the 1870s, Russia's home production of iron and steel yielded only 40 percent of what it consumed: Berend and Ránki (1982), 152.

[85] A smaller railway, 14 miles long, from St Petersburg to Tsarskoye Selo, was opened in 1837 (P. J. G. Ransom, 1990, 575).

[86] Blackwell (1968), 314-319.

[87] Zelnik (1971), 212.

[88] Blackwell (1968), 319.

[89] Gerschenkron (1966), 126.

[90] Berend and Ránki (1982), 152.

[91] Blackwell (1968), 319.

scale coal mining, iron forging, and railroad construction continued through to the end of the nineteenth century, spurring an average annual rate of industrial growth of around 8 percent during the 1890s.[92] The country's steel mills were installed by engineers from Germany, Belgium, and France.[93] "Russia ... had profited from several decades of American and English experimentation".[94] From the 1890s on, it would rapidly catch up with the pioneering nations, to become "a part of the core".[95]

Under the influence of the Americans and other early industrializers, Russian mechanics built and mass-produced machinery for heavy industry, the quantity of which quickly surpassed the volume of imported technology.[96] Half a century later, after the Second World War, Russia—now as part of the Soviet Union—would export its technology for heavy industry to Mao's China.[97] China would overcome its own under-development in the same way as Russia, by borrowing the technologies of industrialization from more advanced countries. That process began in earnest in China in 1896, with the founding of the Imperial Railway Administration. The Hanyang Ironworks became the central supplier of rails for China's railroad system. European finance and British and Belgian expertise enabled the construction of 3,000 miles of railroads.[98] China's borrowing culminated a century later, under the leadership of Deng Xiaoping. A wealth of technologies and labor practices that had grown out of the West's revolutionary period for industry were imported ready-made into China in colossal quantities and at a breakneck speed, from countries including Japan and the United States.[99]

India's railroad system was installed by the colonial government with capital raised in Britain. In this case, too, there was no externally enforced delay in any sense. Railroad planning began in the 1840s, during the "Company" period. By 1860 (two years after formal colonization), there were 838 miles of track in the country; by 1870, 4,771 miles. By 1885, all forty of India's largest urban centers had rail service. By 1890, India was ahead of Italy and Canada in track mileage; by 1910, it was ahead of France, the United Kingdom, and Austria-Hungary.[100] Relatively rapidly, then, India's railroad system was on a par with those of the countries now the target of the historical responsibility thesis.

Prior to the railroad's arrival in India, transportation across the vast country was by pack animals and small sailing vessels. Coal power "revolutionized the mobility of people and goods in South Asia".[101] Transport costs per mile fell to one-fifth of what they had been.[102] Almost all the material for the construction of India's railroad system up until the First World War was imported from Britain. London may have prioritized the project in order to tighten its grip on the country. This does not diminish the railroad's public benefits. As a result of the reduction in transportation costs, Indian exports of raw cotton increased enormously.[103] The railroad also addressed the problem of some Indian regions being perennially short of grain;[104] mechanized transportation, by "distribut[ing] food quickly between surplus and deficit regions" and by

[92] Gerschenkron (1966), 129. This compares with a growth rate of around 3 percent for Europe as a whole: Berend and Ránki (1982), 143-144. On Russia's coal production, see John P. McKay (1970), 141-143.
[93] McKay (1970), 126.
[94] Blackwell (1968), 394.
[95] Berend and Ránki (1982), 143, 152-153; McKay (1970), 113.
[96] Blackwell (1968), 394.
[97] Alexander V. Pantsov and Steven I. Levine (2013), ch. 27.
[98] Feuerwerker (1958), 67-69.
[99] Ezra F. Vogel (2013), ch. 16; Qing-Ping Ma (2021), particularly 19-20.
[100] John Hurd II (1975), 266-267.
[101] Roy (2011), 241.
[102] Hurd (1975), 268.
[103] Roy (2011), 241.
[104] Hurd (1975), 265-266.

helping to converge the prices of foodgrains across India toward a single price, reduced famines in the country.[105] Today, "Indian Railways handles 3 million tonnes of freight and 23 million passengers daily and is the world's third largest network".[106]

Agriculture and Population Growth

As fossil fuels multiplied productivity manyfold through mechanization of industrial production and transportation, they also revolutionized agricultural output. They delivered suddenly (on a historical timescale) vast quantities of good-quality cheap food to hungry people within countries and across continents. They did so in part by enabling the creation of fertilizers and in part through mechanization.

In the biological old regime, the limits to agricultural productivity were reached soon after farming was first practiced.[107] Land had to be left fallow, or else soil nutrients had to be replenished with the ash of burned biomass or with manure, among other labor-intensive methods and scarce sources—only for the soils to lose their fertility again after one or two harvests.[108] The critical ingredient was nitrogen, and there was no easy way to increase it in the soil. Only artificial fertilizers could help farmers break through the old regime's limit: "The major breakthrough ... came in the 1910s with the discovery of nitrogen fixation via ammonia synthesis ... It required only a cheap supply of electricity—and thus a cheap supply of fossil fuels".[109]

Smil considers ammonia synthesis "perhaps the most far-reaching of all modern technical innovations".[110] In 1947, the United States used 17 million tons of synthetic nitrogen fertilizer.[111] Global nitrogen production for fertilizer in 1980 reached 55 megatons per year, 85 megatons in the 1990s.[112] The world's largest consumer of nitrogen fertilizer is China.[113] Its ammonia production still relies overwhelmingly on coal, instead of the climatically less disruptive natural gas.[114] Following Nixon's 1972 state visit to China, the country placed orders for thirteen of the world's largest and most modern ammonia-urea complexes. They were supplied by M. W. Kellogg, the US-based leader in ammonia synthesis. Increases in fertilizer applications "were essential for lifting populous low-income countries from the conditions of bare subsistence and widespread malnutrition".[115] They also polluted waterways, with immediately apparent effects. Little action was taken against the damaging run-off of artificial fertilizers before the advent of environmentalism in the 1970s. In general, however, people have valued their new-found power over food production more than the environmental quality given up in exchange for it.

About a century was to separate the coal-mining revolution in Britain from the revolution in global food production. But the chain of fossil-fuel-dependent enabling technologies is plain to see.

As coal provided energy and feedstock for fertilizer production, so did Watt's coal-driven machine find its way into agricultural uses. In the United States, horse-drawn equipment (reapers, mowers, threshers, binders) began to be replaced in the 1860s with engines.[116] In

[105] Roy (2011), 234, 241.
[106] India (2016), 14.
[107] Woolf (2020), 107-108, 119-121.
[108] Paul Josephson (2012), 341.
[109] Meredith McKittrick (2012), 415.
[110] Smil (2005), 7.
[111] McKittrick (2012), 415.
[112] Houghton, et al. (1990), 27; Smil (2005), 194.
[113] McKittrick (2012), 420-421.
[114] Seyedehhoma Ghavam, Maria Vahdati, I. A. Grant Wilson, and Peter Styring (2021), 3.
[115] Smil (2005), 196.
[116] McKittrick (2012), 413.

the early 1890s, a few hundred steam-powered agricultural tractors were operating in the United States.[117] They were cumbersome by later standards, namely the internal combustion engine. The main early impact of steam power on farming was its facilitation of the transportation of produce through an expanding network of railroads and steamships. “American farmers who sold 30 percent of what they harvested in 1820 were selling 60 percent of their harvest by 1860”.[118]

The first commercial wood-burning steamship service in the United States launched in 1811. It carried hogs from Pittsburgh to New Orleans and cotton on the return journey.[119] As with the railroad, steamships increased the demand for iron. The world’s first iron steamboat began trading between England and France in 1820.[120] Steamships would eventually be powered by steam turbines, which were in themselves a revolutionary redesign of the piston-based steam engine. The Canadian Samuel Cunard’s transatlantic steamships began operating in 1840. They reduced the westward Atlantic crossing time from thirty to fourteen days. Using coal instead of wood fuel, they had more space in the hold for agricultural produce.[121] India acquired its first steamship in 1823; Egypt in 1837.[122] “The railway and steamship were global technologies from their inception”.[123]

The US model of agricultural productivity was exported to technologically under-developed countries ready-made. In 1912 Russia imported 40 percent of its agricultural machinery from the United States. Such imports had increased sevenfold over the period 1898-1918.[124] At around the same time, the US invention of the gasoline-fueled tractor brought the internal combustion engine to the farm.[125] Eighty US companies produced more than 20,000 liquid-fuel tractors in 1913.[126] American private enterprise—Ford, International Harvester, John Deere—perfected the new fossil-powered machine, while promoting the export of its successive models into the global economy.[127] It was much in the way that Watt had done with the steam engine, only a great deal faster. Depending on where the machine was being used, the origin of the oil in its tank might be Indonesia, Peru, or any one of several other under-developed countries, which could now join the industrial transformation with domestically produced petroleum products compensating for a lack of coal (as in the case of Peru).[128] There were 920,000 tractors in the United States in 1930, 1.6 million in 1940, and 2.4 million in 1945.[129] In the year of the IPCC’s first assessment report, in 1990, there were 23.3 million working tractors worldwide.[130] India manufactured 125,000 new tractors in that year. India is now one of the world’s leading manufacturers of tractors.[131]

The twentieth-century agricultural revolution was transmitted to much of the rest of the world through the so-called “Green Revolution”. The program began after the Second World

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[117] Smil (2005), 142.
[118] McKittrick (2012), 413.
[119] Daniel Walker Howe (2007), 138.
[120] Daniel R. Headrick (1979), 237.
[121] Howe (2007), 215.
[122] Headrick (1979), 236-239.
[123] Allen (2009), 178.
[124] Blackwell (1968), 392.
[125] Josephson (2012), 343.
[126] Smil (2005), 143.
[127] Josephson (2012), 343.
[128] Joost Jonker, Jan Luiten van Zanden, Stephen Howarth, and Keetie E. Sluyterman (2007), Vol. 1; Landes (1969), 281; Rosemary Thorp and Geoffrey Bertram (1978), 97-102.
[129] Josephson (2012), 343.
[130] World Bank, “Agricultural Machinery: Tractors.” Accessed November 16, 2022. https://data.worldbank.org/indicator/AG.AGR.TRAC.NO?end=2009&start=1961.
[131] Anupam Sarkar (2013), 56.

War, at the initiative of the US government and private foundations, such as the Rockefeller. Despite the label accorded to it, the system was "completely reliant"[132] on fossil fuels:

> The Green Revolution raised the total world harvest [through its use of high-yield seed varieties, or HYVs]. The initiative, funding, and vision of agriculture that made the Green Revolution possible all originated in the US. ... In 1970, 10 to 15 percent of wheat and rice crops in the developing world were planted in new varieties; by 1991, three-quarters were. ... HYVs were bred to respond to a technological package of synthetic fertilizers, pesticides, mechanization, and irrigation.[133]

That is to say, the package of the mineral paradigm.

The corporations providing the seeds naturally benefited. So did the chemical industry that produced the pesticides that were an essential part of the Green Revolution. The health costs of excessive pesticide use were not seriously addressed until after 1962—the year in which Carson's *Silent Spring* was published. The poisons were redesigned and more closely regulated. This, and a balance of benefit, ensured their ongoing use.

The creation of modern agriculture powered by fossil fuels led to food security for the first time in history. No country was to enjoy such security until it had adopted the carbon-based model.[134] People have lived longer lives as a result, and the global population has grown from around 1 billion in 1800, to 2 billion in 1900, to 8 billion today. Food production since the 1960s has ceased to be a real concern for most people, having galloped ahead of population growth for the past half century.[135] (Equitable access to it is another matter entirely.) The long Industrial Revolution ultimately also reduced the rate of forest loss, by making agriculture more productive through mechanization and fertilizers: "without the Green Revolution, crop yields would have been almost 25 percent lower in developing countries, grain prices would be higher, and far more land would have been placed under cultivation".[136]

Electric Power

William Murdoch, who worked at Boulton & Watt, invented the controlled burning of gas, which led to gas lighting, which by 1798 became an international enterprise. It illuminated streets in the United States from 1805, and it had spread to homes by the 1820s.[137] It is an example of the interconnections among the inventions (and inventors) of that period.

Artificial lighting increased the quality of life and public safety for people everywhere. It was a fossil-fuel technology through and through. Gas lighting began to be phased out in 1870, replaced by electric lighting, which was powered by a dynamo connected to a steam engine.[138] Thomas Edison demonstrated incandescent lighting in 1879, and the first electric street lights appeared a year later.[139]

Universal diffusion of the technological offspring of the Industrial Revolution was, by the late nineteenth century, relatively rapid. However, the history of electric power best illustrates a different point. The emission-intensive technologies of the countries alleged to carry historical responsibility matured into such a variety of interlinked elements that new inventions

[132] McKittrick (2012), 425.
[133] McKittrick (2012), 420-421.
[134] McKittrick (2012), 412.
[135] Jeremy Woods, Adrian Williams, John K. Hughes, Mairi Black, and Richard Murphy (2010), 2996-2997; Food and Agriculture Organization (2021), 222.
[136] McKittrick (2012), 422. In parallel with strong growth in food production, agricultural land has massively *decreased*: Food and Agriculture Organization (2021), 34.
[137] Berend (2013), 75.
[138] Berend (2013), 219.
[139] Smil (2005), 43, 52.

in the chain *had to*—practically, conceptually—keep flowing from those same countries, extending their association from the present point of view with an increasing volume of greenhouse gas emissions—the emissions of invention. Henry Ford worked for Edison before setting up his motor company in Detroit in 1903 with a coal dealer as his principal investor.[140] Arnulf Grübler describes the phenomenon as “a set of interrelated technological and organizational innovations whose pervasive adoption drives a particular period of economic growth”.[141] Smil illustrates the interlinkages in the sphere of electric power:

> The most notable concatenation brought together incandescing filaments, efficient dynamos and transformers, powerful steam turbines, versatile polyphase motors, and reliable cables and wires for long-distance transmission to launch the electric era during a mere dozen or so years.[142]

When the adopting countries, which advocates of historical responsibility would have us regard as being morally unburdened bystanders, purchased such assemblages from the accused countries, they implicitly accepted that the “concatenation” they were benefiting from was, as a historical phenomenon, unfolding on foreign soil.

Automobiles and Jet Engines

The invention and mass production of automobiles occurred over many decades of private investment by hundreds of firms in countries we now call developed.[143] In this particular case, the gravitational center of development was Germany.

> After a full decade of work ... Otto produced the first practical four-stroke engine in 1876. Daimler, technical director [of the factory co-owned by Otto] took the next decisive step in 1887 when he constructed the first petrol-driven car together with ... Benz. Another invention in the 1860s, the process of oil refining, provided suitable fuel for the engine.[144]

There was no “alternative history” to the chain of self-propelled vehicles—wheeled steam engines at first, later powered by the internal combustion engine—that was somehow denied to today’s developing regions, as the historical responsibility thesis would have us think. The technology of vehicle manufacture, culminating in mastery of the low mass/high power machine that outsmarted the steam engine, was too complicated to emerge in disparate places which did not already possess a wealth of manufacturing firms with capital to invest in new ventures and the capacity to withstand technological dead ends. The phenomenon of path-dependency, of one “technology family” begetting another,[145] is plain to see in this history.[146]

The “no alternative” thesis does not deny that solar as opposed to mineral forms of energy had a potential to develop more than they did, in fact, in the 1800s. However, their role could not but be supplementary, marginal, to the coal-based revolution. For instance, in 1860, Italy was far behind even Russia in its use of steam engines. Hydropower in the country compensated to some extent for its lack of coal, supporting the growth of a light industry.[147]

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[140] Smil (2005), 130.
[141] Grübler (1998), 117.
[142] Smil (2005), 11.
[143] Smil (2005), 99-115.
[144] Berend (2013), 218-219.
[145] Grübler (1998), 117.
[146] Smil (2005), 100-102.
[147] Landes (1969), 221.

However, hydropower at scale, in addition to being environmentally harmful in its own right, necessarily required generous quantities of fossil-fuel-intensive cement and steel. These industries, therefore, needed to have attained a more advanced state of development than hydropower technology, and preferably to be installed locally, for ease of access. As solar energy could neither be stored nor transported, Italy remained a tradition-bound agricultural country, with appalling backwardness in the south, until it began to scale up its imports of fossil fuels and the machines and processes they fed, in order to catch up with the core countries in the manufacture, not only of steel and cement, but also of artificial fertilizers—as well as cars before the end of the century.[148]

Automobiles and the technology of car-making spread quickly to the world's under-developed regions. In the case of at least one such country, South Korea (which is still classified as developing under the climate change treaties), the technology came to define its present-day economic profile. Beginning in 1970, Korea's government-controlled industry was the breeding ground for the country's big-three automobile manufacturers.[149] It is an implication of the historical responsibility thesis that Korea can rightfully blame the early-industrializing countries for their early emissions from the steam engine and demand compensation for its unfair loss of "atmospheric space". But this would be an illogical claim. It is undermined by the fact that Korea's government rushed auto-manufacturing technology into the country and staked its future development on it. Here, indeed, at the adopting end, we see *the state* making the choices, not private enterprise, as was generally the case during early industrialization in the core countries. The coherent conception of this history, then, is that the early greenhouse gas emissions in Western Europe were a precondition for the development of the internal combustion engine, which brought the technology ready-made to Korea's door. Like every other non-accused-group country, Korea used the motor vehicle as a basis of its modern economy, although Korea itself benefited far more from it by adopting auto-manufacturing as its major industry.

A notable case of across-the-board adoption is Brazil. This country is one of the most vocal promoters of the accusation of historical responsibility at the international climate change negotiations. Through a submission to the governing body of the UNFCCC in 1997, Brazil formally laid out a case for historical responsibility for climate change.[150] Of the myriad aspects of Brazil's economic history that fly in the face of that submission, we might recall its adoption of its first major railroad, the São Paulo line, constructed by a British company in 1868 to assist the country with the development of its coffee trade.[151] It was a time of intense railroad development in South America, conducted "amid an atmosphere of almost feverish promotion".[152] A century of diverse industrializing adoptions later, the country came to specialize in building commercial aircraft. Brazil's Embraer's order backlog at the end of the second quarter of 2022 was worth US$17.8 billion.[153]

The particular instances represented by Korea and Brazil should not detract from the key point, which is that the embrace of fossil fuels and the technologies built around them was a global phenomenon. Obviously, most countries could not, or did not choose to, pursue automobile or aircraft manufacturing. But those countries still availed themselves of a set of technologies descended from the Industrial Revolution that are so ingrained in our way of life

[148] Berend and Ránki (1982), 150-151.

[149] I.e. Hyundai, KIA, and Daewo; see *Encyclopaedia Britannica*. Accessed November 16, 2022. www.britannica.com/technology/automotive-industry/Europe-after-World-War-II.

[150] Brazil (1997).

[151] Graham (1985), 763-764.

[152] William Glade (1986), 42.

[153] Embraer S.A., "Embraer Earnings Results 2nd Quarter 2022", August 4, 2022. Accessed November 16, 2022. https://embraer.com/global/en/news/?slug=1207080-embraer-earnings-results-2nd-quarter-2022.

as to be almost invisible to us. Smil's perhaps surprising remark about ammonia synthesis being the modern era's crowning glory may thus be appreciated for its insight into how a lifesaving technology of industrialization has been rendered utterly mundane with time.

Development Finance

I will address one last issue that weighs against the historical responsibility thesis. It concerns development finance. Of the twenty-five multilateral development banks (global, regional, and sub-regional) currently in existence, all but six were established prior to the beginning of the "current" period of climate change responsibility in 1990.[154] Of the regional ones, the Inter-American Development Bank, African Development Bank, Asian Development Bank, and Islamic Development Bank were set up in 1959, 1964, 1966, and 1975, respectively. Through to 1990—for a collective total of 96 years—these four banks, underwritten by today's developed countries, fostered economic growth around the world. Most of it was infrastructural or energy-related carbon-based development.

The World Bank's development finance began to flow right after the end of the Second World War. In essence, the Bank took the steam engine's progeny (electrical grids, irrigation systems, roads) and installed them in every corner of the globe.[155] The Asian Development Bank with the support of the recipient countries it was set up to benefit and in conformity, of course, with the agenda of its backers, identified in its first annual report the industrialization of agriculture and the expansion of transportation systems as priorities for the Asian region.[156] The Caribbean Development Bank, which started up in 1969, presently finds itself in the awkward position of needing to raise at least US$30 billion in investment to wean the region off the fossil-fuel dependence that the bank itself created in the region, with the consent of its member states, over the preceding half-century.[157]

While the ideology of the multilateral development banks is a fiercely debated topic,[158] these institutions were certainly committed to a global culture of well-being through industrialization. They were embraced everywhere, except where there was a commitment to centrally planned economies. The Socialist regimes were also industrializing, of course, although with a disregard for environmental values that to us now defies comprehension.[159]

Conclusion

The mineral-fueled technologies of the Industrial Revolution were the product of private industry, of enterprising investors who sought to make a profit. Watt, foremost among them, epitomized "the private R&D model of technical change".[160] The revolutionary technologies needed to be tested, produced in small quantities at first, made safer and more efficient and versatile, before being mass-produced for sale, whereupon they were made available to any buyer, anywhere. There were no "inventor countries", as such. A country's mineral fortune and other "lucky" circumstances (such as the cost of labor being high[161]) facilitated the rise of

[154] Ihsan Ugur Delikanli, Todor Dimitrov, and Roena Agolli (2018), 10.

[155] See World Bank, "History". Accessed November 16, 2022. https://www.worldbank.org/en/archive/history.

[156] Asian Development Bank (1968), 18-21.

[157] See Caribbean Community Climate Change Centre, "Caribbean Needs $30 Billion Of Investment To Cut Fossil-Fuel Use", undated. Accessed November 16, 2022. https://www.caribbeanclimate.bz/blog/2014/08/11/caribbean-needs-30-billion-of-investment-to-cut-fossil-fuel-use/.

[158] Matthias Schmelzer (2022).

[159] John Scott (1942).

[160] Allen (2009), 167.

[161] Allen (2009), 137; Habakkuk (1967), 132 ff.; Landes (1969), 115.

inventor individuals. Their inventions gave the countries in which they happened to be located a natural economic advantage, not only because they were exploited there first, not only because the inventors were entitled to enjoy the income from their patents for a period of time, but also because the things they invented (coal-made fertilizer, oil-powered engines, and so on) were elements of what turned out to be a functionally coherent line of inventions that gave the original inventors and those in their surroundings a better chance to hit upon the next important link in the technological chain.

A small number of uniquely endowed countries led by Britain therefore moved ahead of the rest in a flurry of technological mutations that accelerated a continuous economic evolution for more than a century. As those countries grew their economies, they did not in fact move very far ahead of the rest. Many periphery countries were soon able to copy them and were lifted up at a pace that depended on their own constraining circumstances (such as those of Russia and China). Transmission programs such as the Green Revolution and those of the World Bank ensured that technological uptake was not merely passive but was positively encouraged.

The Industrial Revolution "was the first economic phenomenon in history to generate permanent, sustained growth".[162] It offered a global vision of world industry, transportation, agriculture, and sustained prosperity, resting on the abundant, cheap, energy of fossil fuels. It was created, as I have sought to emphasize, by individuals, not states, although states with their grand projects in peace and war were the leading consumers of these technologies. The uses to which they were put (for example, the steamboat) were sometimes oppressive—imperialistic, Christianizing, "philanthropic".[163] (Early steamboat boilers frequently exploded, killing hundreds.[164]) Many workers, notably in India, who bore the brunt of early competition with Britain, were left behind, but in the long run most were not, at least in absolute, if not always relative, terms. By the end of the nineteenth century, every human life was touched to some degree by industrialization, except perhaps in the globe's remotest areas. Historical responsibility's view of the early historical period of greenhouse gas emissions as one of clubby elite advantage to the exclusion of the international community's poorer members is false. Up until 1990, when the IPCC's first report began to shift attitudes, fossil-fuel development was welcomed and encouraged everywhere, including by scholars.[165] The rich countries had become richer since 1800, but so too had the poor countries Development is not a zero-sum game. The cake metaphor does not apply to it.

In this article, I have recounted, not a history of progress, certainly, but a history of shared responsibility. I have argued that a self-reinforcing process of private initiative in the core countries of the Industrial Revolution, led by enterprising individuals in Britain, invented economic development and spread it to the rest of the world. Ignorance of the greenhouse effect during the early historical period is not the main defense of today's developed countries against the accusation of historical responsibility. Their main defense is that emitting greenhouse gases was a byproduct of a technological breakthrough that benefited humanity as nothing else has before or since. The technological foundations of the fossil-fuel age were transmitted widely by engineers and corporations and other entrepreneurial bodies and were adopted as the development model of every country in the world, creating out of the carbon deposits of prehistory a vast, healthy, well-fed, educated, and leisured middle class the globe over. The greenhouse gas emissions of the Industrial Revolution's first century were exported, we now see, along with the technologies whose development they supported to the world's

[162] Berend (2013), 74.

[163] Headrick (1979).

[164] Howe (2007), 214-215.

[165] It is instructive to look back at literature from the 1980s to be reminded of how uniformly fossil-fuel development was extolled. See, for example, Smil and William E. Knowland (1980), 121-125 (for China), 173-177 and 204-205 (India), 233 (Brazil), 291-294 (Zaire), and 323-324 (Indonesia).

developing regions, diluting across space and time the responsibility for the latter-day phenomenon of climate change. This is the necessary moral implication of universal adoption, in a context where all parties are ignorant of underlying dangers and can see only benefits. If there is a debt that has been incurred, it is that which humanity collectively owes to the rest of the world it inhabits—to the flora, fauna, and ecological systems that have been eliminated or are on the brink of collapse.

One might question whether it is necessary to go to the lengths I have gone to in this article to refute the historical responsibility thesis. I believe it is. What makes humans different from other species, including in their response to life-threatening environmental challenges, is that they evolve their adaptive behavior, not through changing their biological make-up but through learning and cooperation.[166] The universal adoption of fossil-fuel technologies was a product of learning and cooperation for mutual benefit. The management of the problem of climate change must be achieved in the same way. The historical responsibility thesis seeds conflict, not cooperation, when cooperation is needed more than ever before.

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