ENERGY, MINING, AND THE COMMERCIAL SUCCESS OF THE NEWCOMEN “STEAM” ENGINE

A dissertation presented

by

John Paul Murphy

to
The Department of History

In partial fulfillment of the requirements for the degree of Doctor of Philosophy

in the field of

History

Northeastern University
Boston, Massachusetts
April 2012
ENERGY, MINING, AND THE COMMERCIAL SUCCESS OF THE NEWCOMEN “STEAM” ENGINE

By

John Paul Murphy

ABSTRACT OF DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in History in the Graduate School of Arts and Sciences of Northeastern University, April 2012
Abstract

This dissertation is about energy; specifically how prime movers changed at the beginning of the Industrial Revolution. These power needs are explored via the history of the Newcomen atmospheric engine, as it was used in the 18th century to drive pumps in flooded mines. This approach examines society as an energy-converting phenomenon, and uses the concept of an energy rent.

The dissertation seeks to reach past the 19th century’s “high-pressure historiography” of the first engines powered by fire; instead, it traces the actual low-pressure atmospheric technology of the first commercially successful engines, and the surprising, rather than inevitable, transformation they engendered. The costs of fuel are shown to be an essential factor in the success or failure of the first Newcomen engines. Thomas Newcomen’s failed first attempts in Cornwall (1710) are contrasted with success in collieries, located in the relatively distant region of the Midlands, only two years later.

To test the suggestion that coal is needed for a Newcomen engine to be profitable, two detailed case histories compare 18th century engines, both fired using wood fuel, at iron ore mines. The first was a failed engine at Dannemora, Sweden (1728); the second a successful machine built by the Brown brothers at Cranston, Rhode Island (1783). The Brown engine’s case history was based on extensive original archive research, and also provides a detailed history of the Hope Furnace, which used the ore from Cranston. Success for the Browns in Rhode Island is found to have been rooted in their careful planning for fuel needs. The two mines were also found to have significantly different construction of gender roles, suggesting the Rhode Island context had established more thoroughly capitalist relations.
The work shows that the demand for more extensive power, which led to these engines, was propelled by the ability of the evolving commercial market place to convert energy profitably (16\textsuperscript{th} and 17\textsuperscript{th} centuries in Europe). The resulting pressure to expand society’s energy envelope created this “need” for primary power, which was particularly acute at mining enterprises. A vocabulary for cross-comparing primary movers is developed. The Newcomen engine is found to have teetered on the border between negative and positive energy rents. The dissertation concludes that it tipped positive, when applied in an energy intensive environment, thus contributed to a divergence from the equilibrium of an advanced agricultural society.
Acknowledgements

The production of this dissertation would not have been possible without the generous support, intellectual and otherwise, from a number of people. First and foremost I want to thank my dissertation advisor Ballard Campbell. Professor Campbell showed remarkable judgment in knowing when to let me wander in the intellectual wilderness, and when to reel me back in, until eventually I figured out where I was going. Warmest thanks to my committee members Professor Clay McShane, whose horse sense greatly improved the content, and Professor M. Shahid Alam, who was generous with his time and many insights on energy.

Within the history department, I need to thank Professors Laura Frader and Chris Gilmartin; at an interview, oh so long ago, they welcomed me into the department, and guided me along during my first years here. Thank you to Anna Suranyi for her suggestions regarding the Atlantic World; and also Professor Fowler, not just for his insights on colonial history, but also for his example that a good historian should develop a little bit of swagger – a certain panache – as it helps clarify to people that what historians are telling them is important. Critically important. And a special thank you to Nancy Borromey, my guardian angel protecting me from the bureaucracy and deadlines.

I was also helped in my research by a number of people outside the Northeastern community. I owe a debt to the staff at the John Carter Brown library, especially Manuscript Librarian Kimberly Nusco, and also the staff at the Rhode Island Historical Society. The dissertation was improved by being able to draw on the world views of Professor Prasannan Parthasarathi of Boston University, Professor Steve Mrozowski of University of Massachusetts at Boston, and the work of Professor John Sterman, director of the MIT System Dynamics Group.
Thank you, too, to the people who labored in the iron ore pits at Cranston; people like Sharper, a slave who was sent to toil there, and William Tyler, who lost his life there. The fruit of their hard work was rendered into iron; it has no doubt been recast and knocked around in several incarnations since then, but it is still among us somewhere. In their way, they contributed to the building of the world around us today. It is hoped that this dissertation can, in a small way, make a similar contribution to the future.

Finally, saving the best of all for last, I must thank my wife Mary Murphy; she is my biggest supporter and my best friend. Her encouragement and suggestions are woven throughout this entire work. Without her, this dissertation simply would not have been possible.
### Table of Contents

Abstract ........................................................................................................................................... 4  
Acknowledgements .......................................................................................................................... 6  
Table of Contents ............................................................................................................................ 8  
Introduction ................................................................................................................................... 13  
Part I: Literature Review .............................................................................................................. 24  
  Chapter 1: Exceptional Europe, Exploiter Europe ................................................................. 24  
  Chapter 2: Divergence and Energy ......................................................................................... 45  
PART II: The Energy Milieu ....................................................................................................... 73  
  Chapter 3: Commercialization, Energy Demand, and the Flooding of Mines .................... 73  
  Chapter 4: Primary Energy in the 17th Century, and Its Limits ............................................. 96  
Part III: First Commercial Engines 1712 to 1770 .................................................................. 125  
  Chapter 5: Precursors to the Newcomen Engine ................................................................. 125  
  Chapter 6: The Obscure Mr. Newcomen ............................................................................. 139  
  Chapter 7: Technical Improvements and Political Gains .................................................... 162  
Part VI: A Newcomen Engine at an Iron Mine: Dannemora, Sweden 1727 ......................... 181  
  Chapter 8: Energy Demand at the Dannemora Iron Mine ................................................ 182  
  Chapter 9: Energy’s Role in the Failure at Dannemora ....................................................... 203  
Part V: Newcomen in North America ....................................................................................... 223  
  Chapter 10: The First Engines in the Americas ................................................................. 223  
  Chapter 11: Hope Furnace and the Cranston Iron Ore Pits ................................................ 243  
  Chapter 12: Hope Furnace and the American Revolution .................................................. 280  
  Chapter 13: The Brown Steam Engine at Cranston ........................................................... 302
List of Figures

3.1 Kuntna Hora Silver Mine.................................................................87
3.2 Counterfactual Graph of Mine Depths..............................................94
4-1 One-man Force Pump.................................................................98
4-2 Two-man Ball-and-chain Pump..................................................100
4-3 Tread-wheel Hoist.................................................................101
4-4 Horse Whim for Raising Bags of Water......................................102
4-5 Waterwheel Driving a Ball-and-chain Pump.................................104
4-6 Waterwheel Driving an Array of Piston Pumps..............................105
4-7 Wind and Goat-power.............................................................106
5-1 19th Century Depiction of “Hero’s Steam Engine”..........................127
5-2 19th century Depiction of Automatic Greek Temple Doors..............128
5-3 Guericke’s Cylinder with a Movable Top (a Piston).......................134
6-1 Map of Newcomen’s England.....................................................149
6-2 Diagram of a Newcomen Atmospheric Engine..............................152
6-3 “Dudley Castle” Engine, 1712..................................................157, 158
6-4 1717 Engraving of the Engine at Griff.........................................159
6-5 Detail, Rendered from 1717 Engraving........................................160
7-1 Coal Fields of Britain...............................................................164
8-1 Iron Works around Dannemora Mine..........................................190
8-2 Overhead View of Main Works at Dannemora..............................193
8-3 “Dannemora”, Watercolor by Landscape Painter Elias Martin.........194
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-4</td>
<td>Overhead view of “Silverberg” shafts at Dannemora.</td>
<td>195</td>
</tr>
<tr>
<td>8-5</td>
<td>Profile of “Silverberg” Shafts at Dannemora.</td>
<td>196</td>
</tr>
<tr>
<td>9-1</td>
<td>Engraving of Dannemora Engine, by Eric Geringius.</td>
<td>217</td>
</tr>
<tr>
<td>9-1</td>
<td>Detail of Dannemora Engraving.</td>
<td>219</td>
</tr>
<tr>
<td>10-1</td>
<td>Engraving of Colles’ New York Engine.</td>
<td>231</td>
</tr>
<tr>
<td>10-2</td>
<td>A Typical Animal-powered Sugar Mill.</td>
<td>237</td>
</tr>
<tr>
<td>11-1</td>
<td>A Typical Blast Furnace, circa 1736.</td>
<td>250</td>
</tr>
<tr>
<td>11-2</td>
<td>Map Showing Location of Furnace and Ore Beds.</td>
<td>261</td>
</tr>
<tr>
<td>12-1</td>
<td>Typical Reverberatory (“Air”) Furnace.</td>
<td>283</td>
</tr>
<tr>
<td>12-2</td>
<td>A Cannon Boring Mill.</td>
<td>285</td>
</tr>
<tr>
<td>14-1</td>
<td>Map of Atmospheric Engines Discussed.</td>
<td>350</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>Comparative Flexibility of Various Prime Movers</td>
<td>118</td>
</tr>
<tr>
<td>7-1</td>
<td>18\textsuperscript{th} Century Engines in Britain, by Industry</td>
<td>167</td>
</tr>
<tr>
<td>10-1</td>
<td>Sugar Plantations in Louisiana</td>
<td>242</td>
</tr>
</tbody>
</table>
Introduction

Energy, Mining, and the Commercial Success of the Newcomen “Steam” Engine

This dissertation is about energy use, and how it changed during the early Industrial Revolution. It is an old saying that “there is no such thing as a free lunch”; however, if someone else picks up the check, it’s free for you. It would be better still if you could get something else, other than the sweat of your own brow, to pay your tab. Fortunately, just such a transaction occurs when stored energy is converted. As it turns out, the volume of energy processed in a modern economy has produced (for some) the most lavish free-lunch in human history.

A society can be viewed as an energy-using phenomenon. Control over energy – the ability to store it, transport it, and then expend it at a time and place of one’s choosing – has been an important influence over historical change. Different types of energy (agricultural, slave, waterpower, fossil fuels, etc.) require varying types of control. Successful control empowers a society, but the requirements of each energy type also structure the society that controls it. In the Industrial Revolution, these changes empowered the early adapters, but also set in motion a series of historical changes that, through a complex feedback system, reshaped what was already an interconnected world.

Rather than dwell on its causes, the Industrial Revolution can be approached as a phenomenon with certain features. One striking feature is the ten-fold increase in energy use per person between an advanced agricultural society of, say, only 300 years ago and a technological society today. Again, this increase is per person. Controlling new energy sources was also the signature of earlier “revolutions” in human history, but the scale of the increase during the industrial revolution has been without precedent. Was this ten-fold increase a cause or an effect? As will be explored in Part I, some scholars have dismissed this increase in energy consumption
as nothing more than an effect of economic growth. They identify increased income per capita as the cause, with energy consumption as the effect. The weakness of this view is that it treats an economy as if it existed in isolation from its environment; as a result, it is unable to explore the relationship between resources and economic growth. In a more holistic conception, the economy should be seen as a resource-using system; this conception would of necessity consider the contribution of energy-use to increased income per capita. This is not a primitive notion of converting energy willy-nilly; factors that deliver more useful energy, such as efficiency, organization, or distribution, all clearly increase wealth. However, properly assessing the role of primary energy, as for example converted by the steam engine, is an essential part of understanding the historical changes of the Industrial Revolution.

By way of confession, prior to this dissertation work, I have never had any particular interest in steam engines, stationary or otherwise, and was blissfully unaware of their predecessors, the atmospheric engines. I neither belong to a club that restores old engines, nor frequent recreational railroads to ride restored steam trains. My interest in energy has tended towards its renewable form, such as waterpower. As a university undergraduate in Lowell, Massachusetts, an example of the great potential power of flowing water could, quite literally, not be avoided.

The Merrimack River, with its Pawtucket Falls roaring in the spring, flows between the college’s two campuses. It was said that in the early 1600’s Passaconway and his people would go there to gather fish. In the late 20th century, however, it was not a romantic sight. The decadent green water bore the marks of nearly two hundred years of industrialization; this had left the water dark, and the river was strangely strangled in a series of canals and locks. The industry was long gone, but one could see how the old works – the dams, canals, and mills – had
served their purpose in their day. To me, nothing could have been more self-evident than how that tremendous quantity of hydropower, which had formerly spilled blithely over the falls, had been harnessed to drive an explosion in material output. In a narrowly materialist sense, this was the early industrial revolution.

A price had been paid. The fish were gone, the land scarred, and the dark water sometimes had a smell that could not be mistaken for pleasant. But the river’s power had contributed to the surfeit of material goods, an abundance that is the trademark of life in the modern world. And make no mistake: Converting energy to increase material output was the whole point of what is called the Industrial Revolution. Textiles, as in Lowell’s case, were merely one form that it assumed. The root change was in energy transformation. Harnessing novel sources of energy allowed for an unprecedented expansion of material production. Once that had been achieved, all of the rest could arguably be relegated to just a working out of the details. The history of Lowell’s little sliver of the Industrial Revolution, its demand for raw materials, the distribution of its products, its marketing, the poetry of the Lowell Girls, division of its profits, attraction of immigrant labor, formation of labor unions, rise in living standards, depression, recovery, de-industrialization – in fact the whole panorama of industrialization – all that was just the seeking of a happily-ever-after. The struggle and triumph, to use a phrase once popular, had been the harnessing of nature’s energy. By tapping into the flow of this river’s energy long enough to augment human labor, it had created the material of the industrial world.

It slowly dawned on me that Lowell’s exercise in the use of hydropower was a special case, the fortuitous meeting between would-be industrialists and the untapped resources of what was then the “frontier”. The availability of this type of untapped energy resource was, unfortunately, limited. It would soon be fully committed, limiting any further growth. No; the
vast increase in energy consumption, as enjoyed by some parts of the world’s population, has not been based on organic sources such as hydropower, but on mineral energies, such as coal and later oil and natural gas. Thus, the focus of the production question shifts: How has it been possible to convert so much energy? To be clear, as with the first hydropower mills of Lowell, I want to pare down the question by putting aside the issues of organization, distribution, etc. These are necessary, but later, issues. The question here is focused on the sheer circumstances of the actual production. What was the origin of our ability to convert such a vast quantity of energy? That was the question that led to the dissertation topic, the first commercially successful steam engines.

Goal of Dissertation

This dissertation proposes to examine aspects of the change in energy converters at the beginning of the Industrial Revolution. It will do this by focusing on the increasing demand for primary energy engendered by the commercialization of certain parts of the economy. As will be shown, the cost and availability of fuel for the first commercially successful “steam” engines (the Newcomen atmospheric engines) marks a significant border-line of energy demand. The analytical approach of the case study method was used; the cases were selected to provide a cross comparison of examples where the engine was successful, or failed, and was powered by coal or wood. The goal is to draw attention to the interplay of commercialization, power needs, other available energy sources, and fuel cost, in the success or failure of each of the engines.

A complex phenomenon, the Industrial Revolution clearly had an array of contributing causes; Chapter 1 is a survey of the theories that have looked at these various causes. It is shown that it may be useful to divide the process of industrialization into two phases. The first phase
was the expansion of trade and commerce, sometimes called a “commercial revolution”. This was followed in the 18th and 19th centuries by a mechanization of production. It is the early part of this second phase, and how energy use changed during that time, that determined the selection of case studies that follow.

The issue of energy consumption as cause or effect is reviewed; however, when taken as a phenomenon, it seems to make little difference whether the source of wealth was the energy motivating the machines or the capital stock embedded in the machines powered by a readily available unlimited energy. In either case, the conversion of energy needs to occur. Given that the focus would be on energy, what type should be considered? This question is pursued in Chapter 2 where the emphasis shifts towards scholars who have written on the link between human culture and the environment. This inevitably leads to an inclusion of energy, and the transformation of energy, as an essential part of any explanation of the evolution of human culture.

Part II surveys the energy milieu of an advanced agricultural society. Chapter 3 begins by drawing on the literature review of Part I to provide analytical tools, particularly the concept of an energy rent. The focus is then narrowed to the mining sub-sector of a commercializing economy. Mining is interesting during this period for several reasons. Commercialization transformed the nature of mining. Where output had previously been linked to local needs, the production decisions at a commercial mine would have been based on financial decisions. Where this was profitable, it tended to intensify mining. The career of a typical (“generic”) mine is sketched out. Commercialization increased the pace of mining, which could potentially create problems with flooding at the mines. How rapidly these problems arose was conditioned by the original resource endowment of an area. The interaction between the intensification of mining
and organic prime movers available to pump out the mines is used to illustrate the limitations of organic powered prime movers. This generic pattern will serve as a guide for the case studies to follow.

Chapter 4 in Part II is a review of the power sources available to a mine operator in an organically-powered economy. These power types include human labor, animal labor, watermills, and windmills. In an effort to facilitate cross comparison of these sources, their qualities are abstracted based on their spatial and temporal flexibility, and how readily they can be intensified. Chapter 4 concludes with a consideration of the inherent limitation of organic power. These limitations were particularly constritive in the mature mining sector in Britain.

The establishment in Britain of the first commercially successful engines is the subject of Part III. As reviewed in Chapter 5, the historiography of the “steam” engine has generally focused on high-pressure precursors. In fact, the first successful machines had a different, much simpler technology. This may be an important insight when looking for proto-industrialization elsewhere. The actual precursors to Newcomen’s machine are discussed; as will be noted, these had much in common with pumps.

Chapter 6 presents an analysis of Newcomen’s first efforts. The possible reasons for Newcomen’s failure at the Cornwall mines, as opposed to his eventual success in the coalmines of the Midlands, are discussed. Chapters 6 and 7 put the Newcomen engine in its proper perspective for the 18\(^{th}\) century. It was not a scientific curiosity or a toy to divert the wealthy. It was the product of practical, if not always sober, blacksmiths and millwrights. Further, a significant number were built: nearly 700 Newcomen engines had been erected in England prior to the first commercial Watt machine in 1776. Further, at least another 700 Newcomen
machines were built in Britain during the last 20 years of the 18th century, as compared to only 500 Boulton and Watt engines during that same period.

Since failures may be at least as insightful as successes, Part IV examines an engine built in the late 1720’s at the Dannemora iron mine in Sweden. The history of this mine before the engine’s introduction is reviewed, and shown to conform to the generic pattern for mines, as outlined in Chapter 3. The mine operators met the flooding problem with a series of innovations, based on organic energy. For their continued efforts, they were rewarded with ever-greater flooding of their mineshafts. In 1727, Marten Triewald’s proposal to build a “fire-and-air” (Newcomen) engine to drain their deepest pit was accepted. However, the engine only ran sporadically, and was the subject of a lawsuit by 1730. Other than a test in 1734, it never ran again.

The reasons for the failure of Triewald’s engine are reviewed in Chapter 9; among the difficulties faced by the engine, fuel costs are identified as the fatal problem. Sweden lacked coal resources, and so the engine’s boiler was fired using wood. This proved prohibitively expensive, and as a result the mine operators turned against the engine. This case study concludes that cost of its wood fuel was the engine’s downfall; contrasted with the successful coal fired engines of Britain, it may appear on the surface that coal is necessary for a Newcomen engine to be commercially successful. More than one historian has said so. To test this idea, Part V presents the case study of an iron ore mine in Cranston, Rhode Island.

Chapter 10 provides a survey of the Newcomen engines erected on the western side of the Atlantic. The early interest in steam engines by owners of slave sugar plantations is noted and discussed. In addition, the careers of engines built in New Jersey and New York City are reviewed. Chapters 11 through 13 take up the circumstances of a Newcomen-type engine built
by the Brown brothers at their iron ore mine in Cranston, Rhode Island. The Brown brothers of Providence established these pits in 1765 to provide ore for their iron furnace, “Hope Furnace” in nearby Scituate. Hope Furnace, 4 or 5 miles from the ore beds in Cranston, was located a dozen miles from Providence. Because of these distances, the on-site managers at the furnace and ore pits could not readily meet with the Browns in Providence; as a result, they had to maintain a steady correspondence of short business letters back and forth. The archive of this correspondence, most of which is at the John Carter Brown research library on the campus of Brown University, provides a mosaic of this 18th century industrial concern. Research of this material allowed for a detailed reconstruction of activity at the furnace and ore pits from their inception in 1765, through to their liquidation in 1803. This in-depth case study of the Brown engine is the heart of the dissertation, consisting of extensive original archive research. To the extent possible, the Brown brothers, Rufus Hopkins (manager at Hope Furnace), Joseph Shaw (manager at the ore pits), and the others will relate the story of their business in their own words.

The iron pits at Cranston followed the by now familiar pattern of mining; the easily recovered material was extracted over the first few years; eventually flooding became a problem, and the water at the mine had to be dealt with by pumping. The activity at the furnace and iron mine was further intensified by the Revolutionary war. The molders at Hope Furnace mastered the art of casting cannon, and the furnace would produce more than 1,000 cannon during the war. The production of these desperately needed weapons put a significant strain on the ore pits. In response, the Browns enhanced the water pumping ability at the pits through a rebuilding of its pumps, and the millwheel to drive them, in 1780.

Ironically, the engine was not built in 1780, as might be suspected. It was actually erected in 1783, nearly 2 years after Yorktown and shortly before the Treaty of Paris would
formally end hostilities. This change of context speaks to a completely different rational for building the machine. The timing of this investment is discussed in Chapter 13, and found to be a key insight into the engine’s eventually success.

Part VI presents a summary that outlines the relationship between energy and society, why energy needs were so acute at mines, and a recap of each of the case studies. The circumstances of the iron mines in Sweden and Rhode Island are directly compared. The interesting differences in the conception of gender evinced at the two locations are explored. The early interest of slave sugar plantations in steam power is also summarized.

Commercialization, the Need for Power, and Fuel Availability

It is analytically useful to think of the changes that fit under the heading of the Industrial Revolution as two events. The first was the commercial revolution; this could have ended in a steady state economy, as Adam Smith and the other classical economists envisioned at the time. Instead, something totally unexpected occurred: a revolution of mechanization that replaced organic energy with mineral (fossil fuel, non-renewable) energy. The Commercial revolution was a necessary precondition for the second phase of industrialization.

Commercialization had created commodities. These were not produced for household (local) consumption, but for trade; they were produced to make a profit. In other words, the decision to produce something was no longer needs-based, but had become a financial decision. This of course only affected a small portion of the things made in world, but the change was concentrated in some activities, for example mining. The role of mining is noteworthy because of the inflexibility of its location. As a result, its need for additional primary power is felt more acutely. This is not to say that it is different from other sectors, just more “mature” (less
flexible) in its relationship with available organic energy supplies. As such, mining was among the first productive enterprises to be constricted by the limits of organic energy systems.

Why was Britain the first to industrialize? Perhaps it was not an abundance of coal, but the relative maturity of their coal fields. Lacking untapped coal resources, they needed to dig more deeply at existing pits. It may have been unnecessary to bring coals to Newcastle, but additional prime movers were welcomed: The collieries along the Tyne were already pumping extensively by the late 1600’s. This was at a time when the coal needs of China were being met by exploiting new, untapped veins, well above the water table.

However, Britain’s need for additional power did not assure the actual development of the atmospheric engine. As the case studies will show, the cost of fuel made the engine’s success questionable. The example of the earlier Savery engine is instructive. While its design was sound, its fuel consumption, and the technical difficulties of high-pressure steam, rendered it unusable.

Thomas Newcomen’s machine was sometimes, but not always, too pricey to be used commercially. The decisive factor was the cost of its fuel. In its way, it may serve as a marker between the Commercial and Industrial Revolution, and can illuminate the transition from organic to mineral-based power sources. Ironically, its usefulness as a litmus test is a result of its greatest weakness: the engine’s well-known voracious appetite for fuel. Over 99% of the energy used to operate the machine was lost, with only 1% resulting in useful work, typically pumping water. In a number of cases, especially in its first decades, the cost of the engine’s fuel was so high as to make it uneconomical. Put differently: The Newcomen engine’s fuel needs put it along the border between positive and negative energy rents, depending on fuel availability.
In the actual event, a Newcomen engine was able to achieve a positive rent in 1712, but it was a near thing. This first commercial success was followed by a slow rolling back of the negative energy rent border, as improvements to the engine accumulated. The characteristics of this engine, and its fuel needs, has made possible via the following case studies to present a few modest, and hopefully useful, insights into the transition between commercial and industrial modes of production.
Part I: Literature Review

Chapter 1: Exceptional Europe, Exploiter Europe

“The Industrial Revolution” is a deceptively simple phrase. While any history student is familiar with the term, once it is critically investigated, any consensus as to even the meaning of the phrase evaporates. Fortunately, a few things can be outlined at the start. The “who” under discussion is something called the “Industrial Revolution”. The term “revolution” has several different meanings. It can refer to a sudden upheaval, but that definition would be misplaced in this case. In the Industrial Revolution, the change was not so much sudden as it was far reaching. It was revolutionary in the sense that it led to something novel, not seen before.¹ The phrase originated in the early 19th century in France as “Révolution Industrielle”, where it was used to distinguish the subject from the changes of the French political revolution.² The use of the phrase in the English-speaking world was popularized by Arnold Toynbee in his “Lectures on the Industrial Revolution”.³

The “what” that is the signature of this revolution is a shift from a society were agriculture is the dominant (nearly universal) economic activity to one where a progressively smaller percentage of the population earns a living as farmers. This shift was accompanied by a sustained increase in living standards (real incomes). As we will see, some scholars focus on the social changes (or social relations) that brought about this transformation, while others believe its

² While Toynbee is sometimes cited as the having coined the term, the previous use of the term in France has long been documented, see Anna Bezanson 1922 “The Early Use of the Term Industrial Revolution”, The Quarterly Journal of Economics, Vol. 36, No. 2 (Feb. 1922), pp. 343-349. See for example p. 344. http://www.jstor.org/stable/1883486 (accessed May 5, 2010).
roots lie in technological change or environment. Intensification of energy use is a signature of this change.

The “when” of the industrial revolution is a matter of contention. While some authors date its beginnings from the mid-18\textsuperscript{th} century, others see it as a continuous process stretching back half a millennium or more. A third view is that this change was a two-part phenomenon. In this latter view, the first part of the Industrial Revolution was a long lead-up consisting of fundamental changes in social processes, which was followed by a sharp take-off in economic activity. The question of whether the Industrial Revolution was one event or two events is one to which we will return.

While it is generally granted that the “where” the Industrial Revolution first took hold was in Great Britain\textsuperscript{4}, there is a lack of agreement on “why”. The various explanations and theories will be the subject of this and the following chapter. Chapter 1 is intended to provide some sense of the width of the debate. As will be discussed, it is useful to think of the Industrial revolution as two events, or perhaps a single process with two phases. What is sometimes called the commercial revolution was a necessary precursor, but not at all unique to Europe. Note that, whether technology is characterized as changing society in an abrupt revolution, or slowly over the previous 500 to 1,000 years, either view assumes an unlimited pool of passive, available energy will be available.

Chapter 2 examines theories as to what drove the sustained growth observed from the 18\textsuperscript{th} century forward. This can be thought of as an “industrial” revolution to complement the earlier commercial revolution. Several of the theories reviewed focus on energy, examining how the available energy shapes the technology and structures a social system. It may be that the requirements of using a given energy source will determine (or at constrain) the structure of the

\textsuperscript{4} Although even on this topic, opinion is not unanimous; see below on sugar as an industrial production.
society that can best transform it. A closer examination of energy leads to a fine-grained
discussions of technology and mechanization. By this process Chapter 2 will progressively focus
on the subject of this dissertation, energy’s role in shaping the Industrial Revolution. Three
aspects will be highlighted: how the types of energy used changed during the industrial
revolution; how this was conditioned by societal structure; and, how using different types of
energy in turn changed society. The concept of an energy rent (a special case of an economic
rent) will be used to illuminate how benefits were accrued and distributed.
Exceptional Europe

This literature review will assess representative historians and their theories about the factors underlying the transformation that passes under the rubric of “The Industrial Revolution”. This background will provide context for a deeper analysis of the role played by energy. At a certain level, industrialization is about mechanization, energy-using machines. The dominant narrative of mechanization has been technological, its theme an unfolding of the triumph of progress.\(^5\) While dominant, this historiography has not been without its critics. Writing in the 1970’s, von Tunzelmann specifically objected to what he described as the “inevitable” narrative in technological histories.\(^6\)

Rather than a series of inevitable events, the history of technology is being recast as the formation of ideas, decisions and choices. As Pomeranz, in his groundbreaking text *The Great Divergence*, wryly noted, “…the steam engine did not invent itself…”\(^7\) The development of a technological outlook was traced by Ben Marsden and Crosbie Smith who chronicled the construction of a “power” culture in Britain.\(^8\) While the history of technology is a series of choices, these choices may be “path-dependent”. This can serve to reinforce successes, but it can just as possibly create limits. The economist W. Brian Arthur has developed a line of analysis that describes how societies become locked into technologies at early stages of development. This lock-in can make a series of decisions appear inevitable, when originally they were

---


\(^8\) Ben Marsden and Crosbie Smith, *Engineering Empires: A Cultural History of Technology in 19\textsuperscript{th} Century Britain* (New York: Palgrave MacMillan, 2005), see chapter 2.
conditioned by random factors. Arthur has cited the durability of the “QWERTY” keyboard as a commonly experienced example of path dependence leading to a sub-optimal result.\(^9\)

Earlier narratives of technological history also tended to be limited by their focus on national histories, for example British, Chinese, or American. This generally limited the analysis of early steam use outside core areas, for example in Britain’s colonies. More recently this has also been changing, as for example Veront Satchell’s work on the early introduction of steam power to Jamaica\(^10\).

**Why Britain? Technology**

Britain, however, cannot (and should not) be avoided. Why did mechanization take hold in Northwestern Europe, particularly Britain? A solid presentation of the case that technology was the driver of the Industrial Revolution can be found in Joel Mokyr’s *Lever of Riches*.\(^11\) Mokyr defined the Industrial Revolution as a period of unprecedented economic “growth”, growth being defined as an increase in total income, sustained over a long period of time.\(^12\) Mokyr outlined the four processes that could have been the source of this increase in output.\(^13\) The first is investment: by postponing consumption, resources could be used for investment to increase future output. A second option is commercial expansion: trading with a wider group allows for productivity growth from specialization.\(^14\) A third way of expanding a society’s potential output is through an increase in scale or size. This leads Mokyr to the fourth option, the


\(^12\) A more precise definition might be an increase in income per capita; see review of Wrigley in Chapter 2.

\(^13\) Mokyr used the technical term “Production Possibility Frontier”.

\(^14\) This “specialization” is the kind of growth Adam Smith discussed at length in *An Inquiry into the nature and Causes of the Wealth of Nations* (1776) Modern Library Edition (New York: Random House, 1937), see for example Chapter 3 of Book I.
subject of his book, augmenting production through an increase in the stock of human knowledge. His term for this is the “Application of Information”, which means to promote technological change and innovation. In this, he is following in the insights of Joseph Schumpeter.  

Mokyr defines technological innovation as the application of new (or not yet applied) knowledge. This is distinct from invention. Invention creates new knowledge but does not necessarily have any economic impact. Invention is necessary to produce knowledge, but it is the second phase, its application, that produces change. Mokyr noted that Western history has had periods of technological innovations, or lack thereof. For example, ancient societies had inventive power, but not the inclination to innovation. As a result, their growth came from “Smithian” gains, that is, they had trade networks, allowing specialization.

Mokyr, in his depiction of the Ancient world as lacking innovation was echoing the conclusions of M.I. Finley in his classic studies of the Greco-Roman economy. This view was readily accepted in the 1960’s and 1970’s, as it made a neat contrast with the idea, emerging at about that time, that the medieval period was an era of technological innovation. Recently, this depiction of the ancient world as uninterested in technology has been called into question. Combining the archaeological work of the last few decades with classical studies, Andrew Wilson outlined the truly extensive application of technology to Roman silver mining in the first

---

16 Mokyr, Chapter 2.
18 This point was stated by Andrew Wilson in “Machines, Power and the Ancient Economy” in *The Journal of Roman Studies*, Vol. 92 (2002), pp. 1-32 (Published by: Society for the Promotion of Roman Studies).
and second centuries, particularly in Spain. He cited the wealth from these mines as a significant contributor to the prosperity of Rome during those centuries.\(^{19}\)

Technical change in Europe was relatively slow, but between the years 500 to 1000, a number of longstanding technical problems were overcome. The horse collar, wheelbarrow, and stirrup were all “Dark Ages” innovations, and clocks were developed only a few centuries later. Mokyr notes that some, Mumford in particular,) have identified that the mechanical clock, not the steam engine, as the key to the modern industrial age.\(^{20}\) There is some merit in this suggestion: Clocks, a point of local pride, were precise, standardized, and their construction required great skill. These characteristics of precision workmanship and standardization were concepts that would be important during the Industrial Revolution. David Landis identified the development of the clock as “…comparable to movable type in its revolutionary implications for cultural values, technological change, social and political organization and personality.”\(^{21}\)

In Mokyr’s view, the late Middle Ages and the Renaissance were times of minor improvements and the gathering of big ideas such as flying machines and submarines. By circa 1500, Europe had achieved technical parity with the advanced parts of the Islamic and what Mokyr termed the “Oriental” worlds.\(^{22}\) Thereafter Europe began to pull ahead in a series of technical advances that culminated in the Industrial Revolution. Mokyr termed the period 1750 to 1830 as the “Years of Miracles”, and he deemed the steam engine as the quintessential invention of this period.\(^{23}\) He traced the engine’s development as a pump in coalmines, from Thomas Savery, to Newcomen, to James Watt. Mokyr, quoting from Watt’s autobiography,

---

\(^{19}\) Wilson also suggested a possible link between the Athenian silver mines and Athens’ ascendancy in the 5\(^{th}\) century BC.
\(^{22}\) Mokyr, p.55
\(^{23}\) Ibid, Chapter 5.
noted that he embodied the thinking that created the Industrial Revolution in that “‘his mind ran upon making engines cheap as well as good.’”.\textsuperscript{24} In this he seems to be suggesting the profit motive as a driving force for change, but Mokyr does not follow it up.

**Sources of Technological Innovation**

Since he identified the application of new technology as the driving force of change, Mokyr sought to outline the causes (or failures) for technical progress. He suggested that technical innovation appears to be path-dependent by nature: the innovative innovate, and find it easier to further innovate. This is a self-reinforcing loop and, once in motion, technological progress would accelerate. By implication if we could identify the initial source of the progress, we would know the “why” of the Industrial Revolution.

While scientific discovery is a necessary precursor, by itself it is not enough. Without application, invention would languish. Geography and natural resources may stimulate application, however Mokyr is unclear whether it is scarcity or surfeit that induces innovation.\textsuperscript{25} War was seen as a factor working against growth. Mokyr notes that military organizations are conservative, war is destructive, and thus works against technological improvements.\textsuperscript{26} Values enter into Mokyr’s exposition through the backdoor: technical innovation comes only to those who value it. If the “good life” is success in sports, literature, or religion, than there will be little incentive for innovation. By this, he implicitly links technology together with “European values”, which combined provide the mainspring for the Industrial Revolution.

\textsuperscript{24} Ibid, p. 87, quoting Watt’s autobiography; note that Watt modestly followed the example of the great Caesar and referred to himself in the third person.

\textsuperscript{25} For the potentially stimulative properties of scarcity, see Arnold Toynbee below on the role of stimulus-response mechanism.

\textsuperscript{26} In this he follows John Nef *War and Human Progress* (New York: W. W. Norton & Company, 1950). While agreeing with his conclusion, one finds little support for it in Britain’s foreign policies during the “Years of Miracles”.
To illuminate the factors that promoted innovation, Mokyr turned to a comparison of China and Europe. Why did Europe industrialize and not China? Mokyr sees it as a difference in attitude. Political and mental diversity promoted technical creativity in Europe; by contrast China’s elites were not interested in innovation, and they were in a position to thwart technical change.\(^{27}\) China enjoyed economic growth, but it was of the Smithian kind (more people, more specialization).

Given the assumption that technology is the key factor and, once begun, innovation would be self-sustaining, the determinant of which area would develop first can be identified: it would be the society most accepting of the initial change. Once begun, the nature of macro-invention would bring additional changes in its wake; this would undermine the (formerly) powerful in society, promoting further growth. Having asserted Europe’s \textit{mentalite} as more conducive to growth than China’s, Mokyr sees this as having setting off a spiral of growth. As for Britain, their “political economy of technological change” was stronger than on the Continent, and so they were the first in Europe to industrialize.\(^{28}\)

Mokyr has been discussed in some depth as a moderate example of the “exceptional Europe” explanation for economic growth. As with the best of this tradition, he presented an excellent description of the innovations that occurred in Europe during the Industrial Revolution, noting many key linkages. However, he ultimately locates the source of these changes as something unique to Europeans. In this case, it was their outlook that was more amenable to innovation. Since he also presented a good case for the belief that innovation is path dependent, once past a vague beginning, the explanation flows smoothly.

\(^{27}\)Mokyr, pp. 235-6.
\(^{28}\) Mokyr, p. 255.
The suggestion that Europe, or more specifically Britain, had some exceptional characteristic that was simply not found elsewhere has appeared in a number of different forms. A century ago, for example, the racial superiority of Europeans was assumed, at least by European scholars. To their credit, succeeding generations have rejected this belief. When discussing the historiography of the Industrial Revolution, it is customary to acknowledge Max Webber, who identified a certain spirit among Europeans (at least the protestant ones) as the source of their dynamism.\textsuperscript{29} Weber has been charitably described as professing only “moderate” racism.\textsuperscript{30} Genetic superiority as a reason for economic success has generally been discredited, although it still finds an occasional proponent.\textsuperscript{31}

After Weber, later scholars have proposed that certain other characteristics, unique to Europeans, were the source of their economic growth. These have included rationality\textsuperscript{32}, culture\textsuperscript{33}, and or environment.\textsuperscript{34} This later body of scholarly work is well researched and much of it is entertainingly written. What is found wanting is a causal explanation for the Industrial Revolution first appearing in Northwest Europe. To say that Europe developed differently because Europe was \textit{a priori} different is a belief, not an analysis. As Parthasarathi noted, “…despite their disagreements, they explain divergence in the same way. They all identify something that made Europe different, to which Europe’s divergent path is then attributed.”\textsuperscript{35}

\begin{footnotes}
\item[31] Gregory Clark’s \textit{A Farewell to Alms} (Princeton: Princeton University Press, 2007) presents solid genealogical research; however Clark then goes well beyond his data to assert that the genetic superiority of English nobility and wealthy was the source of the Industrial Revolution (see Chapter 12). Curious.
\item[33] Landis (1969).
\item[34] Jared Diamond \textit{Guns Germs and Steel: The Fates of Human Societies} (New York: W.W. Norton & Company, 2005).
\end{footnotes}
Exploiter Europe

An alternative school attributes the economic advances of Europe to exploitation by the Europeans. This conception does not necessarily credit any technological precociousness to Europe, but instead cites their capital accumulation. By exploiting others outside of Europe, or classes within European society, (or in some constructions having fortuitous access to unappropriated capital), the process of capital accumulation was accelerated in some countries, particularly Britain. This allowed for much greater investment, causing their development to exceed what was experienced elsewhere.  

In broad outline, exploiter Europe can be characterized in one of three ways: 1) an exploiter of subgroups with its own territories; 2) an active exploiter of other parts of the world, or 3) a fortunate Europe that benefited from “privileged access”.

Internal Exploitation

In the first category, advancing capitalism, particularly in Britain, allowed expropriation of labor from workers, accelerating development. This is distinct from the core-periphery model in that the capitalist dynamic is viewed as coming from within a society itself, in this case Europe. As conceptualized by Marx, it was the development of certain forms of social relations that advanced the accumulation of capital. For Marx, this change worked progressively to remove from an individual’s own control their means of making a living. This had two results: first, the individual would be required to offer their labor to others to survive, and, just as importantly, the means of making a living would become an abstract collection of capital.  

Note that investment was Mokyr’s first option for expanding output.

incidentally, the wage laborers would also necessarily be consumers, dependent on the economy. An exposition of this reshaping of labor into consumers, with less “preference” for leisure, is found in Jan de Vries analysis of the Dutch Republic in his “The Industrial Revolution and the Industrious Revolution”.  

Thus the transformation of the “means of production” into capital also created wageworkers; capital and wageworkers together produced commodities for exchange. This was identified by Marx as essential because “…the means of production and subsistence, while they remain the property of the immediate producer, are not capital. They become capital only under circumstances in which they serve at the same time as means of exploitation and subjection of the labourer.”

It was not some grand conspiracy of the capitalists that made this system exploitative, but the nature of the system itself. The owners of capital themselves were squeezed by the declining rate of profit, which eventually would ruin most of them. However, these declining returns were also what gave the system its dynamic, transformative aspect. If the capitalist was to have any hope of producing a profitable commodity (i.e., surviving), the owner of capital was forced to innovate and increase efficiency. In Marx’s view, this made capitalism the most progressive social structure (at least so far). Sounding more like a publicist for the Chamber of Commerce than a herald for socialism, he proclaimed that capitalism would draw all “…even the most barbarian, nations into civilization. The cheap prices of its commodities are the heavy artillery with which it batters down all Chinese walls…” Note that by “barbarian” Marx does in fact


39 Marx (1887), pp. 537-8. They just don’t write ‘em like that no more.

mean the Chinese. In his view, the process of commodity production for profit feeds on itself, producing with each cycle additional capital, and discarding any unprofitable capitalists, which served to further concentrate wealth.\(^4\) This process of capital accumulation drove the industrial revolution.

**External Exploitation**

In a second group of exploiter theories, Europe is characterized as having benefited from colonization of other parts of the world. These are variously described as core–periphery or dependency models. In a variation of this, Europe (again, primarily Britain) enjoyed accelerated capital formation as a result of the profits from slavery.

**Slavery and Capitalism**

An interesting variant of the exploiter explanation was provided by Eric Williams in *Capitalism and Slavery*.\(^2\) Williams sought to challenge the ‘traditional’ (circa 1940’s) view that the colonies had benefited from metropolitan benevolence. While no longer mainstream, the view that Western empires were beneficial to the colonized still has its proponents.\(^3\) The opposite view, that colonization is detrimental to economic development, is supported by the quantitative analysis presented in Alam’s *Poverty from the Wealth of Nations: Integration and Polarization in the Global Economy since 1760*. His work demonstrates a strong link between sovereignty and economic progress.\(^4\)

---

\(^1\) See Marx (1887), Part 7 “Accumulation of Capital”.
\(^3\) See Landis (1998).
Williams had sought to show how colonies were used to construct the prosperity of the imperial power. In the case of Britain, the profits of slave production accelerated their capital accumulation, providing the seed money to finance the Industrial Revolution.

On the origins of Negro slavery, Williams observed that where there is ample land, wage labor is impossible. Plantations in the land-rich new world could not succeed using wage labor, as people would rather work for themselves. Therefore, a non-market source of labor was required. Since slavery was based on a demand for labor, it was not a racist phenomenon but an economic phenomenon. Racism did not create slavery; it was slavery that created racism. New World slavery began with the enslavement of “Indians”, which was followed by indentured servants. Negroes were cheaper than indentured servants, and for that economic reason they were favored.

Here, Williams has touched upon the industrial nature of sugar production. The process of turning sugar cane into raw sugar has strict time constraints. The cut cane must be crushed before it sours. The crushing of the cane itself is an energy intensive, extractive activity, requiring concentration of force. This work has been described as agro-industrial, requiring required strict organization.

Sugar in the 16th and 17th centuries provided additional calories for European populations, particularly in Britain. Adding this to Williams’ insight, slavery provided, via sugar, additional energy through calories and allowed for capital accumulation. As a result of their capital accumulation, the Caribbean planter-class became the super wealthy of the mercantilist era. This put them in a position to finance the capital needs of industrialization. Williams noted that even

---

45 Williams, p. 7.
James Watts’ development of the steam engine received financing from West Indian planters, as Boulton and Watt borrowed from Lowe, Vere, Williams and Jennings.\textsuperscript{47}

Interestingly, by promoting capital accumulation sugar plantations sowed the seeds of their own demise. Once established, industrialism found little room for the West Indian sugar monopoly, as it only acted as a break on productive forces.\textsuperscript{48} By the 19\textsuperscript{th} century, Britain’s new industrial order emphasis on free trade would lead to the elimination of the Corn Laws and the sugar subsidies.

\textit{Sugar and Capitalism}

The influence of sugar, with its dual nature as both a food-energy source and a potential accumulator of capital, was traced back in time by Barbara Solow’s “Capitalism and Slavery in the Exceedingly Long Run”.\textsuperscript{49} In this view, the origins of the capital accumulation that would lead to the Industrial Revolution can be found in the 12\textsuperscript{th} century. “European expansion did not begin with Columbus, and the economic organization of the Atlantic Economy is not of northern European origin.”\textsuperscript{50} For Solow, the original development of sugar plantations resulted from the Crusades. She notes that when Venice seized the island of Tyre in 1123, they proceeded to produce sugar on the island, and that both Venice and Genoa used slaves in the production of sugar on Crete and Cyprus. Solow made a case study of the Cornaro family of Venice and their organization of sugar production on Cyprus. She characterized their methods as thoroughly capitalist. Capitalist production involves the commoditization of land, labor and capital, and this was the methods used by the Cornaro’s sugar production: the land was controlled politically;

\textsuperscript{47} Williams cited financial advances to Boulton and Watt, p.102.
\textsuperscript{48} Ibid, p.126.
\textsuperscript{50} Solow, p. 51.
slave labor was imported to work the sugar fields; and capital equipment (copper boilers) was brought to Cyprus to process the sugar.

Western Europe may have still been dominated by feudal agriculture, but sugar from its inception was an international agri-business: Organizing the production of a commodity, processing it, and then distributing it through a distant marketing network. “Slavery plays a role in the development of capitalist forms of economic organization from their first appearance.”

In this way, the process of European expansion can be retraced as a process of exploitation, as revealed in the history of the sugar islands. Madeira, for example, was discovered, and then quickly “developed” to produce sugar. On the other hand, since sugar could not be grown in the Azores they languished as an unimportant backwater.

This activity, and other products of slavery, would transform the economy of Britain. At the beginning of the 17th century, four-fifths of Britain’s foreign trade was in wool. A century later, British ships were crisscrossing the Atlantic carrying sugar, tobacco, wine, molasses, fish, lumber, horses, and flour. All of these things were either produced by slave labor or produced to support slave labor. Although Solow did not make this point, it should be noted that sugar, with its dual nature as a source of useful calories and an accumulator of capital, is somewhat analogous to coal mining, which also produces useful calories of energy and its production causes capital to accumulate.

From Solow, several important strands of thought can be gleaned that will be useful for understanding the Industrial Revolution. First, the process may extend back much further into history than a survey of technology might indicate, and so we are confronted with the issue of when to date the beginnings of the Industrial Revolution. A second insightful observation is that

---

51 Ibid, p. 55.
52 Ibid, p. 70.
commoditization of the inputs to production is a necessary precursor to any industrial production. Inputs into industrial production become undifferentiated commodities, tradable and substitutable. This includes both labor and the physical inputs. The implication is that social changes are required for industrialization. Further development of these ideas can be found in the work of Douglas North.

**Exploitation: The Inheritors**

North is an example of a third way of looking at Europe’s accumulation of the wealth of others (“exploitation”, for some authors). For North, Europe (particularly Britain) was not so much an exploiter as a lucky inheritor: they had privileged access to the riches of the New World, and evolved the social structure necessary to take advantage of it. The term “inheritor” is used here in its strictest sense. If the New World was an “empty wilderness” it was a result of the virgin soil epidemics that killed up to 90% of the people living in the Americas. The plagues that struck Central America are well known, but the same dynamic occurred throughout the Americas. New England presents a typical, tragic, example. Early European explorers, such as Samuel de Champlain, encountered and charted many villages and planted fields crowding what would later become the coast of New England. These were thriving societies, quite capable of defending themselves. In 1606, on what would become Cape Cod, Champlain’s group had a falling out with the Nauset and Monomoy people living there; Champlain’s party had to flee.

---

53 I have chosen to describe this accumulation as a form of “exploitation”; North himself did not use this term. Douglas North *Structure and Change in Economic History* (New York: W.W. Norton & Company, 1981).

54 Privileged access to the continents of North and/or South America is an important factor in the “Rise of Europe” for a number of authors. See Pomeranz, below or Blaut’s *The Colonizer’s Model of the World: Geographical Diffusionism and Eurocentric History*, New York: Guilford Press, 1993. An earlier exposition of this model is found in Walter Prescott Webb’s 1951 *The Great Frontier* (Lincoln, Nebraska: University of Nebraska Press, 1951).

leaving five dead sailors behind.\textsuperscript{56} All this changed after the great epidemic, which struck the region sometime between 1616 and 1618. This plague killed 50\% to as much as 90\% of the Massachusetts and Wampanoag people along the coast of Massachusetts Bay. A voyage in 1619 by the English Captain Dermer revealed that the previously settled coast “was now void”. This depopulation of the coastal areas of Massachusetts Bay made room for the Pilgrims, who founded their colony of Plymouth on the recently abandoned village of Patuxet.\textsuperscript{57} Thus, the English presented themselves as heirs to Algonkian.

\textit{Social Organization and Privileged Access}

In North’s \textit{Structure and Change in Economic History}, he expanded potential explanations of economic growth by adding a social dimension to the land-labor-capital of the classical economists. As with Solow, North does not view the Industrial Revolution as a sudden break with the past, but as the culmination of a long running process. Resource endowment, population, and capital stock (“land, labor and capital”) are all important, but for North it was the social organization that structured the economy (the “structure” in his title). He sees the establishment of property rights as the key. Firm property rights permitted returns to accrue to innovators; these potential rewards were what inspired technical change. The extent to which individuals have property rights, in turn, is determined by a society’s structure.

North usefully points up the inadequacies of neo-classical economic explanations that ignore social structure. “Indeed, a neoclassical world would be a jungle, and no society would be viable.”\textsuperscript{58} To correct this, North developed a theory with three parts: property rights; the

\textsuperscript{57} Johnson, p. 129.
\textsuperscript{58} North, p. 11. It seems to me that North is saying that neoclassical economics cannot explain historical change without some input from anthropology.
state (the property-rights enforcer); and a theory of ideology. North noted that an invention provides both private and social returns. Unfortunately, without secure intellectual property rights, the private benefits of many inventions would not justify their cost, even if the overall public benefits would. For sustained growth, a society needs to address the distribution of any benefits as well as any technical problems of production.\(^59\) Added to his theory of property rights is a theory of the state as the enforcer of property rights. Organizations (such as the state) can exist because they have a comparative advantage.\(^60\) Since compliance by coercion is expensive, societies undertake a substantial investment to convince individuals of the legitimacy of exiting institutions. Thus, compliance is linked to the role of ideology. Stability in a society rests on the perception by the general populace that things are fair; an ideology supporting this legitimacy is essential (again, the distribution question needs to be addressed).\(^61\)

The first economic revolution (Neolithic revolution) did not depend on the “discovery” of domesticated plants. People were well aware that plants grew from seeds. North attributes the establishment of agriculture to the development of personal property. People pursued improvements to fields and domesticated animals only after it was worked out how the benefits could be retained. The dominant dynamic in an agricultural society was population growth, and political entities tended to grow larger, ultimately resulting in the Roman Empire. North does not mention it, but a similar dynamic established empires in Africa, such as the Songhay, and of course in the Americas, India and China. North attributes the decline in the Ancient (Western)

\(^59\) Ibid, p. 16.
\(^60\) This may be a comparative advantage in violence; see Pomeranz in Chapter 2.
\(^61\) Here North is specifically using an anthropological analysis. See Clifford Geertz, cited on p. 46 in North, on the establishment of legitimacy.
world to a scarcity of marginal resources, usually land. It should be noted that land was the source of food energy in the pre-industrial economy.

For North, technology did not lead to change; technology followed paths cleared for it by social change. The idea that social context was a determinant of technology had been advocated by members of the *Annales* School. The same interplay between technology and social context can be found in the work of Braudel. Social organization, then, would determine which countries would advance economically.

North identified the period of 1450 to 1650 as the transformational centuries for Europe. He suggested that the Dutch, in contrast to Spain, managed sustained economic growth because of their open economy, and strong emphasis on property rights. But it was England that evolved most rapidly. Why? North cited the rising power of Parliament as a check on the Crown’s monopolies. Parliament was made up of merchants and landed gentry, who benefited from economic growth and trade. This suggests that representative government was the social structure that could better exploit the emerging energy source (wind, water, coal), and escape the Malthusian trap that ensnared France and Spain.

North agreed that constant technical innovation drove industrialization, however, this was only possible because of innovation in securing property rights. These rights were established in a process that pre-dates the traditional dates of the Industrial Revolution. This is not “laissez-faire”, which implies no restrictions, but a set of restrictions that guaranteed property rights.

Protection of patents increased private returns, addressing the distribution problem, which

---

62 See Chapter 9 in North.
63 See discussion of Wrigley, below.
65 North, Chapter 11.
66 Secure property rights would greatly reduced transaction costs; note that this provided powerful feedback in the exploitation of available resources.
67 North specifically cites the “Statute of Monopolies” (1624) which protected patent rights.
allowed the public benefits from technological advancement to accrue. While “learning-by-
doing” improvements can occur over time, concentrated study of innovation required investment; this was unlikely to occur unless there was a protected return to capital. These key changes were part of the changes in society that would make innovation not merely possible, but mandatory if a business entity were to survive.
Chapter 2: Divergence and Energy

Divergence

In his *The Great Divergence*, Kenneth Pomeranz takes the question of “what held back Asia” in industrial development and turns it on its head.\(^{68}\) He begins by summing up evidence that, in 17\(^{th}\) and 18\(^{th}\) century, the advanced areas of Europe, China, and Japan were at roughly the same level of economic sophistication. Critically, they were all bumping up against similar natural resource constraints. The idea that, circa 1750-1800, the advanced parts of Europe, China, and Japan were at roughly the same level of development has also found support in the work of Bin Wong.\(^{69}\) Parthasarathi, in his *The Transition to a Colonial Economy: Weavers, Merchants and Kings in South India, 1720–1800*, has made a similar case for India.\(^{70}\) Viewed in this way, it is industrialization that is the deviation needing explanation, which is different from assertions that China and India have somehow “failed”. Instead, the question is: When did the European economy diverge from that of Asia? More specifically: when and why.

Level of Comparison

When comparing “Asia” “Africa” and/or “Europe”, it is important to stop and consider what type of entity is being constructed for the comparison. Are they nation-states? Societies? Civilizations? Geographic expressions? A second related question is the extent to which an author views each area as an isolated, or interacting, with others. Over the past century, the view of “civilizations” has evolved form one of isolated areas to that of a world system consisting of interacting areas. For example Spengler, in his *Decline of the West*, compared “cultures”. He

\(^{68}\) Pomeranz (2000).
\(^{69}\) R. Bin Wong, *China Transformed: Historical Change and the Limits of European Experience* (Ithaca: Cornell University Press, 1997), see particularly Chapter 2.
considered them as equals, where he “…admits no sort of privileged position to Classical or the Western Culture as against the Cultures of India, Babylon, China, Egypt, the Arabs, Mexico…”.

He did not see any interaction between or among these entities, characterizing these cultures as “separate worlds of dynamic being.”

Arnold Toynbee compared “civilizations” which he identified as “an intelligible field by comparison with its component communities – nations, city-states, millets, castes, or whatever else these components may happen to be.” He saw these civilizations as having contact with each other, but primarily via conflict among independently developed entities. For both of these conceptions, the idea of a culture area or civilization is something larger than the nation state. By the 1960’s, the idea that civilizations might have been in closer contact, exchanging ideas and influencing each other, was further developed in McNeill’s *The Rise of the West*.

Pomeranz, working towards a much more detailed comparison, needed a more specific geographic comparison. He pointed out that individual European countries are simply not comparable with an abstract “Asia”, as either China or India is the size of all of Europe. For comparison, Pomeranz suggested a number of “core” areas within the Old World, among them parts of England, the lower Yangtze River, Gujarat, and parts of Japan. None of these was a core to the rest, but the whole was an interacting system. These areas were the inheritors of the Old World system Janet Abu-Lughod described as existing prior to the catastrophes of the 14th

---

71 Oswald Spengler, *Decline of the West: Form and Actuality (Volume 1)*; translated from *Untergang des Abendlandes* by Charles Francis Atkinson (New York: Alfred A. Knopf, 1926) p. 18.
73 Ibid, Chapter 44.
century. Pacey has noted that technological innovation flowed among these interacting cores, with each society adapting a version most suited to their own needs.

Circa 1750, all of these areas featured sophisticated agriculture, commerce, and the beginnings of industry. To the extent that these areas diverged, the difference must have occurred after this time. The normal, or default, path would be for all of these areas to solve the ecological dilemma by resorting to more labor-intensive solutions; this was what occurred in Yangtze Delta and Gujarat. Pomeranz sees the default growth path leading to a Malthusian world. The “Malthusian trap” is based on the limited availability of land, relative to population’s ability to grow. In brief, the trap arises because whereas population can grow at an exponential rate, land is limited (and the best land is used first). The unfortunate result is that population will eventually outstrip available land. This precipitates an environmental crisis, marked by high costs for raw materials and, tragically, food. Since production depends (in Malthus’ view) on a mix of land, labor and capital, this lack of land must be offset by the other two. Increasing labor intensity in the use of land is one obvious solution. Other partial solutions may be found in the application of organization, i.e. Adam Smith’s division of labor or additional capital, such as the building of a transportation network to provide access to additional land.

**Disequilibrium in Europe**

What factors diverted Western Europe from this expected path? Pomeranz tested theories that claim some special advantage for Europe. Did Europe have some advantage in ecology

---


78 Note that this assumes land, labor and capital are the only three inputs; energy and organization may offer additional opportunities for expansion.
(land), or demography (labor) or accumulation (capital) or even business organization?

Pomeranz found these suggestions lacking. He concluded that, for each of these factors, core areas in Asia were as advantaged as any part of Europe, especially in coal and iron production. Ultimately, Pomeranz identifies two factors that pushed Europe into “disequilibrium” (in this case, growth): privileged access to New World Markets, and the geographic accident that coal was located in economically viable areas of Britain.

In the case of Europe, privileged access to “new” land in the Americas provided Western European nations with additional land, which postponed their need to increase labor intensity in their homelands. The “privileged access” to which Pomeranz refers is similar to the “comparative advantage” North was talking about when he noted that a group’s advantage may be in the use of violence. In this new kind of periphery Europe could flout market forces and extract surplus, a surplus sometimes produced by slave labor. Pomeranz cites this use of other people’s land as a contributor to Western Europe’s ability to follow a different path.

*Mining Coal in Britain*

The second factor that would lead to industrialization was the use of coal. Pomeranz notes that, while ample coal was available in both China and Britain, the two countries had different transportation and technical challenges. In Britain, the mines were located near easy-access to water transportation; by contrast, the mines in China were more remote. Further, in Pomeranz’s characterization, the coalmines in Britain were “wet” (below the water table) while in China they were generally “dry” (above the water table, with no need for pumping). Dry mines were susceptible to explosion, and so required proper ventilation, while the wet British

---

79 See especially Pomeranz, pp. 63-64
80 Ibid, pp. 18-19.
81 Ibid, p. 65.
mines needed more powerful pumps. The British mines eventually experimented with a fire-powered engine, powered by the coal itself.

Pomeranz sees this as the decisive divergence that allowed Britain to eventually access unlimited (steam based) power. While this was the result, the development of that power would not at all been obvious at the time. “Living after two-hundred-plus years of gradual improvements… we tend to assume that the potential of even the crudest steam engine would be so obvious that people would adopt it rapidly; but this is only true in retrospect.” “In fact pit-head steam engines often used inferior “small coals” so cheap that it probably would not have paid to ship them to users elsewhere, making their fuel essentially free.” Take away these developmental advantages in the coalfields and “…the steam engine could seemed not worth promoting.”

Parthasarathi has been critical of Pomeranz’s coal-resource explanation, pointing out that merely having the coal resource is not an explanation for its use. Parthasarathi offered a refinement of the links between coal and the Industrial Revolution in his Why Europe Grew Rich and Asia Did Not: Global Economic Divergence, 1600-1850. He believed state support was an overlooked, but essential, element in the development of latent coal resources. Both Britain and China faced ecological difficulties in the 18th century. In Britain a political decision was made to provision London with coal, while in China, a political decision was made to intensify food production. An unintended consequence of policy in Britain was the development of coal powered mechanical power, the power that would eventually transform their economy.

Mining Coal in China

---

82 The technology of the pump itself may have been an important step towards the steam engine.
83 Pomeranz, pp. 67-68.
An alternative view of Chinese mining, but one that gets to the same conclusion, can be
found in Volume 5 of Joseph Needham’s *Science and Civilization in China.* Rather than wet
vs. dry, Needham noted that the China enjoyed extensive, unexploited coal resources. As in
Britain, flooding still occurred, but the presence of ample untapped coal above the water table
afforded mine operators in China an alternative to extensive pumping. Needham stated that
“...excessive water most often led to abandonment of mines. Nowhere was this more true than
in coal mining where there was so often another deposit nearby waiting to be exploited.”
In other words, the relative abundance of untapped coal resources provided the option of opening a
new shaft. In China, moving to a new vein proved the lower-cost alternative to intensive
pumping in an existing mine.

The lack of a need to grapple with water problems may have engendered the relative
absence of mechanization at Chinese mines. Needham stated that, prior to the Renaissance,
European and Chinese mining technology were on a par. By contrast later developments, such
as the rag and chain pump, which was in use in Europe circa the 15th century, were not applied in
China. The differing water problems would have far reaching effects on each area’s relative
mechanization of mining over the next few centuries: “Unlike in central Europe where, in the
late 15th century, mechanized windlasses powered by horses or by waterwheels were the
harbingers of a wave of mechanization that would soon transform much of European mining,
windlasses in Chinese mines overwhelmingly continued to be powered by human muscle right
into this century.”

---

85 Joseph Needham and Peter Golas, *Science and Civilization in China, Volume 5, Chemistry and Chemical
86 Ibid, pp. 344-346.
87 Ibid, pp. 308 and 344;
In Needham’s conceptualization, technology and economic development in China and Europe were, taken as a whole, on a par. However, in the mining sub-sector of the economy, Europe, particularly Britain, had been induced to work their resources more intensively. An overabundance of coal in China discouraged mechanization in that sector. This may be an important insight.\footnote{Chapters 3 and 4 of this dissertation look in greater detail at the energy needs of mines.}

Pomeranz and Needham, explicitly or implicitly, identified coal mining as a causal factor in the development of mechanization. Pomeranz and Wong both cited ample coal reserves as a key factor in the industrialization of Britain. They believe this handy source of ample energy contributed to the divergence. It should be noted that, writing in a different venue, Alfred Chandler (\textit{The Visible Hand}) came to a similar conclusion about the advent of managerial capitalism: he stated that the energy provided by inexpensive coal was a necessary precursor to the transformation of American businesses in the 19\textsuperscript{th} century.\footnote{Alfred Chandler, \textit{The Visible Hand: The Managerial Revolution in American Business} (Cambridge, Massachusetts: Harvard Belknap, 1977) pp. 13-14.} Beyond that, the very nature of coal may have contributed to the divergence. Unlike most other mined commodities, coal itself is also a source of thermal energy, and potentially useful work and power.

Parthasarathi, in his review of Pomeranz, said that while he thought Pomeranz had broken new ground, further work was needed. Identifying the structure (coal availability) was not enough. He called for focusing on the “nuts and bolts” (Parthasarathi’s phrase) of the process of technological change that accompanied the adoption of steam technology.\footnote{See especially pages 284-286 of Parthasarathi’s review of \textit{The Great Divergence} in \textit{Past and Present}, 176 (1) 275-293. \url{http://0-past.oxfordjournals.org.ilsprod.lib.neu.edu/content/176/1.toc} (accessed February 1, 2008)} Parthasarathi has noted government support for the development of coal as a key factor. To delve more deeply into the nuts and bolts of Britain’s divergence, we need to examine the nature of coal itself.
Organic vs. Mineral

To assess the nature of coal, we can turn to E.A. Wrigley’s *Continuity, Chance and Change*. In this text, Wrigley sketched out the relation between energy use and the process of economic development in Britain during the “Industrial Revolution”. It is significant that Wrigley does not see the Industrial Revolution as a unitary, progressive process. Instead, he suggests that there were two interacting developments that between them produced something later called the Industrial Revolution. The first phase was the development of what he termed an “Advanced Organic Economy”; this occurred during the two centuries before 1800. The second was the rise of the “Mineral Based Economy”, after 1800. Wrigley notes that there was extensive overlap between these two, but he chose to separate them at the year 1800 for purposes of analysis.

By “organic” Wrigley means production based on land use (or “renewable energy”, as it might be styled in the 21st century). The key attribute of an organic economy is that annual production is ultimately constrained by the *rate* at which economically useful things can be produced on the land. A “mineral” economy, by contrast is not limited by rate of production, but by the ultimate level of (or total *stock*) of a resource. Unlike an organic source, a mineral is not produced each year; instead, its production draws-down from its pre-existing stock. If the stock (resource endowment) of the mineral is sufficiently large, its annual production can be increased without practical limit.

The annual production of a non-renewable mineral resource such as coal may be limited for other reasons. In the example of coal, on the supply side, the pre-existing stock may not be

---

93 Wrigley, pp. 3-9
94 This is the type of economy developed in Pomeranz’s core areas.
large, relative to demand. On the demand side, the resulting pollution loadings (smog) may give the residents of London or Beijing pause to consider the wisdom of their current usage.

However, there isn’t any *a priori* reason to inhibit accelerating use of the mineral resource. The organic-to-mineral energy transition may be at the core of the changes alluded to by Pomeranz, changes that broke the equilibrium in agricultural societies. A more detailed examination of the two types of production can be drawn from Wrigley’s work.

### Organic Economy

In an organic economy, the fuel for energy provided by human labor, animal labor, or heat energy is produced from the land. Since land is limited, the amount of energy that can be derived from it is limited. Energy is based on the flow (or rate) of conversion.

There is a strong negative feedback to growth in an organic economy, as Malthus noted. Economists express this as the law of diminishing returns. The best land is used first, leaving only land of decreasing quality available for future expansion. As a result, ever more inputs are required for each succeeding unit of output. The returns, sadly, diminish.

It is also characteristic of advanced organic economies that all resources are already employed; any future option typically displaces some current use. Take the case of using animal power to increase agricultural output. The familiar story of how the horse collar and the heavy plow revolutionized food production in Northern Europe is an illustration of this. While providing a net gain, this improvement (using capital and organization) displaced some previous use, as feeding the additional draft animals required displacing some of the same agricultural land.

---

95 “Land” is used in an agricultural sense; it includes production from sea-bourn activities such as fishing.
96 See for example Chapter 2 of Lynn White’s *Medieval Technology and Social Change* (Oxford: Oxford University Press, 1962) regarding the horse and plow.
An advanced organic economy can increase productivity, but it is necessarily limited. This was the world described in detail by classical economists, particularly Adam Smith, Thomas Malthus, and David Riccardo. Within this economy, a laundry list of things can improve real incomes. Per the classical economists, these improvements would include such things as an appropriate legal framework, property rights and “free” labor (labor dispossessed from their agricultural rights and obligations). These types of improvements do lead to growth, but decreasing marginal returns will of necessity limit any real increase in average wages. Adam Smith expected economic stagnation at a relatively low level of material comfort (food, clothing, shelter, and heat) for the average person.\(^9\)

**Mineral Based Economy**

The development of an advanced organic economy certainly improved agricultural productivity in Britain, but it brought only modest improvements to living conditions. Wrigley asserted that Britain’s economy would have drifted towards a state of steady (stagnant) equilibrium, except for a second important development: the use of mineral based fuels. Mineral based fuels were able to avoid the constraints that would have eventually limited any organic-based improvements in real incomes. A “divergence”, to use Pomeranz’s term, occurred.

In activities where mineral-based energy could be substituted for organic (land), the constraint on annual production would be eliminated. For a mineral such as coal, its only limit would depend on the stock of coal recoverable from the ground. It was pointed out as pointed out as early as 1810 by Thomas Malthus, ever the optimist, that once used, coal was gone forever. As such, since coals exhaustion was only a matter of time, he believed it could not

\(^9\) This interpretation of Smith is shared by Wrigley, Chapter 2 and Parthasarathi (2011), p. 8.
support long-run growth. While Malthus may yet prove ultimately correct, this limit does not necessarily have any short-term impact, “short-term” defined as the most recent few hundred years. This is because, in the case of coal, the ratio of annual use, relative to the mineral’s total availability, is quite small. As a result, it is available in effectively unlimited quantities.\(^98\)

The implication of this unlimited availability of a non-organic source of heat was first felt in the production of non-organic products such as iron, pottery, or brick. The volume of these non-organic products, when produced using a non-organic fuel, could be increased without additional pressure on the land. Further, Wrigley casually notes that when an efficient device had been developed for turning “heat” into useful mechanical energy, it could provide what was effectively unlimited power.

Historically, Britain was not slow to exploit this resource, as neither was Europe in following them. In 1700, Britain produced 2.5 to 3.0 million tons of coal, which by Wrigley’s estimate was 5 times the rest of the world’s output. By 1800, Britain produced 15 million tons of coal; however, this was now only 5 times all of the rest of Europe.\(^99\) One could profit from the consideration of the acreage required in an organic economy to produce that much fuel. Wrigley estimates a sustainable yield of two tons of wood per acre; since wood has half the heat content of coal, each ton of coal displaces one acre of dedicated timberland. The 12 million ton increase in annual production of coal would have required harvesting an additional 12 million acres of timberland \textit{annually} in Great Britain.\(^100\) To put this in perspective, consider that the entire land area of Great Britain today is only about 60 million acres; about half of this is in agriculture and

\(^{98}\) For an example of an energy source where the annual ratio is high, see discussion below regarding the use of peat in the Netherlands.

\(^{99}\) N. von Tunzelmann, p. 111, arrives at a lower figure for 1800, suggesting output could have been as “low” as 10 million tons; the specific level of output does not alter the dynamics of the changes.

\(^{100}\) Wrigley, pp. 54-55.
one quarter (15 million acres) in forest. A 12 million acre increase would be equivalent to not much less than a doubling of forested lands; a 20% increase in available land area, per year.

*Modernity and Industrial Revolution were two different phenomena*

Wrigley strongly argued that modernity and the industrial revolution were two different phenomena. He noted that Holland in the 17th century was much further down the path to modernity and being fully capitalist than was Britain, but thereafter it failed to industrialize. He suggested that the reason was that modernization and capitalism are necessary, but not sufficient, to escape the steady-state trap of an organic economy. What the Dutch lacked was a source of mineral energy to complete the energy transformation. Note that this is in direct contradiction to Marx, who assumed unlimited energy would be available as capital accumulated.\(^\text{101}\)

Consider the underpinnings of the “Dutch Golden Age” of the 17th century. While it was propelled by many factors and not just energy alone, its mineral energy base was peat. Unfortunately for the Dutch, it is estimated that they were using 3% to 5% of their total available peat per decade during the 17th century.\(^\text{102}\) This pace – this ratio – of energy consumption was simply not sustainable. This is an example of a mineral resource where the available stock is relatively small compared to the annual usage.\(^\text{103}\) Wrigley does not believe energy availability was the sole reason for the rise and fall of Dutch power in the 17th century. He does, however, note that it affords a significant contrast with energy availability in Britain.\(^\text{104}\)

\(^{101}\) To be fair, the Neo-classical economists, Marx’s arch-antagonists, believe the same thing.

\(^{102}\) Wrigley citing DeZeeuw, p. 58. For an analysis of Dutch peat supplies, see Chapter 2 of Jan de Vries and Ad Van der Woude *The First Modern Economy: Success, Failure and Perseverance of the Dutch Economy, 1500-1815* (New York: Cambridge University Press, 1997).

\(^{103}\) Put another way, the ratio of annual use to total ultimate supply was too high to sustain.

\(^{104}\) Wrigley, p. 60.
Limits to Organic-based Growth: Sheep Devour Men

“...your sheep that were wont to be so meek and tame, and so small eaters, now, as I heard say, be become so great devourers and so wild, that they eat up, and swallow down the very men themselves. They consume, destroy, and devour whole fields, houses, and cities.”

-Sir Thomas More, *Utopia*

Wrigley’s distinction between two different types of energy systems can be used to clarify certain aspects of the Industrial Revolution. In a pre-industrial, organic-based economy, any improvement displaces some already established part of society. As Thomas More famously characterized the enclosure movement, sheep devour men. The expansion of the wool trade, England’s primary export in the 16th century, came at the expense (and impoverishment) of others. Put differently, in an organic economy, negative feedback is dominant; this will tend to limit its growth.

Although an advanced organic economy can improve a great deal, each increase in output makes the next potential increase more difficult. This was the world clearly understood historically by the Classical economists, circa 1800. Some improvements, for example the potato-based agriculture in Ireland and Scandinavia, can increase output, but such innovations only temporarily relieve the constraints of organic production.

Wrigley concluded that it was increased energy usage that allowed Britain to enjoy increased output per head. This produced rising real incomes, which he saw as the defining characteristic of an “industrial revolution”. The transformation from an agricultural economy to an industrial one was sustained by substituting mineral energy for labor in the agricultural

---

106 Not incidentally, Moore presents an early (16th century) example of an economic basis for crime.
107 “Negative” is not a value judgment, but instead means growth in one area causes a decline in another; thus the two areas tend to move inversely to one another (negatively).
108 Wrigley, p. 130.
sector. He cites Grigg on the dynamics of agricultural change, as highlighted by the radical shift in the energy input/output ratio in agriculture. Grigg estimated that in the agricultural sector for the year 1700, each 1-calorie expended resulted in 10 calories produced. By contrast, in the year 1990, 3 calories of energy were used up for each 1-calorie of output. The apparent loss of energy in the food-producing sector was made up by mineral energy use. The balancing factor was the value of the output over the cost of the (energy) input. The cost of the lost energy was offset by the value of the agricultural output; thus mineral energy use freed up human labor. Animal labor was rendered largely unnecessary.

The Economy as an Energy Using System

Thus far, we have followed a line of scholarship that identified the energy shift as an essential factor in the Industrial Revolution. Further elucidation of this shift can be found in the work of Andrew Tylecote via his analysis of the evolution of “technological styles”. Tylecote affirmed that energy use could only be understood within its social context, and his identification of institutional development as the driving force behind historical economic change is similar to North’s. He sees social organizations as the determining factor of which energy opportunities will be exploited.

Tylecote took as his meter of the industrial world the economic “long wave”, which had been described by Kondratiev as a wave of price and economic activity. The long wave, with a period of 45 to 60 years, is one of the cycles, such as the much shorter business cycle, that can be observed in industrial societies. Kondratiev thought the long wave was generated by over investment, spurred on by a bloc of technological innovation, what has more recently been

---

109 Grigg cited in Wrigley, p. 80.
termed a “bubble”. Tylecote more specifically sought the source of the long wave in the structural changes that can occur in a society rapidly adapting new energy using technology.112

Tylecote cited the work of the “regulationist” school in France: a radical change in production methods (“the regime of accumulation”) is not necessarily harmonized by a change in income distribution (“the mode of regulation”). For example the “Fordist” assembly line (circa 1915) shifted power towards the capitalist (regime of accumulation); however, because the pre-existing mode of regulation remained unchanged, the result funneled income distribution away from the workers. This eventually led to a crisis and depression. Societies were faced with a critical political test, which they solved with varying degrees of success. As North might have said, a successful resolution is conditioned by social / political change.

Tylecote identified a succession of technological styles (technological long waves). The first was the “Water Transport Style” of production, 1780 to 1830. This was succeeded by the “Steam Transport Style” roughly the years 1830 to 1870. Steam was succeed by the “Steel and Electric Style”, 1870 to 1915. Although Tylecote did not seek to explain the Industrial Revolution, his ideas about technological styles and “mismatch” between production and distribution are useful concepts in understanding what prompts change, and how change can engender crisis. This political crisis was prompted by the change in technical style, and the determinant of a technological style was its energy source. Taking this cue, we will pursue this thread by examining the work of thinkers who have described the society as an energy using system.

---

111 Tylecote, p. 15. Schumpeter held a similar view.
112 Tylecote cited Carlota Perez in the development of the concept of “technological styles”.
Converts Energy and Collecting Rents

In their text *Les servitudes de la puissance: une histoire de l’energie* (translated as *In the Servitude of Power: Energy and Civilization Through the Ages*) the French scholars Debeir, Deleage and Hemery introduced the insightful concepts of an “energy converter” and an “energy rent”.¹¹³ Their work reviewed all of human history, but their insights can be applied to the Industrial Revolution. “*Les servitudes de la puissance*” has been translated literally as “In the Servitude of Power”; an alternative translation would be “The Restraints of Power”; the sense is energy will only serve a society if the society structures itself to its potential energy sources. Thus using an energy source empowers a society, but also restrains its options.

They noted that, as a practical matter, energy in the universe is unlimited; historically, the problem has been a lack of converters. Thus a history of energy is a history of energy converters. To be successful, a converter needs an energy source with specific characteristics: the energy must be of a certain quality; in an economic location (affordable transportation costs); and available at certain times (storable and distributable, as needed).

Their hypothesis was that energy is only one, but the most restrictive, mediator of humanity’s relation to nature. Among the other mediators are: social, technical, political, and mental constraints. Taken together these form an energy system. To understand the historical change in society requires taking into consideration all of these restraints, and how they interact. Debeir Deleage and Hemery are particularly critical of suggested explanations that stop at the technical level, as they believe this falls short of a full understanding of historical change.¹¹⁴

---


¹¹⁴ Debeir Deleage and Hemery, Introduction.
The authors’ level of analysis is that of an energy system, a system being a collection of energy converters. The technological, social, political, and mental elements must all be integrated in order to form a successful energy system. To explain an energy system, an analysis needs to answer these questions:

1. Ecological and technological elements: where does the energy come from? How is it converted?

2. How is it appropriated? How consumed? While this may seem a “soft science” question of social relationships, it will condition what types of energy technology can be successfully developed.\(^{115}\)

They give the example of Pharonic Egypt, which used technology and energy sources (#1 above) that had been previously developed. What changed were the social relations (#2), which re-ordered their society.\(^ {116}\) Energy systems can bolster a social class, but they of necessity obey the logic of the social formation, of which they are a part. Conflicts about energy systems are conflicts about who gets to control the surplus production, the “energy rent”.

**Energy Rent**

The authors introduced an important insight: the distribution of returns in a society depends largely on control of energy use. By this they mean the use of an energy source to provide an “energy rent”. An energy rent is gained when the output from using an energy source exceeds the marginal inputs required to produce that energy.\(^ {117}\) Thus, social surplus can come from not only from labor, but also from energy.

An energy rent is the surplus provided by energy in one of four possible situations:

1. Absolute rent (natural form);
2. Differential rent (provided by a “spatial” – geographic – advantage)

---

\(^{115}\) Again, North’s notion that a distribution perceived as equitable is essential for a functioning system.

\(^{116}\) Debeir Deleage and Hemery, p. 6.

\(^{117}\) Note the similarity to Tylecote’s conception of energy use.
3. Monopoly rent (where the mode of appropriating the energy limits access); and  
4. Technical rent (that surplus accruing to the technically advanced).

Absolute rent, its “natural” form, is the energy returned directly for an activity, such as hunting or gathering.\(^{118}\) The second case, the possibility of creating a differential rent, is the basis of trade: items are transported to where they are relatively more valuable. Monopoly and technical rents accrue where a power differential allows for extraction and retention of surplus.

Within any established energy chain, there will be competition for limited resources, as for example when land use is allocated among production for food, fodder, or fuel. This was what occurred when Thomas More’s ravenous sheep competed with, and then displaced, small landholders. There is also a reactionary side to this competition: Vested interests within the society will invariably look for solutions to shortages in more of the same, eschewing “alternative energy” solutions.

*Endosomatic vs. Exosomatic Energy Use*

As a whole, the Earth is not a closed energy system; it receives solar energy. Living organisms are machines for converting this solar energy. They are autotrophs, directly converting solar energy, or hetero-trophs, which are critters that eat autotrophs (or perhaps other heterotrophs, and in some cases both). The authors ranked living things according to their ability to convert energy. Efficient plants convert 2% of solar energy they receive; herbivores eating these plants will capture perhaps 10% of that energy; carnivores typically capture 10% of what herbivores have stored. Humans share with animals this ability to convert “endosomatic” energy, endosomatic being a fancy word for digestion. Humans are highly efficient, converting

\(^{118}\) See Chapter 4 below.
about 20% of their food intake into useful energy. Note that this is better than horses, which convert only about 10%. Where humans differ from other animals is in what the authors term their “exosomatic organs”, by which they mean the ability to use energy from outside of our bodies. Over the last 10,000 years, humanity’s exosomatic energy use has radically increased. Systems to produce, control and exploit cereal power, slave power, and wind power (ships’ sails) were developed early in this period.

*European Industrialization*

By the late Middle Ages, Europeans were faced with repeated shortages of land and resources, and thus energy. This problem was addressed in three ways: intensification of the then current methods; seeking technological advances; extractions from the periphery. As noted earlier, intensification of a given energy chain creates competitive friction. This may intensify the impetus to seek an energy source outside the chain. If successful, this would confer an advantage on a society. The authors cite the use of wind energy through sailing and navigation technology as an example of an outside energy source. Significantly, sailing was an energy use that did not displace food production. Also, unlike waterpower, this type of wind power had much greater room for expansion. In a sense, Europe’s expansion of long-distance maritime trade from the 15th century onward was, in its essence, a desire to extend the West’s energy frontier. Control of maritime routes allowed the controller to collect the energy rent from this form of wind power. Although Europeans may have expressed it differently, this concept

---

119 Debeir Deleage and Hemery see this converting advantage for humans as one of the supporting pillars of slave society.
120 They note that Rome was an example of the slave as biological converter, and suggest that, away from the Mediterranean rim, the empire faltered because there were not enough slaves for exploitation.
121 Debeir Deleage and Hemery. P. 87.
122 With certain patent and property rights, a portion of the wealth would accrue to the investors.
123 This is an example of a spatial advantage; this is the type of comparative advantage (to use Adam Smith’s term) that is the basis of the profitable trade.
was not lost on them. As a result, control of trade routes was an area of endemic conflict among them from the 16th to the 19th century. Britain would eventually merge as the principle collector of this rent: by 1800 they had twice as much tonnage of ships as France, and 10 times as much per capita.

The authors viewed the development of James Watt’s efficient steam engine as the true start of an energy revolution. They noted that engines of the Newcomen type were used only at coal pits. Debeir, Deleage and Hemery also touched upon the positive feedback that accompanied the application of the steam engine. It is significant that one of the first non-pump uses of a steam engine was in 1775, when a Watt engine was built to power a 60 kg hammer for Wilkinson’s forges. These same forges were used for the production of improved steam engine cylinders, rendering the engines even more efficient.

*Structure vs. Statistics*

Debeir, Deleage and Hemery criticized statistical methodologies for their weakness (if not outright failure) to capture structural change. They point out that energy’s role cannot be understood by looking at its economic cost, for example, as % of GNP. This is because their selected measuring standard, GNP (money cost), *already* incorporates the effects of the energy transformation. Even in 19th century Britain coal, if looked at on a GNP basis, appears unimportant, perhaps no more than a few percentage points of GNP. A similar case can be made as regards railroads. However, this measure masks the transformation that has occurred. GNP

---

124 Debeir Deleage and Hemery, P. 88.
125 Ibid, Table 5.2, p.93.
126 They are correct that, if it had never been improved from the Newcomen version, the steam engine would not have been the transformational technology it became. One might also observe that, without the original invention of the Newcomen engine, it never could have been improved.
has expanded *because* rail transportation and coal are so inexpensive, i.e.: the same factor that renders them such a small part of GNP.

To properly assess the impact of coal, the authors suggest that a displacement analysis is required. They cite an excellent illustration, which can profitably be considered here. In 1850, a train of 14 cars, pulled by a 100 HP engine, could carry 90 tons of merchandise. This displaced 18 stagecoaches, 18 drivers, and 144 horses that took two and a half days to make the trip from Paris to Lille. The train took under 5 hours, consuming one-ton of coal in the process. One ton is the daily output of two miners. As contributors to total GNP, the toil of the stagecoaches and horses would be considerably greater then the 5 hours of train “labor” and one ton of coal.\(^1\) A full gross of 144 horses and their support would have had a much greater impact on GNP, but this should not to be confused with actual increase in living standards.

Following Debeir, Deleage and Hemery, we have extended and generalized insights (such as North’s) on the relation between society and production, now focusing specifically on energy. Their concept of extracting an energy rent, by which they meant tapping into an energy stream, provides a generalized overview of the method living things use to exist. This view can be applied consistently from plants converting sunlight to the evolution of societies as energy using systems.\(^2\)

**Energy as an Essential Factor of Production**

In the 1960’s, the Romanian economist Georgescu-Roegen formed a view of economic growth that incorporated energy and the environment, eventually coining the term “Bio-economics”. Georgescu-Roegen explicitly drew on thermodynamics (the transformation of

---

\(^1\) Ibid, p. 104.  
\(^2\) Particularly interesting is their conception of sailing vessels as collectors of a wind energy rent. The British ships crisscrossing the 18\textsuperscript{th} century Atlantic, as described so eloquently by Williams, were at their core a profitable exploitation of wind power.
energy) to explain economic growth. As with other scholars in this vein, he saw the shift from an organic to mineral energy source as a change with a transformative historical impact.\textsuperscript{130} Combining this concept with the analytical tool of an energy rent will aid in examining the case studies that follow.

Further theoretical development of the idea of an energy rent can be found in Bernard Beaudreau’s \textit{Energy and the Rise and Fall of Political Economy}.\textsuperscript{131} Beaudreau objected to the notion that only labor or capital can be productive, citing energy (the environment) as a missing factor in the production equation. In this work, he also explicitly used the concept of an energy rent.\textsuperscript{132} As Beaudreau developed his argument, much of his interpretive insight was linked to how the surplus produced by the energy rent is divided in society. As with Tylecote, he contended that a society’s exchange technology is linked to its production technology.

Political economy is the study of how wealth is created and distributed. Much of the study of industrialization by political economists has focused on the displacement of labor by capital (humans by machines). Beaudreau sees this as approach as too narrow. The industrial revolution re-cast society not just because it was the transformation from hand to mechanical production; the real change was the substitution of different energy types. Separated from the energy that motivates it, the dynamics of capital cannot be understood.\textsuperscript{133}

Beaudreau asserted that this was why the development of Political Economy has languished. He contrasts this with progress made in physics: while political economy has


\textsuperscript{132} Beaudreau, pp. 4-5.

\textsuperscript{133} In Beaudreau’s view, 19\textsuperscript{th} century moral philosophers did not differentiate between tools and power. This created two related problems for the understanding of productivity: miss-specification of the “productivity” problem; and failure to considers the apportionment of the energy rent.
stagnated, physicists developed thermodynamics, the science of energy. To put energy in its proper perspective, Beaudreau believes that there should be five factors of production: Labor, Capital, “Land” (mineral resources), Energy, and Organization. 134

Beaudreau saw the Industrial Revolution as an energy revolution that radically changed the roll of “labor”. Rather than acting as a prime mover by providing muscle power, labor was left with the roll of a low-level supervisor, “…overseeing the workings of continuous-flow machinery.” 135 This represented a fundamental change: in an industrial society, human labor is replaced by machine labor; the human “laborer” is now a low-level supervisor, overseeing the machines that are doing the actual labor. Beaudreau pointed out that Alfred Marshal had cited this “machine-tending” as the key characteristic of labor after industrialization. 136

In a pre-industrial productive system, labor provided both power and organization; after industrialization, labor provides only organization (low-level management). The power comes from elsewhere. As a result, a labor theory of value (such as from Robert Owen or Marx) cannot properly diagnose these issues, as it focuses on workers as the source of energy inputs. By contrast, the Neo-Classical Economists (such as Marshall) viewed energy as part of consumption. Unfortunately, this treatment also fails to contribute to understanding the Industrial Revolution. Rather than treat energy explicitly, in these theories it is assumed to be a constant. As a result,

134 Beaudreau is addressing an important problem. When outlining the evolution of productive social systems, land, labor and capital alone are not sufficient to describe their evolution. Additional factors for organization (management) and energy (non-human) are needed to describe the changes. Adding these will allow for a more fully-founded description of the historical changes of the Industrial Revolution.
135 Beaudreau, p. 47.
historical change was relegated to the role of a series of periodic updates or unexpected shocks.\textsuperscript{137}

Beaudreau criticized trying to base a science of wealth in an industrial society on a Neolithic (agricultural) outlook. In his work, he drew on thermodynamics (energy transformation) to describe the actual drivers of growth in material wealth. By placing energy at the center of analysis, the first Industrial Revolution (circa 1780 to 1850) can be seen as a shock to society. This shock stemmed from the new power source, not specialization and the division of labor. This is the period of the “industrial take-off”. As North might have phrased it, specialization and division of labor were the organizational changes necessary to exploit the potential recourses. In either case, an energy using system is the proper level of analysis, rather than a “Neolithic” analysis focusing on “labor” as the driving force. In reality, with “free” energy available (energy unlimited in quantity, at least in the short run), human labor becomes merely an organizational power. Labor no longer provides any energy, that is, labor is no longer a “prime mover”. The course of industrialization can then be seen as the systematic replacement of human and animal labor by cheaper, previously stored, energy sources.

\textsuperscript{137} Beaudreau notes that in quantitative economic analysis, technological change is slipped in as part of the “A” scaler in the Cobb-Douglas production function. Beaudreau, p. 85.
Summary

The concepts developed in this literature review will be used to structure and inform the case studies that follow. The hope is that an emphasis on energy will shed some light on the historical transformation gathered in under the title of “Industrial Revolution”.

The Industrial Revolution was Two Events

A number of authors see the industrial revolution as having two phases. The first phase was the establishment of a “for profit” mode of production (or an “advance organic economy”). The second phase was an increasingly rapid replacement of animal and human energy as prime movers, first by other organic energies and eventually by fossil fuel energy. The second phase can be thought of as the “industrial take-off”.

Parsing the Industrial Revolution into two events resolves the analytical conundrum of dating its start. Production for profit is a necessary precondition for the industrial take-off, but it developed slowly in the prior centuries. Scholars who see the Industrial Revolution beginning 500 to 1,000 years in the past are citing this phase as its start. It should be noted that free market capitalism was not required; mercantilism was able to do just fine. It makes little difference even if the participants are pursuing restraint of trade, as long as a profit is retained. The necessity of a “for profit” system was a point on which North was most eloquent. If profit can be arbitrarily taken away from the innovator, it will stifle innovation. The innovator’s profits may be taxed by the government (certainly), sued for in court (maybe), but may not otherwise be arbitrarily separated from the investor.

The prior phase of the development of merchant capital is an essential, but not sufficient, cause of industrialization. Pomeranz and others have made an excellent case that a number of core areas in the old world were at about the same level of mercantile development, circa 1750.
The second phase, the “divergence” of Pomeranz’s title, was characterized by the exploitation of long-term stocks of energy. Once these two elements were in tandem - the profit motive, combined with effectively unlimited energy - they proved a powerful cocktail for sustained increase in income per capita.

**Energy marks the second phase, the Industrial Take-off**

To properly assess the phase the Industrial Revolution entered in the 18th century, we can draw on Wrigley’s analysis of the difference between organic and mineral energy. He contended that access to a stock of energy that is independent of an annual production cycle could sustain open-ended growth. Consider, for example, the rate of energy output maintained by growing wheat in a field. A certain energy input would result in a certain output, depending on the weather and other factors. Many improvements are possible: output may be enhanced through fertilizing, improved plowing techniques, or some form of multiple cropping. All of these methods tap into a renewable energy flow, and capture energy at an annual rate. Now consider the radically different dynamics of the situation if there was a vein of coal under the field. In this second case, the energy latent in the land could be accessed immediately: All the coal-energy that the field will ever produce is available immediately. The loosening of this energy all at once would produce a phenomenal amount of useful work, enough perhaps to result in steadily rising output per capita.

*Economic rents; Energy rents*

---

138 These stocks are not just fossil fuel energy; particularly in North America, original forests and untapped rivers for hydropower were used first.
The benefit of energy exploitation is that one can get more work out than is put in. To reverse the colloquial expression, there is such a thing as a “free lunch”. An energy rent is available when it requires less work-energy to secure an energy source than that source will produce. In a hunter-gatherer society, this calculation is used to determine which food sources to pursue. The available food sources, and their “cost” of acquisition, determine the optimal size of a society. This can be thought of as a form or arbitrage. If the cost of acquiring the energy is less than the value of the output attributable to the energy, the source will be exploited. Conceptually, the controller of the energy can collect an energy rent.

Society needs to solve several problems before any collecting may begin. As Debeir, Deleage and Hemery noted, not only must energy converters be available (the technology), they also need to be socially controllable. Part of the issue of control turns on another problem society needs to solve: distribution. As North, Tylecote and others have noted, an acceptable distribution of the gain is needed to avoid constant struggle. At its base, this can be viewed as a resolving the struggle over the energy rent.

Both wind and annual crops are short-term products of solar energy. Longer term, trees represent years of stored energy. Longer still is the energy stored in a vein of mineral energy, such as peat, coal or oil. Mineral energy is solar energy gathered, condensed, and stored over an extremely long period of time; controlling and releasing that store of energy over a short period of time produces a tremendous bonus of “free” (or at least cheap) energy. The controller of this source is in a position to extract an energy rent when selling items produced using these energy sources.

Mokyr did not miss this point, and considered the whole rational for improving technology was to secure what he called additional “free lunches”.

These concepts are further developed in Chapter 4.

As Marx or Williams would note, “socially controllable” is essential, but not always pretty.
The Development of a Prime Mover (the steam engine)

The steam engine allowed the transformation of stored mineral energy into mechanical energy. As a result, mechanical energy became extremely cheap. This was a key ingredient in industrialization. The steam engine not only opened the door to unlimited energy, it provided a generic prime mover. The radical changes put in motion by this commodification of energy cannot be overstated. Energy could be shifted into whichever venue of production was most profitable. Marx, in book one of Capital, noted:

“The greatness of Watt’s genius showed itself in the specification of the patent that he took out in April, 1784. In that specification his steam-engine is described, not as an invention for a specific purpose, but as an agent universally applicable in Mechanical Industry.” ¹⁴²

In other words, the prime mover and energy source were, for the first time, spatially separate. As the Debeir Deleage and Hemery, put it: “The intensification of the medieval energy system had made possible the first stage of industrialization, but with steam and coal, a new energy system was born.”¹⁴³ Beaudreau noted that workers would eventually no longer provide labor (motive force); instead they would become low-level supervisors, their job to direct the motive force of the machines. Given these transformative impacts, understanding factors in the origin and development of the steam engine emerges as an essential part of understanding the Industrial Revolution.

¹⁴² Marx (1887), 260-261.
¹⁴³ Debeir Deleage and Hemery, p. 102.
PART II: The Energy Milieu

Chapter 3: Commercialization, Energy Demand, and the Flooding of Mines

Did industrialization begin in the late 18th century, or is it really the earlier development of property rights, trade, and the commercialization of certain segments of the economy that began at least as early as the 13th century? Unfortunately, this does not appear to be a “yes-or-no” question. The developments of markets, property rights, technology, access to resources, etc, are so interdependent that attempts to assign causality become entangled in the spiraling feedback among these phenomena. To disentangle the causality of the “Industrial Revolution”, it may be intellectually useful to think about it as two mutually conditioned phases. The first phase is marked by an expansion of production for exchange and trade. These developments are sometimes grouped under the heading of the Commercial revolution.\(^{144}\) This phase stretches back five hundred to a thousand years and saw the development of essential elements of the Industrial revolution, such as technical innovation, property rights, and double entry bookkeeping.\(^{145}\) Using this division, the second phase began in England in the 18th century. This phase was marked by a number of interrelated global changes, the full consequences of which are still playing out. The second phase can be thought of as the mechanization revolution.

A number of historians have shown that commercial advancement was not unique to Europe, but in fact a global phenomenon.\(^{146}\) They suggest that the difference (or divergence) occurred after 1700. At the same time, the innovations in the 18th century would not have been

---

146 See for example Abu-Lughod or Pomeranz.
possible without the earlier developments. As will be shown, although the two phases of commercialization and mechanization were interconnected, they were markedly different in the way they used energy. Focusing on energy use will allow a clear demarcation between the two phases. The result will suggest that commercialization was a necessary, but not sufficient, cause for the changes that followed in the 18th century.

This dissertation is focused on energy, and traces the expansion in societies’ ability to process energy. Specifically, its goal is to examine specific case studies for evidence as to why certain societies diverged from the expected equilibrium result of the commercial revolution. While the debate on the proper naming of these periods may shift in the future, for this dissertation’s purposes, the phase prior to the 18th century will be referred to as the Commercial revolution. For the period after 1700, it is tempting to devise a new label these changes, such as the “mechanical” revolution. However, little additional clarity can be expected from adding a third “revolution” to the debate. When discussing this mechanization phase, and how it changed the way energy was used to power machines during and after the 18th century, the convention of using the term “Industrial” revolution will be followed. It should be understood, however, that the focus is on why the commercial revolution did not reach an equilibrium result, but instead diverged onto the path of mechanization.

The mechanization of the Industrial Revolution could not have occurred without the establishment of commercialization. The other side of the coin is that without the energy transition of the mechanization revolution, the Commercial revolution would have in short order settled into an equilibrium. The brake on the otherwise unlimited expansion of commercialization was the limited nature of the primary energy sources then available. This was
certainly the view of Britain’s classical economists, Smith, Ricardo, and Malthus.\textsuperscript{147} Perhaps a successful transition was inevitable, but along with the classical economists, I find that prospect dubious. People often see their own business successes as inevitable and natural, while their failures (or a competitor’s successes) result from a series of unfortunate and avoidable events.

It is sobering to recall that industrialization as such did not exist in the 18\textsuperscript{th} century, and we should be careful not to anachronistically project it backward in time as an influence on the historical actors who preceded it. Parthasarathi, cautioning about the dangers of historical anachronisms, noted of industrialization that: “It was an unanticipated, unforeseen and unintended outcome of the economic and social needs that were found in that part of the world.”\textsuperscript{148}

\textsuperscript{147} Adam Smith did not foresee open-ended progress; for a clear description of the dynamics that would bring growth to a halt, see the dreary Reverend Thomas Malthus.
\textsuperscript{148} Parthasarathi, (2011) p. 10.
Commercial Revolution to the 18th Century: Energy, Converters, and Social Need

The Commercial revolution is today viewed as a global phenomenon. The research of Pomeranz, Parthasarathi, Wong, and others, taken together, has made a convincing argument that in the 17th and 18th centuries a number of areas of the world were at least as commercially advanced as Northwestern Europe in the 1700. In this conceptualization, industrializing societies diverged from the normal agricultural orientation. If we accept the idea of a late divergence, what was its source? Pomeranz and Wong have both cited ample coal reserves as a key factor in the industrialization of Britain. Was coal really essential to industrialization? Perhaps; but considered more broadly, one could say that it was access to energy that contributed to the great divergence. Coal in this case is only the historical form the energy took in Britain. The importance of energy should be broadened beyond Britain’s historical experience to a more generalized view of the role of energy in the divergence. To do this, it would be useful to understand the energy environment prior to the mechanization of production.

The role of energy is intimately connected to that of a converter that will allow it to do useful work. Without a converter (a steam engine, for example) to transform a fuel, all the coal or oil (or uranium, for that matter) has no effect on the society. At the same time, without the social need for additional energy, there would not be any incentive to develop additional converters.

In his work, Pomeranz put forward the steam engine among the key reasons why the history of northwest Europe diverged from the default path of “stagnation”. He saw the flooded coalmines of England as the catalyst that spurred development of a novel energy converter, the stationary steam engine. Needham, writing about coalmines in China, saw their

---

149 “Useful” in a commercial context is defined as controllable by the investors.
150 “Stagnation” is generally considered undesirable, particularly in the growth-oriented modern world; a more neutral term would be equilibrium.
lack of pumping needs as a disincentive to mechanization in those mines. Here again, we need to push back further into the past to understand this difference. If water pumping was the catalyst, it is good beginning to note that the mines were flooded; the next step is to figure out why. The rest of this chapter will present a theoretical overview of why the mines in Britain were flooded, and why at that time. The case studies that follow in the later parts of this dissertation will provide illustrations of this process. The example from mining will exemplify how energy use changed under commercialization. By implication, it will also support the idea that commercialization was a necessary precursor of industrialization.

**Commercialization: the Creation of Commodities**

Broadly speaking, “Commercialization”, is marked by an increase in production for exchange. This can occur even while the vast majority of production is still for local (or even household) consumption. A number of factors, including finance, political stability, technical innovation, and capital accumulation, need to be in place for exchange to increase. The confluence of these necessary conditions has occurred at various times during the last several thousand years. They came together again at a number of nexuses worldwide in the centuries leading up to the 1700’s. This is not to say any great percentage of labor, materials, or output was bought or sold in a market. However, while only a tiny portion of labor, materials, or goods may have been monetized, for some goods the market was growing.151

The establishment of a commercial economy changed the nature of certain items. When virtually all production is destined for local consumption, items such as firewood, cloth, or iron

---

151 By a static view, the commodity portion of the economy at this time was insignificant; however, viewed dynamically, commercialization has set in motion important changes.
would be produced as needed.\textsuperscript{152} By contrast, the development of trade creates opportunities for production beyond immediate domestic needs. It is probably not a coincidence that the coal industry along the Tyne at Newcastle was developed “…by a Newcastle merchant oligarchy that lacked neither capital nor ability.”\textsuperscript{153} This export-oriented product proved quite profitable.

As commercialization of the local economy expands, some items will become desired not as final products, but as intermediate goods to be used for further production. Rather than finished goods, they are now commodities. These were produced not for their use-value but for their exchange-value. These items were destined to be traded.\textsuperscript{154}

**Enter Energy**

Viewed dynamically, commercialization used energy in a qualitatively different way, which set in motion important changes. Looking at how energy was converted to useful work reveals the implications of this difference. A society can be thought of as a system for processing energy.\textsuperscript{155} The volume of goods produced each year is dependent on a productive system’s ability to process energy. To process energy, a society needs converters of some kind. Examples of converters would be crops in the field (converting sunlight to grain) or animals (converting grass to milk, meat, etc). In an agriculturally based society, these converters are

---


\textsuperscript{154} Elsewhere, Marx used the terms “use-value” and “exchange-value”, applying both to commodities to develop his labor theory of value (*Capital*, vol. 1). Here “use” and “exchange” are intended only to differentiate between the production for the household (“use”) and production specifically for trade outside the local area (“exchange”).

linked to the annual rhythm of planting and harvesting. The quantity of energy this type of society can process into societally useful goods is limited by the converters available to transform energy to agricultural production. In some cases, organic-based converters are used to produce mechanical power; examples would be a horse that converts feed into potential work, or a waterwheel that turns a stream’s flow into useable work. Mechanical power, as a more generic form of energy transformation, is itself a commodity.

 Tradable goods from commercial production generally do not necessarily escape the energy-conversion limit; agriculturally produced commodities are still restrained by the limitations of that type of production. However some certain commodities, those that are produced non-agriculturally, are not limited by this annual cycle. A deposit of tin, for example, is available in its entirety; it can be used slowly over many years, or it can be dug out in one season. There are no a-priori seasonal limitations, such as exist for agricultural production.

The stock of the potential commodity need not be inanimate. Codfish or Right whales in the North Atlantic, for example, can be caught slowly over time, or all can be taken in one season. Which method is best in the long run is a different question, especially from the cod’s point of view.

The removal of these limitations has crucial implications for the dynamics of a commercialized commodity. In a commercial environment, with a sufficiently large market serving as a profitable outlet, we can expect an ever-greater field of play for primary energy as an input into non-agricultural production. This is because it would not be limited by the seasonal

---

156 Sometimes this “annual” rhythm involves more than one planting cycle.
157 The distribution problem remains, having only been transformed from a socially sustainable distribution of materials to a distribution of profits.
158 This is the same concept as the difference between the organic and mineral energy, as outlined in the discussion of Wrigley’s work.
cycle that restrains the application of energy to agriculture. For production of a non-agricultural commodity, the commercial economy opens the door to the conversion of additional primary energy; it was no longer restricted to merely needing to reproduce the local economy. The additional energy could be turned to profit.\footnote{The Commercial revolution would also need to provide a socially sustainable solution for the distribution of profits.} There are questions about the sustainability of resources, but these issues, particularly pollution and resource degradation, are in the unseen future, and would not arise until after the arrival of all-too-successful converters.

**Energy Rent**

As suggested above, the demand for energy to produce commodities for commercial trade is qualitatively different from energy that is used for local production. The concept of an “energy rent”, as introduced in the literature review, can be used to grasp the how the dynamic of an energy surplus for a non-commercial purpose changes under commercialization.

Beaudreau defined an energy rent as the difference between the value of the useful work a certain amount of energy can do (the value of what is produced), compared to the energy’s cost.\footnote{His more technical description is: “Put otherwise, energy deepening has given rise to energy rents, defined as the difference between the value of the marginal product of energy and its price/cost.” Beaudreau, p. 27. He used the energy rent concept to examine systems of distribution of production.} Note that when production is for direct local consumption, “value” and “cost” do not have a financial meaning, but refer to the energy expended compared to the energy gained.\footnote{Debeir, Deleage and Hemery’s work used the energy rent concept in a similar way.} The goal is to extract a positive energy rent. To illustrate this concept, consider the energy rent transaction in its most basic form, among hunter-gatherers. If a hunter-gatherer group expends more energy gathering a food, for example acorns, than the food itself will provide, the activity has a negative energy rent. They will not long survive if this is their only activity. If an activity
requires less energy than it provides, for example gathering blueberries, it has a positive energy rent.\(^{163}\)

_Energy Rent and Commercialization_

There is a qualitative difference when energy is used for a commercial commodity. When production is for local consumption, the decision to collect an energy rent depends on, and is limited by, local needs. The activity must return more energy to the local economy than is spent, and be socially useful (controllable). Following the example of blueberry gatherers, even if their available field of blueberries was infinitely large, no one would collect more than could be readily used locally. It would not be worth the effort. By contrast, in a commercial setting, the decision whether or not to pursue an energy rent, picking more blueberries, becomes a _financial_ decision: Will the cost of expending the energy return more than is spent? In dollar terms, if it costs less to pay laborers to pick the blueberries than they sell for, then the tendency will be to pick as much as the market will bear.

This distinction is a crucial change, as will be seen when moving beyond blueberries to analyze the energy applied to non-agricultural commodities. However, even limiting the analysis to commodities that are agriculturally based, this change sets in motion a different series of decisions. The difference can be illustrated by an example where an individual controls the rights to a stand of wood. The trees are a potential source of thermal energy. Within the context of the local economy, wood fuel is typically used to heat dwellings. In this case, the decision whether or not to use it would follow the same logic as in the Hunter-Gatherer example: Will

---

\(^{163}\) Marvin Harris and Orna Johnson _Cultural Anthropology, sixth ed._ (Boston: Allyn and Bacon, 2003) see Chapter 5; Harris does not use the term energy rent, but the “Optimal Foraging” strategy he describes uses the same concept of energy expended vs. energy collected.
harvesting this wood provide more energy for some local need than is expended to collect it?¹⁶⁴

Once the local need is met, the effort to harvest additional (unnecessary) fuel would result in a negative energy rent. By contrast, in a commercial environment, the decision to use the potential thermal energy in the stand of wood hinges on the profitability of the converter to which the wood provides fuel. As long as output from the converter, for example a blast furnace making bar iron, remains profitable, it will use all the wood fuel available, without any limit.¹⁶⁵ It is the removal of this limit that may set in motion a steadily increasing energy demand.

*Keeping track of who is collecting the “energy rent”*

A positive energy rent is not unlike the rent collected by a landlord. Landlords, by virtue of the fact that they control a property, can collect a profit from its use. The landlords’ control allows them to potentially get more out of the process than they put into it. With the introduction of the concept of “control”, we touch upon one of the reasons converters have been limited: a social structure adequate to the control of the converters is necessary. Establishing control is not always a harmonious process. Slaves, one might expect, are much less keen on maintaining the socially constructed relationship in which they find themselves than are those cast in the role of masters.

The evolution of energy using technology, then, has two differing but connected elements:

- The technical system that uses a converter to create a surplus from a given energy source, and

---

¹⁶⁴ Not a trivial calculation. Recall *Good King Wenceslas*: according to the Christmas carol, he came to the aid of a peasant whose gathering of winter fuel was producing a possibly fatal negative energy rent.

¹⁶⁵ Lack of other inputs might impose limits, and presumably the cost of wood would rise as more of it is used, but again, these bottlenecks are in the future.
A social arrangement that shares out, usually unequally, the produce of these energy sources.

For this analysis, we will examine the first half of this pair. These case studies will examine how energy surpluses – energy rents – were sought out by organizers of commercialized processes. Where these processes were used to produce non-agricultural commodities, the organizers had potentially unlimited opportunities to seek additional energy rents. This of course pre-supposes that the activity is profitable, which was not always true. However it is now the question of profitability, not social need, which determines demand for energy. This change set in motion a dynamic of increasing energy demands.

166 “Control” implies a social structure that should not be glossed over, but that is a different question.
Commercialization, Commodification, and Mining

Commercialization created a greater field of play for primary energy. With it, the application of additional primary energy was no longer restricted what was needed to reproduce the local economy, but now could also be used to produce goods for trade. Where these tradable commodities were based on agricultural production, their availability depended on the society’s ability to apply energy to agriculture. This was of course governed by the rhythm of the growing seasons, the ebb and flow that gave stability to Braudel’s *longue durée*.\(^{167}\) It also limited the opportunities where energy could be applied to gain additional rent.\(^{168}\)

By contrast, some of the commodities produced for exchange were non-agricultural. These tradable commodities had the potential to find, in a commercial environment, a profitable outlet for production that greatly exceeds local demand. Glass, iron ore (or bar iron), and coal were examples of these types of commodities. These commodities were not restricted by annual seasons; if sufficient energy inputs were available, they could be produced up to the level of all that could be traded.

To sketch a theoretical outline of energy demand in a commercializing society, consider one of the leading sectors in energy use from among the extractive industries. In advanced agricultural societies, “extractive” activities included mining (pumping water), milling (grains), and grinding (sugar cane) activities. These activities typically require concentrations of substantial quantities of primary energy. The energy for these activities was provided by human labor, animal power (horses, oxen, or donkeys) and, where available, wind or waterpower.\(^{169}\)

---

\(^{167}\) The *longue durée* of Braudel described the stability of a society where agriculture was the primary energy converter.

\(^{168}\) See Wrigley on how organic systems are limited.

\(^{169}\) The energy needs of extractive activities led them, when possible, to use waterwheels. See Terry Reynolds *Stronger Than a Hundred Men: A History of the Vertical Water Wheel* (Baltimore: The Johns Hopkins University Press, 1983), especially Chapter 3.
In this quest to unearth how commercialization led to increasing demand for energy, enlightenment may be found by pursuing energy use underground, into the realm of the mining industry. In this extractive industry as practiced in Europe, the confluence of three factors came together to produce rapid changes during the 17th century:

1) Extensive primary energy requirements created opportunities for energy rents;
2) The commodities produced were non-agricultural (no annual limits); and
3) The mined commodities were typically “exported” (not consumed locally).

In 1556, George Bauer, under the pen name “Agricola”, noted that the most obvious reason for abandoning a mine was, not surprisingly, that the vein of minerals had “become barren”. The second most common cause was flooding:

“The second cause is the quantity of water which flows in; sometimes the miners can neither divert this water into the tunnels, since tunnels cannot be driven so far into the mountains, or they cannot draw it out with machines because the shafts are too deep; or if they could draw it out with machines, they do not use them, the reason undoubtedly being that the expenditure is greater than the profits of a moderately poor vein.”

Pomeranz suggested flooded mines as the causal factor in the development of thermal-powered machines. To pursue this suggestion, and in light of Agricola’s observation, we are led to ask: Why there was flooding in the mines? Why did a need exist for additional primary power? The answer to these questions will suggest that the intensified exploitation of mines, which followed upon the heels of the establishment of a commercial economy, created a pattern

---

of intensified energy needs. This pattern will tend to be repeated in numerous mines, and it can be outlined in a generalized model (a “generic mining model”). In later chapters, this generic model will be used to provide insight into specific case studies of mining operations that adopted Newcomen engines.

**Determinants of Mining Volume**

Mining is not a new activity, having been pursued in one form or another for thousands of years. The first question to address: What determines the volume of mining undertaken in a pre-commercial society? It appears that the amount of mining conducted would be fairly stable from year to year. Precious metals aside, mining activity would be under no pressure to expand. For example, the volume of iron ore dug each year would probably depend on an area’s population, and their need for iron implements. This low-level of demand for mined products, relative to untapped deposits, would allow mine operators to be flexible about where to operate. If they encountered any flooding, they would likely find it easier moving operations to a less-wet site than to deal with the water.

As mentioned, mining for precious materials, such as silver or gold, would probably follow a different logic. Even in an economy operating at a pre-commercial level of demand, one would expect the owner of a mine producing precious metals to show persistence, even after reaching the water table. At a minimum, they would insist on their slaves persisting. For example, in Europe, the history of pumping water in mines stretches back to the Romans and their silver/lead mines of Spain.

---

171 What qualifies as “precious” depends on the local culture. In the Americas for example, obsidian, a volcanic glass, was pursued and traded over considerable distances.

172 See Wilson, 2002, citing Pliny and Strabo. Precious metals tend to impose a control of their own on the human mind. It is significant that virtually all the gold ever mined is still above ground, and it whereabouts is well known:
At the silver mine in the medieval town of Kutna Hora, in what is now the Czech Republic, miners showed great resolve and ingenuity when their digging encountered water. An illuminated gradual from the 1400’s shows the activity at the mine, including the use of a horse whim for raising water.

Figure 3-1. Kutna Hora Silver Mine. In this detail from an illustration accompanying a gradual, a horse whim is depicted under a conical roof at the Kutna Hora silver mine (late 1400’s). Note man at lower right handling a bag of water; a second man sits astride the stream of water emptied from the bags and pans for silver.

When commercial activity transforms the products of mining into commodities, the nature of the mining activity is itself changed. While local need for these items may have been we can be fairly certain that every owner of a pound or more of gold was certain it was safe before they went to sleep last night.
satisfied through simple recovery methods, the intensified production in a commercial setting pushed mining activity deeper. The easily recovered (surface) sources would certainly be used first. However, once these were exhausted, pits had to be dug deeper. Surface mining became shaft mining.

To return to the example of iron ore, it is relatively plentiful throughout the world. For local consumption, sufficient quantities could typically be recovered from outcroppings or surface recoveries. Once it became a commodity, iron ore, or more properly the bar iron produced from the ore, was subject to steadily growing demand. Mines associated with profitable smelters would expand excavations. Eventually, the surface mining of iron ore would also become shaft mining. As these shafts were dug deeper, they would inevitably reach the water table. If fresh deposits were not to be had, the result of commercialization would be that miners of the more humble commodities, such as iron ore or tin, would be inclined to adopt the water-control techniques developed earlier in pursuit of precious metals.

**Generic Mining Model**

While the details would certainly vary, a rough caricature of mining in a society producing for local consumption, contrasted with mining in the advanced parts of the world in the 17th century, will be sufficient for our purposes here.

*Mining for Local Demand*

When mined materials are dug for local consumption, we can expect the volume of mining (that is, the total cubic feet of mining activity at any one time) to be relatively static.\(^{173}\) An examination of this process in the abstract suggests a generic structure to the life cycle of a

---

\(^{173}\) In any actual case, there would be considerable variation due to discoveries of new resources or emergency needs, such as additional iron for military purposes.
mine producing non-precious minerals. Sketching out this life cycle, we would expect a mine to progress through four phases:

1. New mines, where digging had just begun;
2. Active mines that were reliably producing material;
3. Mature mines that were nearing either the limits of their veins or had dug deep enough to reach the water table; and finally
4. Closed mines, those that had either exhausted their minerals or been dug far enough below the water table to be flooded (the two main reasons, as noted by Agricola).

The depth of any given mine would vary, depending on which of the four stages it was in. However, and this is the key point, the average depth for all mines, relative to the water table, would be roughly constant. It would be constant because, at this early stage in the history of mining, there would still be ample untapped resources. Given these still available resources, old mines would be abandoned as soon as they reach the water table. As a result, on average, mines as a whole would have been worked at a depth about halfway to the water table. As for water problems, there would be little or no advantage keep digging in a shaft that required pumping, given the relative abundance of untapped resources.\footnote{See Agricola on abandonment of mines.}

\textit{Mining for Commodities, a Financial Decision}

"Another commodity that this river bringeth forth is coal in great abundance; most of the people that live in these parts live by the benefit of coals, that are carried out of this river to most parts of England southward, into Germany, and other transmarine countries."\footnote{"Trade at Newcastle Upon Tyne" in \textit{Chorographia: or a Survey of Newcastle-upon-Tyne} (1649); reprinted in \textit{Seventeenth-Century Economic Documents}, ed. John Thirsk and J.P. Cooper (Oxford: Clarendon Press, 1972) p. 363.}

With the development of a commercial economy, the volume of mining would be subject to a steady increase. This is because, as with the earlier mining of precious metals, the decision to initiate a mine depends on the prospect of profit. As new finds were made, digging would be
begun. A significant horizon was crossed once all known deposits were in production. Lacking the option of moving on to new deposits, deeper digging at existing mines would be the only option.

Thus, the initial endowment of any mined resource is a key determinant of when the primary energy needs to recover it begin to grow. Once all the known deposits are in production, any increase in output has to come from more persistent digging at existing mines. Recall that a mine in pre-commercial production has four stages: new; actively producing, mature; and flooded.\textsuperscript{176} To this, commercial production would add the category of “flooded, but water being pumped”.

As a result of pumping, the average depth would begin to increase, relative to the water table. Surface mining would become shaft mining.\textsuperscript{177} Note that it does not matter how extensive an area’s endowment of a mined commodity might be. At some point, all available resources above the water table will be in production. As these pits deepen, it is only a matter of time before the average depth of mines for a given commodity reaches the water table.\textsuperscript{178} From a micro-perspective, a single mine needs to pump water; seen from a macro-perspective, the average depth of all mining will henceforth be \textit{below} the water table. Further digging only compounds the problem, as the descent below the water table increases the amount of flooding.

At this point, the essential difference in the decision-making process that arises with commercialization asserts itself: Whether or not to continue deeper has now becomes a \textit{financial} decision. Previously, when production was for local consumption, the decision governing additional digging probably depended on the health of the kingdom (i.e.: was iron ore needed for

\textsuperscript{176} For clarity, pits where the minerals were exhausted are ignored here.

\textsuperscript{177} Note again the Kutna Hora miners, in their pursuit of silver, had been long since been shaft-mining. It may significant that a guide for commercial mining, as produced by Agricola, was not assembled until the 16\textsuperscript{th} century.

\textsuperscript{178} Discovery of new resources would only alter the schedule of this process, not the dynamics or result.
weapons? Could silver be recovered to enrich the kingdom?). For commercial mines, the decision to remove the water and continue digging, or not, was now determined by operating costs. Unfortunately for mine operators, pumping was now part of those costs, and it was growing. Slowly, but inevitably, the cost of securing the primary energy to remove the water would become the make-or-break factor for a mine.

Of course, the initial removal of water was not too onerous. Even in a pre-commercial setting, a mine would not be abandoned simply because some small amount of water removal was necessary. However, as shafts were carried deeper, the volume of pumping would increase, as did the required vertical lift of the water. This accelerating need for primary energy would be a problem for any one mine, but when viewed industry-wide, the quantity of pumping required would be an exponentially-growing dead-weight loss to the society’s production. The terms “accelerating” and “exponential” are not used casually: For each foot below the water table that the digging continued, more water would be encountered and it would need to be lifted further to clear the shaft. A simple linear increase in the quantity of water to be lifted would result in a true acceleration of the energy required. In simple figures, 1 pound of water lifted 1 foot = 1 foot-pound; 2 pounds of water lifted 2 feet = 4 foot-pounds; 3 pounds of water lifted 3 feet = 9 foot-pounds, etc. The volume of primary energy required would accelerate at a surprising, and to mine owners no doubt alarming, rate.

Sadly for the investors in the mine’s commercial interest, the energy spent pumping water does not, of itself, produce any additional merchantable material. This exponentially growing expense could rapidly overwhelm a seemingly sound enterprise: The thriving 15th century silver-producing town of Kutna Hora became a forgotten footnote by the mid-16th century. Having

---

179 Mines producing precious metals had always followed this decision tree: did the mine produce more than required to operate it, water removal included?
greater initial available resources, or the discovery of a new source, would not alter the dynamic of this picture. It only postpones the inevitable. With commercialization, pumping eventually becomes part of mining’s production process.

As Agricola recorded, miners were resourceful in their efforts to deal with flooding. What he did not observe was that, each time mine operators increased their efforts, they were led into a self-defeating loop. If the pumping was successful, the mine was dug deeper. As we shall see, operators used animal power, wind power, or water-powered mills to drain their mines (often all of the above). Although initially successful, any further mining only confronted them with additional flooding, which again increased their pumping needs. Any and all successful pumping brought the operation closer to the point where the costs of pumping an ever-increasing volume of water eventually overwhelmed the profitability of the mine. The more mature a mining sector (that is, the more commercialized), the more thoroughly this seizure could be expected to afflict it. Eventually, production would be suspended. Although it was known that potentially profitable veins lay beneath the water, the mines would be shuttered.\footnote{180}

**China, Britain, and the Water Table Beneath their Coal Mines in the 17th Century**

The average depth, relative to the water table, of coalmines in China and Britain reemerges here as in important difference between the two.\footnote{181} Needham observed that, when flooding was encountered at a coalmine in China, instead of continuing to dig below the water table, their extensive endowment of coal afforded them the option of moving on to an untapped resource. China had not reached the stage in commercialization where all the easy resources

\footnote{180}{If this “intensification leading-to-flooding” model does describe a generic problem along the path of industrialization, it could hardly be limited to Britain. Worldwide, occurrences of intensified mining should be examined for signs of application of mechanical power.}

\footnote{181}{See Chapter 2.}
were in production.\textsuperscript{182} The essential difference in Britain was that by the 17\textsuperscript{th} century all the readily exploitable coal areas were already in production. Lacking China’s surfeit of resources, they were challenged by a shortage of options.\textsuperscript{183} This is a potential answer to the “why Britain, why then” question posed earlier.

\textit{It’s Not the Flooding; it’s the Negative Energy Rents}

\textquote[Stephen Primatt, The City and Country Purchaser and Builder, London The Valuation of Lands for Agricultural and Industrial Purposes, 1667, in Thirsk and Cooper, page 292. Emphasis added.]{“…and what engines they use to draw their water for the convenience of their working; whether they use of water in any river, and so draw water with water, or whether they make use of tread wheels, or horse wheels, or what other device they have there, \textit{there being very many devices for that purpose, but very few good for anything}.”}\textsuperscript{184} (p.292)

We have speculated that, prior to the Commercial revolution, the average depth of mines in relation to the water table had been steady (or little changing). Commercialization, assuming a sufficient market, prompted the miners to bring all the easily available resources into production. Without the option of new pits, the existing shafts would have to be worked more deeply. This eventually brought about the need for pumping water. Whatever ingenuity was brought to the activity, eventually the cost of pumping would match the value of output.

Had this process continued, it seems likely that the increase in depth would have traced out an “S” curve, arriving at a new average depth (see Figure 3-2). The actual depth below the water table of this new equilibrium (stable average) would depend on the cost of pumping a given volume of water. Any attempt at calculating a figure for this depth would be an empty exercise: the arresting factor is not the water flooding the mine, but the animate energy

\textsuperscript{182} They are probably there now. In 2009, China produced over 45\% of the world’s coal; the U.S. was second, at under 16\%. In 2009, Britain produced only 0.2\% of the world’s coal, slightly less than Estonia. \url{http://en.wikipedia.org/wiki/List_of_countries_by_coal_production} (accessed March 12, 2011).
\textsuperscript{183} This is reminiscent of Toynbee’s “challenge-response” concept.
converters available to remove the water. Relative to the limited animate-energy sources, a comparatively *infinite* supply of water was available to flood the mines. Ironically, to provide more water than could profitably be removed, all the miners needed to do was to keep digging. This they did.

![Average Mine Depth, Given Organic Energy Sources](image)

Figure 3-2. Counterfactual Graph of Mine Depths. An extremely hypothetical curve, presented to show the pattern of increase in mining depth, had it relied only on organic energy sources.

The limited nature of animate energy, as exposed by the expansion of demand resulting from the Commercial revolution, was the structural element that would have limited mine output. By extension, this limited availability of organic energy would have arrested the growth of any
energy using activity. The Commercial revolution would have returned to a stasis; this was the reasonable, although dismal, prognosis provided by the classical economists.\textsuperscript{185}

In the event, fire-powered engines provided a lower cost solution to pumping in the mines. This would ignite a long fuse that would eventually set off an energy transition from organic to mineral-based power in the 19\textsuperscript{th} and 20\textsuperscript{th} centuries. In the mines, the volume of pumping accelerated beyond the wildest imaginings of any 17\textsuperscript{th} century observer. This success at pumping has been overshadowed by the other astounding increases in production that would mark the mechanization phase of the Industrial revolution. Today, it is overlooked. However, this humble beginning, a genuinely surprising ability to use thermal energy for pumping water, shifted the potential increase in the depth of the average mine onto a completely different “S” curve. Perhaps by going back to these mines, figuratively speaking (no boots or lamps required), we may gain some insight as to where the “S” curve in energy use, upon which we actually find ourselves, is headed.

\textsuperscript{185} See discussion of Adam Smith, Chapter 1.
Chapter 4: Primary Energy in the 17th Century, and Its Limits

Commercialization had increased the opportunities to for mined commodities. While mining was not unique in this regard, the inflexibly of a mine’s location, plus its attendant water problems, tended to push it more rapidly to the limit of affordable organic energy. This section will examine the primary energy options available to mine operators of the 17th century. The limitations of each of these energy types will be examined in turn. As will be shown, the strengths and limitations of various prime movers cannot be understood outside the context of their respective fuels. Each will be discussed in turn. The terms developed here will be used in the case studies that follow.

“A hauling machines are of varied and diverse forms, some of them being made with great skill, and if I am not mistaken, they were unknown to the Ancients. They have been invented in order that water may be drawn from the depths of the earth to which no tunnels reach…” “Agricola” (George Bauer), 1556.

A wealth of information on both the mining and refining of metals in 16th and 17th century Europe is contained in Georgius Agricola’s extraordinary 1556 book De Re Metallica (“Of Things Metal” or metallurgy). “Agricola”, whose real name was Georg Bauer, was born in Glauchau in Saxony. In the style of the Renaissance, he wrote in Latin, consciously imitating the ancient Roman authors (his title suggests an echo of Lucretius’ De Rerum Natura). His work, a summation of all that was known about the subject, was intended to provide a useful guide for...
miners and metal workers. The text consists of 12 books, extensively illustrated with a series of woodcuts. “Book VI” of the work is dedicated to the lifting of ore, pumping water, and ventilating of mine shafts.

The actual lifting of water out of a mine requires a great deal of effort, and was only undertaken as a last resort. Prior to that, miners would, for example, dig a drain (technically called an adit), through to a lower level so that the water could run out. These adits were small shaft onto themselves. Typically, they would be dug from an adjacent valley up into the shafts, to allow sufficient gradient for the water to flow out. They were as narrow as possible, sometime no more than 4 feet high by 18-inches wide.\footnote{See “Appendix O Note on Drainage Devices” in John Nef \textit{The Rise of the British Coal Industry}, vol. two (New York: Archon Books, 1932; second impression 1966), pp. 449-451.} However, “…the drawbacks of drainage by adits were made plain because mining operations more and more frequently reached depths at which such drainage could not lay dry all the workings, attention focused on efforts to raise water to the surface” \citep{Nef_1932} (or to the level of the adit).

Agricola described the lifting water by leather bags, as had been done in Kutna Hora in the 1400’s \citep{Glanvill_1667}. This method was still employed in the 17\textsuperscript{th} century (1667) at mines in Somerset, England, where “They make use of leathern bags, of 8 or 9 gallons apiece, drawn up by ropes to free the water.”\footnote{Joseph Glanvill and others “A Description of Lead Mining in Somerset, 1667” in \textit{The Philosophical Transactions and Collections to the End of the Year 1700 Abridg’d…}, ed. John Lowthrop, vol. II, 1716, pp. 573-6, reprinted in Thirsk and Cooper, p. 285.} To this basic method, Agricola added the chain pump. This “pump” was a series of barrels or buckets attached to a chain, led over a wheel and down into the water at the bottom of the mine (see Figure 4-5, below). A more sophisticated pump was the “ball and chain”. This consisted of a pipe set down into the sump, through which a chain, with a series of “balls” (balled up rags) was lifted. As each successive ball trapped water in the
pipe, it pushed the water ahead of it to the surface as it rose (see Figure 4-2). A third type, the piston pump, is probably the most recognizable to the modern world. It consisted of a pipe with a sliding piston inside. On the down stroke, a flap opened in the top of the piston, allowing water to pass; on the up stroke, the flap closed and the water was lifted the height of the stroke (see Figure 4-1).

Figure 4-1. One-man force pump (upper right).
Types of Primary Power: Human, Animal, Water, and Wind

Agricola’s purpose in this section was to discuss the various types of pumps then in use, from the simplest to the more complex. From an energy-use point of view, we are more interested in the prime movers used to drive the pumps. By re-arranging Agricola’s work, we can assemble a gazetteer of the energy landscape of an advanced agricultural society. These sources can be grouped into four categories:

1) Human Labor

Figure 4-1 (above) shows a one-man pump; note that this type of “power” is practical only for shallow lifts. Figure 4-2 depicts two men operating a chain pump, from an unspecified depth. Alternatively, human labor could be used via a treadmill to provide power to a hoist, as in Figure 4-3.
Figure 4-2. Two-man Ball-and-chain Pump. A hand-cranked ball-and-chain (rag-and-chain) pump.
2) Animal Power

For heavier tasks, animal power was used. Figure 4-4 shows a detailed illustration of the mechanism a horse whim used to raise bags of water out of a mine, similar to the whim used in the previous century at Kutna Hora (note bag of water “K” in background). Agricola related that
Figure 4-4. Horse Whim for Raising Bags of Water. Note bag marked “K”, rising out of shaft.
These water bags were typically made out of cowhide. Although horses were usually depicted, many types of animals, from dogs to goats, were used as prime movers.\textsuperscript{192}

3) Water Power

By Agricola’s time (1550’s) the need for primary power at many mines was extensive. He noted that the limits of human and animal powered machines:

“Thus water is drawn through the pipes by the balls from a depth of \textit{forty-eight feet}. Human strength cannot draw water higher than this, because such very heavy labour exhausts not only men, but even horses; only water power can drive continuously a drum of this kind.”\textsuperscript{193}

Agricola showed how each of the three types of pumps could be powered using water. Figure 4-5 shows a ball-chain pump; Figure 4-5 is particularly interesting as the waterwheel is depicted as operating underground (note miner digging, bucket being hauled to the surface, and “cutaway” effect of ground at top of engraving). The water lifted by the wheel would most likely be carried the rest of the way out of the mine by an adit. Figure 4-6 is of interest, as this woodcut shows the type of piston-pumps that would be widely used in the mines in England.\textsuperscript{194}

\textsuperscript{192} For a survey of animals used as prime movers, see J. Kenneth Major \textit{Animal Powered Machines}. (Oxford: Shire Library, 2008 edition).
\textsuperscript{193} Agricola, p. 195 (emphasis added).
\textsuperscript{194} This is the type of pump that would be driven by the first atmospheric engines, 150 years later.
Figure 4-5. A Waterwheel Driving a Ball-and-chain Pump. Note that the wheel is depicted as being underground.
Figure 4-6. A waterwheel driving an array of piston pumps.

4) **Wind Power**

Figure 4-7 rounds out the available energy sources. For reasons that will be discussed below, wind power was not as significant supplier of the power-needs for mines. A windmill is incidentally shown in this figure, which features a treadmill powered by goats.
These four fill out the potential energy menu for lifting water, a mechanical task. Beyond these sources of mechanical energy, another commonly used energy source was thermal energy:
heat provided by wood or coal. In mining, wood would be employed to fire-crack rock. It also provided heat for other processes, such as glass making and brick making. Thermal energy could be fitted under the broader heading of chemical energy, which would also include gunpowder.¹⁹⁵

The mine operator of the 16th and 17th century could select from among these power options, if they were available. This begs the question: just what defines availability? Beyond merely listing these potential energy sources, we need to think about their strengths and weaknesses in a more rigorous way. By considering the qualities of each source, a general outline of energy in an advanced agricultural society can be constructed.

¹⁹⁵ Metallurgy, the other half of Agricola's topic, employs chemical processes whereby the composition of the ore is altered into useful metals. These chemical processes use extensive amounts of energy.
Qualities of Energy: Spatial, Temporal, Intensity

This section will develop a list of the key factors that determine an energy source’s availability. Each of the energy sources available in the 16th and 17th century will then be rated, relative to these factors. The results, summarized in Table 3-1 below, will provide a ready reference for cross-comparing the energy uses that actually occurred in the case studies that follow.

Energy in the social sciences has been approached using a varying vocabulary, as appropriate to each author’s analysis. While this may suffice if we stay within each analytical view, problems arise when trying to view energy comprehensively. Wrigley, for example, divided energy sources into organic (such as wood) vs. mineral (coal). This dichotomy illustrates the difference between fuels that are agriculturally based, and those that are resource based. While this does highlight how mineral fuel use can be intensified, it may not be sufficient when trying to examine the historical transformation of the Industrial Revolution. This is because organic sources, such as waterpower and wood fuel, were the first fuels of choice, when available, in early industrialization.

Beaudreau used the terms “animate” and “inanimate”. Animate specifically includes humans, animals, wind, and water. What then of wood fuel? Clearly it is organic, but is it animate? For his part, Lindqvist saw power as coming in two types, mechanical power (horses, water, wind) or thermal power (wood and coal).196

These “binary” (either / or) distinctions have been able to provide insight into how energy was applied, but using only two dimensions fails to adequately describe a fuel source and the

---

196 Svante Lindqvist Technology on Trial: The Introduction of Steam Power Technology into Sweden, 1715-1736 (Uppsala, Sweden: Almqvist and Wiksell International, 1984); see also Beaudreau, Chapter 2 “Steam Power and Political Economy”.
prime mover powered by it. A broader taxonomy of energy types is required to advance our understanding of the historical changes in energy use.

Three Flexibilities

To develop a rough sketch of this taxonomy of energy types, we shall again return to the mines. As with other commercial activities of the 16th and 17th century, mining had created opportunities for wider application of “available” primary energy. A primary energy’s availability was not a haphazard thing. Whether or not a prime mover could be used depended on the flexibility of its respective fuel. These “flexibilities” can be categorized by answering the following questions:

1) Spatial, or geographic, flexibility: Where is the energy located?  
   i) Is it ubiquitous or restricted?  
   ii) How readily can it be transported / transmitted to where needed?

2) Temporal flexibility: How much control is possible over when a fuel may be used?  
   i) Can it be stored, and then used as needed?  
   ii) Is its availability limited by the seasons? Is this predictable?  
   iii) How long does it take to be restored? (Example: re-growth of a stand of trees.)

3) Intensification flexibility: This can be thought of as “exploitability”: can the use of the energy source be intensified? To what extent? Does it become used up?  
   i) Economic flexibility: does increased use diminish its energy rent?  
   ii) Physical availability: are useful sites limited? What quantity has a positive energy rent?  
   iii) Concentratability: How readily can the energy in the fuel be concentrated for heavy tasks?\textsuperscript{197}

The first thing that can be concluded from this list is that fuel, rather than the prime mover itself, that is generally the limiting factor. When we talk about the geographic flexibility of a prime mover, we are really talking about the flexibility of its fuel. To say that waterwheels

\textsuperscript{197} Landis (1969) p. 96-97 clearly grasps the importance, and difficulty, of concentrating human and animal labor beyond a certain point; he cites the 1586 example of using 800 men and 140 horses to move a 327-ton obelisk.
have poor spatial flexibility is really to say its fuel, running water, has poor flexibility. The wheel could actually be built anywhere.\textsuperscript{198}

These three areas of flexibility, spatial, temporal and intensity, will be briefly reviewed for clarification; following that, the fuel for each of the four power sources (human, animal, water, and wind) outlined above will be qualitatively evaluated on the basis of these flexibilities.

\textit{Spatial Flexibility}

For fuels, spatial flexibility has two dimensions. The first is where the fuel can be found. Food for human labor, for example, can be found (in varying levels of abundance), most places. Since humans are also quite mobile, the result is that humans as prime movers have excellent spatial flexibility. At the other end of the spectrum, running water suitable to power a mill is only found in a limited number of places; this results in a prime mover that is spatially (geographically) constrained.\textsuperscript{199}

A second spatial factor to consider is how readily transportable the fuel might be. Even in the case of water, it may still be possible to transport it via a canal to the location where the power is needed. In a later era, the transmission of power itself, in the form of electricity, would be revolutionary in its impact.\textsuperscript{200} It may also be possible to transmit the power over short distances using mechanical means.\textsuperscript{201} Note that cost of transportation diminishes a power source’s economic sustainability.

\textsuperscript{198} Indeed, in some cases the waterwheels were built where needed and the water was transported, via aqueduct, to the site. See for example the mine at Poullaouen, France, in the 1770’s described in J. Morton Briggs’ “Pollution in Poullaouen”, \textit{Technology and Culture}, Vol.38, No.3 (July, 1997), pp.635-654.

\textsuperscript{199} Areas with hilly geography and a reasonable amount of annual rain fall will of course have far more potential sites than a flatter, dryer climate.

\textsuperscript{200} See Tylecote, Chapter 10.

\textsuperscript{201} See discussion of \textit{stagenkunsts}, in Reynolds \textit{Stronger Than a Hundred Men}, p. 141-142.
**Temporal Flexibility**

The concept of a fuel’s temporal flexibility addresses the question of how much control can be exercised over when its energy is released. Temporal flexibility depends primarily on how readily a fuel can be stored. For example, the wind that powers a windmill has poor temporal flexibility: it cannot be stored at all as it is only available on its own schedule. On the other hand, water rates well on this score, as it can be impounded in a pond until needed. Related to storability is how promptly a fuel can be converted when needed for useful work.\textsuperscript{202} Food for humans and fodder for animal labor is storable to a degree, but both need to eat, whether actually working or not.

A secondary issue is that some fuels are subject to a seasonal availability. In the example of water for a mill wheel, local climate may subject it to seasonality as a result of freezing in winter or low water in summer. Another example would be the availability of feed for animal labor, which can be relatively abundant, or scarce, depending on the season.

**Intensity (Exploitability)**

How readily a fuel might be intensified is governed by the extent to which its use can be increased, without increasing its cost or diminishing its availability.\textsuperscript{203} This has both a physical and economic dimension. Physical sustainability has to do with the endowment of the energy resource available. Is the current usage a large or small fraction of the total amount available?

A closer examination of waterwheels will clarify the distinction between “renewable” and “sustainable”. Sustainable in this context means a fuel can support increased exploitation,

\textsuperscript{202} Dealing with this same concept, operators of modern electric grids phrase this question as: Can a fuel type be “dispatched”? For example, hydropower is “dispatchable” meaning it can be promptly brought on line to meet changes in demand. This is in contrast with nuclear power, which requires a much longer lead-time.

\textsuperscript{203} This use of the term “sustainable” should not be confused with “renewable”; sustainable in this sense means enough is available that increased usage does not significantly reduce the potential amount available.
and not be exhausted. Physically, the number of useful waterwheel sites is finite, which enforces a physical limit on the ability to intensify the use of waterpower.\textsuperscript{204} A waterpower site can still replenish itself indefinitely, and so is renewable, but as the number of potential water sites is limited, it will not sustain unlimited growth.

Economic intensification depends on the energy rents a fuel provides. Put differently: If the use of a fuel is intensified, will its costs increase? Wind as a fuel, for example, is not diminished by its use, and so can be readily intensified. By contrast wood, although it is renewable, is diminished through use. If harvested faster than it re-grows, its increasing scarcity will increase its price, imposing a limit on its intensification as a fuel.

An additional consideration that is sometimes important is the ability of a power source to be concentrated. Human labor, although extremely flexible, can be difficult to concentrate. This makes it relatively less suitable for processes that require simple, bulk force, such as operating pumps in mines. Waterpower, by contrast, can be readily concentrated.

**Flexibility of Prime Movers, and their Fuels**

The relative flexibilities outlined in the previous section can be used to evaluate the prime movers available to an advanced agricultural society. The four basic power sources, as illustrated in Agricola, are human muscle, animal power, water power, and wind power. The fuel for each of these energy types will be discussed in turn, rating their spatial, temporal, and intensification flexibility. To provide context for relative concepts such as availability, transportability, or storability, keep in mind that these are being evaluated in terms of an advanced agricultural society of the 17\textsuperscript{th} century.

\textsuperscript{204} Again, see Reynolds’ indispensable *Stronger Than a Hundred Men* for utilization of waterpower, p. 6.


Food for Human Muscle Power and Fodder for Animal Power

The original source of motive power available to a society was of course human labor, fueled by food. Food energy, and the labor powered by it, has excellent geographic flexibility. Although some areas are better than others at food production, transportation over more than a short distance is problematic, unless transport by water is available.

Temporally, it is no accident that food is readily storable. The food ways of various parts of the world were founded on storable staples such as rice, wheat, or corn. Developing the ability to store food allowed early civilizations to exercise temporal control over their food energy. The energy in stored food could then be used at a time of the controller’s choosing. This removed the otherwise seasonal nature of food’s availability and, as in Pharaoh’s dream, opened up the possibility that the seven good years could preserve the people during the seven lean years (Genesis 41:17-41:36). A temporal weakness of human labor is that the worker needs to eat, whether actually working or not.

To intensify human labor a method of expanding food production, such as finding additional arable land or multi-cropping (as of rice) on existing land, is required. Human labor is also relatively difficult to concentrate for tasks involving heavy labor. It is true that people do have a certain dexterity and intelligence that is difficult to find in a waterwheel; however, where prime movers are called upon to provide heavy, repetitive power, such as is needed to lift up water and put it down somewhere else, human labor is quickly exhausted.

Animal Power

The flexibility of fuel for animal power is similar to that for human labor. Spatially, grass and hay for oxen or horses are readily available, but limited as to how far they might

---

205 Developing a “storable staple” is seen by some anthropologists as the essential cornerstone of larger social units, such as kingdoms. See for example Harris and Johnson.
profitably be transported. The exploitability of food and fodder is no more than fair. It can be increased, but as all arable land comes under cultivation, the opportunities for intensification diminish. It is true that the potential direct power supplied by horses is not limited, as horses can be reproduced ad infinitum. However, each additional horse requires a certain quantity of feed, and thus requires additional agricultural land. A significant benefit of animal power is that it is more readily concentrated than human labor. Oxen or horses are easily used in teams of two, and if used efficiently can be the equivalent of about a dozen men.

Water Powered Mills

Water flowing along streams and rivers provides the “fuel” for waterwheels. As Agricola observed, this can be a source of extensive primary power. In general, geographic availability of waterpower depends on climate and topography, but even where these elements are favorable it is still subject to poor spatial flexibility. Streams are found where they are, and water as a fuel is amenable only to modest transportation. The limited spatial flexibility of waterpower presents less of a problem if the work can be brought to the mill site. In the case of grain for grinding, or iron ore for smelting, the raw material could be carted to a powerful stream, although the carting expenses did impinge on economic flexibility.

In certain cases, the power of a wheel was transmitted mechanically. Most notably in Germany and Sweden, the spatial flexibility of waterpower was increased using a mechanical transmission of power through a system of poles supporting pivoting rods. These were known as

---

206 The economics of supporting horses as working machines, in the 19th century, is detailed in chapter 6 of McShane and Tarr’s *The Horse in the City: Living Machines in the Nineteenth Century* (Baltimore: The John Hopkins’ University Press, 2007).

207 The concentration of effort could be considerable: Agricola noted that at a site in the Carpathian mountains three pumps using 96 horses lifted water in 3 stages from 660 feet below the surface to an underground adit). *Agricola*, pp. 194-5.

208 See Lindqvist, p. 62 for a discussion.
stakenkunst. Reynolds cites examples where these systems were used to transmit power over a mile (1.6 km), although one suspects the power losses over this distance would be significant.\textsuperscript{209}

The geographic inflexibility of waterpower was an acute problem for the production of resource-based commodities such as mining: the waterpower either was, or was not, near the mine. Even in those fortuitous cases where it was available to mine operators, it is still subject to the limits of any organic power source. Only a certain amount of power is available and so, given accelerating demand, it would be only a matter of time before its power was eventually overwhelmed.\textsuperscript{210}

The temporal flexibility of waterpower is good, but not excellent. While it may not be available year round, the seasonality of waterpower is generally predictable. Its temporal limitations are due to freezing in winter months and low water in summer. With this in mind, iron furnaces, for example, would time their activities to seasons when waterpower could be relied upon. In addition, a certain amount of “storage” of this potential energy was accomplished using dams and millponds.

Water as a fuel does provide for exceptional concentration of primary power. The waterwheel complex at built in the 1680’s at Marly, France to provide water to the fountains and gardens at Versailles is estimated to have developed over 37-horsepower. Even an average wheel could typically provide nearly 7-horse power.\textsuperscript{211} Unfortunately, the total number of water sites, which is to say its ultimate physical exploitability, was limited.

Overall, its temporal flexibility and ability to concentrate made waterpower the energy fuel of choice when large amounts of primary energy were called for in a commercializing economy. It provided excellent energy rents and its use was intensified during the 17\textsuperscript{th} century.

\textsuperscript{209} Reynolds, p.141.
\textsuperscript{210} See the case at Dannemora, Chapter 8.
\textsuperscript{211} Reynolds, pp. 175-176, pp. 182-183.
To take a coalmining example, in Newcastle, in the valley of the River Tyne, the use of waterwheels for pumping spread at coalmines after 1600. This brought the mine operators into conflict with grain mills and others who were already utilizing the river.\textsuperscript{212} This conflict is interesting because it points out both the limited availability of water power, and more broadly how the intensification of an energy chain, in an organic-energy economy, requires displacement of other users.

\textit{Wind Powered Mills}

Wind as a fuel for primary power has weak-to-neutral spatial flexibility. Wind is a widespread phenomenon, but a site needs to have steady winds of sufficient strength. Seashores and other coastal spots, due to their reliable breezes, are favorable for wind-powered mills. Occasionally, these sites receive a surfeit of wind, a potential risk to the mill. Also, since wind as a fuel cannot be transported, it is limited in its usefulness as a primary power source.

Wind also has an unfortunately poor temporal flexibility. It cannot be stored. For this reasons, wind as a power source was restricted to applications where time was not of the essence, for example grinding wheat. For needs where timing was a factor, such as grinding sugar during the harvest, wind (or at least wind alone) was not a viable option.

Wind does have good concentration of power. Large wind-powered mills could develop perhaps 18 horsepower, at least when a stiff wind was blowing.\textsuperscript{213} Wind, as a fuel, also has the virtue of not being used up, and so has excellent potential physical exploitability. For pumping water out of mines, wind as fuel was sometimes used for large operations that had extensive primary energy needs. In this application, the wind power was not relied on, but was part of the

\textsuperscript{212} Clavering. pp. 211-241.
\textsuperscript{213} Marin Watts \textit{Water and Wind Power} (Buckinghamshire, UK: Shire Publications Ltd., 2005) p. 67.
overall menu of power sources used for pumping. During the wind’s downtime, the other sources had to be available to pick up the slack.\textsuperscript{214}

\textit{Thermal power}

Two other fuels should also be mentioned at this time, the thermal power provided by wood and coal. Although widely used for productive processes, as well as the heating of dwellings, thermal sources were not used as a fuel for primary power in the 17\textsuperscript{th} century.

Spatially, wood has excellent flexibility; it is ubiquitous, and can be transported via water. Coal by contrast has relatively poor spatial distribution. It is located where the caprice of several hundred million years of drifting continents has left it. Coal, like wood, is somewhat redeemed by the ease with which it can be transported by water, but unlike wood it is not always found near navigable waterways.

Temporally, wood has good to excellent flexibility, while coal’s is even better. Both can be stored and then used as needed, with coal being more stable for truly long-term storage. The difference between these fuels becomes apparent as the usage of wood approaches an area’s sustainable production. This is the difference between an organic and mineral resource. Wood requires a period of years to replenish itself, while coal’s availability is open-ended.\textsuperscript{215}

\textsuperscript{214} See Chapter 8 regarding the windmill erected at the Dannemora mine.
\textsuperscript{215} See discussion of Wrigley, above.
Table 4-1

<table>
<thead>
<tr>
<th>Comparative Flexibility of Various Prime Movers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Flexibility</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Human Labor</td>
</tr>
<tr>
<td>Animal Power</td>
</tr>
<tr>
<td>Water Mills</td>
</tr>
<tr>
<td>Wind Mills</td>
</tr>
<tr>
<td>Engines</td>
</tr>
</tbody>
</table>

With engines, operators regained something they had not enjoyed since human labor was the primary input: Excellent control over both the spatial and temporal flexibility of the converter.

This admittedly broad-brush analysis is summarized in Table 4-1. This table of prime movers and their energy sources will be discussed in the context of the case studies that follow.
On the Inadequacy of Animate Power

Pushing on Energy Constraints

Northwestern Europe was hardly alone in its increasing demand for power. The demand for additional prime movers was expanding throughout the commercializing world. The energy demand at the mines in Northern Europe was acute, but it was not unique. Given that the commercial revolution had expanded the opportunities to employ power profitably, the not too surprising result was an increased demand for additional power. By deconstructing the mechanism implied in the phrase “demand for additional power”, the limitations of an organically powered society begin to come into view.

First, it must be noted that merely increasing the demand for something does not automatically increase its supply. Demand is a necessary, but not sufficient, precursor to using additional supply. The demand for any specific fuel (wood, for example) has two factors that work in opposite directions. On one side, the expanding opportunities to convert energy may make it worthwhile to bring even difficult-to-reach resources into the productive stream. On the other hand, the available resources (acres of wood) may be limited. In the example of England, whatever its initial availability had been, wood was certainly increasingly dear as the 1600’s progressed.

Eventually, the constraints on a fuel’s availability in an organically powered society would emerge to cut off increasing its usage. Growth would come to an end, and the system would return to equilibrium. In their typical fashion, the English did not choose to go quietly to equilibrium. As constricted supply increased prices, less desirable substitutes were sought out. In activities where wood had been used as a thermal fuel, peat or coal was used when its price was lower.
Energy in, Energy Out

The increasing commercial demand for coal as a wood substitute in England’s domestic market of the 17th century is a cliché of economic histories. Coal, as a mineral resource, was potentially free of the limits on annual supply. In the 17th century however, coal was produced using mechanical-power driven by organic sources. The energy sources available for this work were limited by factors both obvious, and others more subtle. Limited availability of primary movers was an obvious bottle neck (i.e.: waterpower needs to be near the mine, if it is to be useful). More subtly, production of coal, a mineral commodity, was limited by the organic mechanical power available to pump water. This mechanical power was typically provided by horses, and could prove more expensive than the coal produced would warrant. A mine would typically need 50 to 60 horses for this work; one mine in Warwickshire used 500 horses to hoist water.

As the easier-to-get coal was consumed, the cost of recovering additional coal would increase. The process is somewhat more complex, as typically learning-by-doing, and economies of scale tend to lower costs as an industry is first developed. However, one suspects that coal mining in 17th century should be considered “mature”, at least as far as its application of organic power to lift water. Initially, the energy inputs needed to lift and deliver coal can be expected to have increase linearly, or nearly so. Lifting coal from a mine twice as deep would require twice the effort, but hiring twice as many miners or retaining twice as many horses should suffice. Costs would increase linearly.

---

216 See Wrigley, discussed in Chapter 2.
It was water, the universal solvent, which would eventually expose the limits of organic energy. As mining activity descended below the water table, it drew increasing quantities of primary power into mining. In turn, human labor, then animal power, and finally waterpower and windpower were employed until the inflexibility of each rendered their energy rents to zero. If water removal needs, in addition to the other costs of operation, exceeded what a mine’s products could fetch, activity at that shaft would come to a halt. This was the world described by Adam Smith, where demand for lower-cost alternatives increases until their price rises. The market will eventually return to a steady-state equilibrium.

It may be argued that further de-forestation would raise the price of wood, once again making coal mining at a flooded shaft profitable. However, this would in turn lead mines deeper and confront them with increasing volumes of water, until a new equilibrium asserted itself. Thus, even the availability of mineral resources would be limited in an organically-powered commercial system.

**Pushing on resource organic energy constraints redeux: The Illusion of Initial Plenty**

When a resource is first utilized, its limited nature may not be obvious. In the initial stages, there is an illusion of plenty. Early in its exploitation, a “new source” of energy can keep up with expanding demand. Where there was ample unexploited wood, such as in colonial America, an illusion can be created that wood could sustain, in an open-ended way, industrial development. In reality, the dynamics of the situation are that the low use, relative to untapped supply, temporarily suspends the limits imposed on an organic source by its need to replenish itself. However, as demand for the resource bumps up against the available number of acres (in the case of wood), the sustainable volume of that can be produced is reached.
Staying with the wood example, the long run nature of organic energy had already shown itself in the circumscribed area of England. Their earlier experience had shown that sustained energy production from wood requires allowing for the fuel to re-grow. Rather than using up a set stock of wood, the time to replenish the resource needs to be accounted for to estimate ultimate availability. To use a concrete example, if it takes 20 years for a harvestable stand of trees to grow, then no more than 1/20th of all available acres can be harvested, per year, on an on-going basis. Harvesting more than that produces a downward spiral in the availability of the resource.

A Specific Example: Mining in Britain

“There are many projectors (who have more of fancy and imagination in their designs, than any real operation) that do undertake even impossibilities in the draining these and other sort of mines; being many times such as the owners value at little or nothing… go forward with their designs, not questioning but to remove all obstacles that hinder the same, until at length by sad experience they find that instead of draining the water, their pockets are drained.”

Commercialization will tend to push a productive system’s ability to supply affordable energy to its limit. This appears have been the case in the mining sub-sector of Britain’s economy in the 1600’s. As an incentive to surpass these limits, they had the commercial markets in need of mined commodities, and the capital accumulation that encouraged speculators to try mining. As the above quote notes, the lease on a flooded mine could be secured for “little or nothing”; if a way to free it of water could be found, the profits would be spectacular. The flooded mines must have appeared in the minds of the late 17th century English speculator like

---

219 This is referred to as a “closed loop” view, estimating the amount of sustainable resources available.


221 Primatt, (1667), p. 293.
unto so many piñatas, awaiting just the right stroke of a stick to break them open and let their riches shower out. Unfortunately, as the above quote also notes, the result often found the speculators’ fortune spilled first.

The mines were an acute example of the need for additional primary energy, but they were hardly unique. Other enterprises such as glass making, brick making, and iron smelting were also energy intensive, and produced a merchantable commodity. Mines were, however, more spatially restricted; they were not always in places where organic primary power was available. As a number of mines followed the generic path, flooding eventually rendered acquisition of their coal impossible.

Coal had been mined along the River Tyne since the Middle Ages. By the 1600’s, the easy-to-get coal had already been used. As the mines went deeper, they were dug below the water table and became prone to flooding. For the mine owners, this was not a welcomed opportunity to develop new technologies; it was a simple business problem: what would be the cheapest way to get the water out?

The potential for profit, along with the availability of venture capital, prompted a number of schemes to find additional energy sources to bring to bear on the problem of pumping out mines. As we turn to the story of Thomas Newcomen and his success, we should note that success was not at all certain. The cautionary tale of one Mr. Beaumont and his misadventure in coal country is well taken:

---

222 For an excellent, readable summary of coal use see Barbara Freese Coal, A Human History (New York: Penguin Group Inc. 2003).
223 Freese, page 56.
“Some South gentlemen have, upon great hope of benefit, come into this country to hazard their monies in coal pits. Mr. Beaumont, a gentleman of great ingenuity and rare parts, adventured into our mines, with his thirty-thousand pounds, who brought with him many rare engines, not known then in these parts; as, the art to bore with iron rods, to try the deepness and thickness of the coal; rare engines to draw water out of this pits; wagons, with one horse, …etc. Within a few years, he consumed all his money and rode home upon his light horse.”

---

224 "Trade at Newcastle Upon Tyne, 1649" in Chorographia: or a Survey of Newcastle-upon-Tyne: p.364. This story of Mr. Beaumont illustrates an old piece of trading wisdom that runs: “The only certain way a speculator may make a small fortune is to start with a large one.”
Part III: First Commercial Engines 1712 to 1770

Chapter 5: Precursors to the Newcomen Engine

This chapter will present a brief overview of the technical developments that set the stage for Newcomen’s atmospheric engine. This material, tracing the development of technology from the experiments of Torricelli and von Guericke to Savery’s “engine” has been well covered by a number of authors over the past century. These technological precursors will be described in brief to provide context, but this review also has two additional goals:

1. To deconstruct the historiography that presents the emergence of a thermal-powered prime mover as an inevitable march to the steam engine, and

2. To put the technology into its proper contemporary context.

These two tasks will advance goal of answering one of this dissertation’s main lines of inquiry: What would proto-mechanization look like? What were the necessary elements, which would have worldwide application, as distinct from the particular historical realization that occurred in Britain i.e.: was coal necessary for industrialization or would any energy–rich environment sufficed?

---

“High Pressure” Historiography, Anachronism, and Popular Anecdote

When interpreting the past, historians have a curious burden: they know how events were resolved. Rather than an aid to see more clearly, this knowledge may sometimes make it difficult to evaluate factors outside the direct story line. Technological histories seem especially prone to a linear projection into the past when tracing the development of a technology. For example, from the perspective of the 20\textsuperscript{th} century, it was obvious that high-pressure steam engines powered industry in the late 19\textsuperscript{th} century. As a consequence, when tracing the precursors of these engines, technical histories tend to focus on writings that seem to describe high-pressure steam concepts. These descriptions are adequate as a pedigree of the steam engine, but they may be inadequate as a history because the examples cited might take on importance all out of proportion to the actual significance they enjoyed in their own time.\textsuperscript{226}

The historiography of the stationary steam engine typically begins with “Hero’s steam engine” circa 100 AD, touches briefly on Savery and Newcomen, before moving quickly through Watt and on to the high-pressure steam engine of the 19\textsuperscript{th} century. This etymology of the steam engine selects for precursors that (with the exception of Newcomen and Watt) utilized high-pressure steam, not the atmospheric pressure actually used by the first engines.\textsuperscript{227}

Anachronism

It should also not be missed that this historiography would have the original engine “invented” by “Hero”. In actuality, his name out of the Greek was Heron, and he described himself as a compiler of known and proposed devices, not an inventor. It is tempting to attribute the steam engine to a heroic act of invention, but if we are to understand the original commercial

\textsuperscript{226} This certainly true of the work of the Marquis of Worcester in the mid-1600’s; see \textit{A Century of Names and Scantlings of the Marquis of Worcester}, below.

\textsuperscript{227} The “Hall of Power Machinery” in the Smithsonian’s National Museum of American History is neatly laid out to step the visitor through this story.
successes of a mechanical power that used fire as its motivating force, we need clear away the seductive mist of high-pressure steam.

To begin at the beginning, steam engine histories typically start with a nod to “Hero’s steam engine”, more properly Heron’s Aeolipile (Figure 5-1). The description of this device appears to show the principle of a reaction turbine where the propulsive power of steam turns a ball.

![Figure 5-1. A 19th Century Depiction of “Hero’s Steam Engine”. (Woodcroft, Hero of Alexandria).](image)

The fact that this device is well known today is probably due to the modern world’s familiarity with high-pressure steam, as promoted in the historiography of the 19th century. However, like the folklore that dwells on Watt’s youthful “discovery” of the propellant force of steam, it is misleading. Its fame is likely because, in retrospect, engineering evolved to the point where high-pressure steam would eventually completely replace engines driven by atmospheric pressure. If the Greeks had built a full-scale example of an aeolipile, it would not have been capable of doing any useful work. It may be a testament to the allure of high pressure that a
research as careful and thorough as Mokyr incorrectly stated that the aeolipile could do useful work: "Among the devices credited to Hero are the aeolipile, a working steam engine used to open temple doors." In this, he appears to confound a high-pressure toy with the low-pressure device that was apparently actually used to open doors.228

Hill has noted that one of the ironies of high-pressure steam is that it works well with small-scale models or toys, but presents significant technological challenges for full-scale applications.229 This is not to say the Greeks lacked understanding of steam, rather it is to note that to find proto-industrialization, we need to focus on low-pressure technologies. When seeking pre-cursors to mechanical devices that could exploit thermal imbalances to do work, Heron’s description of devices to open temple doors is more informative. He described a device using pressure differentials and transfer of weight to do useful work, in this case open the doors of a temple (see Figure 5-2).

---

229 Hill, Chapter 2.
Figure 5-2. 19th Century Depiction of Automatic Greek Temple Doors. After the fire is lit in the alter, the increase in air pressure in the sphere below forces water from the sphere into the hanging bucket; as the weight in the bucket increases, it pulls on the ropes opening the temple doors. (Woodcroft, *Hero of Alexandria*)

Another source often cited in the history of the steam engine is a reference in the book *A Century of Names and Scantlings of the Marquis of Worcester* (AKA Edward Somerset), published 1663. Worcester described the power of steam under pressure to raise water, and apparently made some attempts using vessels cast at the cannon factory at Vauxhall.\(^{230}\) This machine was described in Robert Stuart’s *History of the Steam Engine* (1831), but as Rolt and Allen note, this was purely conjectural.\(^{231}\)

**A Popular Anecdote**

This focus on high-pressure steam has a curious echo in anecdotes told about both Newcomen and Watt, which relate to steam under pressure. A widely spread folkloric story about James Watt tells how he, as a small boy, observed steam lifting a pot lid in his Aunt’s kitchen.\(^{232}\) Young James is said to have suddenly realized that steam could be used to propel machinery. A similar, although much more obscure, legend was told about Newcomen.\(^{233}\) The durability of these stories suggests that the “modern” sensibility (mid-19th century forward) latched onto examples of steam under pressure, used as a propellant. While these folk anecdotes about Watt and Newcomen dovetail with the eventual dominant technology (the historical result known by the late 19th century), they completely misconstrue the actual technology.

\(^{230}\) See Rolt and Allen, p. 17.
\(^{231}\) Hill also dismissed the idea that Worcester ideas had any merit. Stuart’s history is an excellent early example of high-pressure historiography.
\(^{232}\) Ben Marsden *Watt’s Perfect Engine: Steam and the Age of Invention* (New York: Columbia University Press, 2002), see the charming illustration on p. 11.
\(^{233}\) Rolt and Allen, p. 14.
As charming stories, these are fairly harmless; however in their mischaracterization of how these first engines were powered, they widen the gulf between modern understanding and the actual history. Even the least mechanically inclined citizen of the 21st century, given cursory experience in a kitchen, has a sense of steam’s ability to push things. While modern cooks probably do not boil pots as often as Jamie Watt’s aunt, they no doubt have had greater experience than she with microwave popcorn. Since the 19th century, nearly all steam engines have been driven by the same expansive power of steam that lifts the lid of a boiling pot or explodes a popcorn kernel from the inside. A modern hearer of the Watt or Newcomen stories would reasonably assume the first engines were also powered the same way.

By contrast, the principles that actuate a Newcomen engine, or its descendent the Watt engine, are alien to the modern sensibility. Both of these engines drew their power from condensing steam back into water to create a partial vacuum. Reacting to that vacuum, air pressure (normal, everyday air pressure such as the reader is experiencing in this room) pushes the piston down into the vacuum created in the cylinder until the reduced volume under the piston restores the pressure inside the cylinder to the same as the outside air pressure.

It is important to keep the nature of this technology in mind when thinking about what proto-industrialization might look like elsewhere in the world. This shift in emphasis from steam under pressure to steam used to create air pressure differentials may seem subtle, but it prompts us to examine technology that has significantly different – much less demanding - requirements. The efforts to harness differentials dealt with pressures of less than one atmosphere. In other words, the materials technology would only need to be able to withstand one atmosphere of pressure (or less) to function. While high-pressure steam could only be described in theory or

---

234 The weight of ocean of air over our heads varies according to altitude. At sea level, it exerts 14.696 pounds per square inch (PSI), while at 5,000 feet above sea level it is only 12.23 PSI.
used for small toys, the partial vacuums of air pressure differentials required much simpler levels of metallurgy.

This technology, so different from that of the 21st century, is what we need to be alert to when examining science in other cultures. As we shall see, the art of pumping water was similar to the technology of the earliest engines. In retrospect, this should not be surprising. Pumping involves variations in pressure; this area of technology should be closely reviewed in other proto-industrial areas, as it seems a likely area for developing mechanical power.
Actual Precursors: The Development of the Notion of Air Pressure

Atmospheric engines are driven by pressure differentials. To follow their development, we need to examine the history of pumps and other mechanical devices that operate using differences in pressure. It was, in fact, problems with pumps that led to the development of an understanding that the surface of the earth is at the bottom of an ocean of air. The weight of this air would drive the first “steam” engines.

In 1641 Ferdinando II de Medici, Grand Duke of Tuscany ordered the building of a suction pump to draw water 50 feet from a well at his villa in Florence. Note that, unlike the piston-lift pump described by Agricola, a suction pump raises water by creating a vacuum in the pipe. The understanding at that time followed Aristotle’s belief that nature abhorred a vacuum, and would always seek to fill it.

Unfortunately, the builders found the suction developed by their pump was insufficient to draw the water higher than about 30 feet. The Grand Duke was out the cost of his pump, and, as Grand Dukes will, he wanted an explanation. He called upon his foremost scientist, Galileo Galilei. Galileo unfortunately died early the following year (1642), but the work was continued by his assistant Evangelista Torricelli. Their experiments led Torricelli to conclude that water could not be drawn any higher into the vacuum created in the pump because of something he called “air pressure”. Previously, it had been thought that water was pulled up the pipe because of the vacuum created by the piston. Torricelli explained that the actual reason the water rose up into the vacuum was the air pressure pushing down on the water outside the pump. This was the ocean of air that is always pressing down on the surface of the earth, with a force of 14.7 pounds per square inch. Once the column of water inside the pump tube weighted the same 14.7 pounds per square inch, no more could be drawn up no matter how complete the vacuum. The reason

235 Rolt and Allen, p. 20
was that the weight of the column of water inside the tube balanced the ambient air pressure pushing down outside the tube. Both weighted 14.7 pounds per square inch.

To put this in perspective, a column of water with an area of one square-inch would, if it weighed 14.7 pounds, would be 34 feet high. This was the reason the Duke’s vacuum pump could not raise water much over 30 feet. A wider tube could hold a greater volume of water, but would not be able to raise it any higher.\textsuperscript{236}

In the 1670’s Otto von Guericke of Magdeburg conducted a series of public demonstrations that dramatically illustrated the potential power of the atmosphere’s weight. Von Guericke had conducted a series of experiments where he used a small hand pump to exhaust the air from inside spheres made of copper. The spheres were made up of two identical halves, which were then fitted together and sealed with leather gaskets. Once the air had been pumped out, Von Guericke found that the halves could not be separated until the vacuum in the sphere was broken. In a famous experiment performed for the Emperor Ferdinand III, he had constructed two large hemispheres, 12 feet in diameter. After the halves had been fitted together and the air pumped out, eight horses were hitched to each hemisphere, and they attempted to pull them apart. The horses failed. Subsequently, when air was restored to the great sphere, the two sides were easily parted.\textsuperscript{237}

\textsuperscript{236} Note Torricelli would substitute much denser mercury for water, allowing for a tube less than 34 inches high. This was the invention of the barometer, and weather reports still report air pressure in “inches” of mercury.\textsuperscript{237} Rolt and Allen, p. 22.
Figure 5-3. Guericke creates a vacuum in a cylinder with a movable top (a piston). It is stronger than “viginti vel 50 et plures homines robustos” (“twenty or 50 or more strong men”).

The “Magdeburg Spheres” are justly famous, but in retrospect the experiment where von Guericke proved most prophetic was in the evacuation of a cylinder he had fitted with a piston. He demonstrated that atmospheric pressure was stronger than 20 men.\footnote{This is sometimes cited as “50 men” (see Hill, p. 15), but that seems to be a mistranslation of Guericke’s Latin, perhaps based on the numeral “50” in his description of the engraving. In his text, page 110, Guericke actually uses a future conditional, not a literal, construction: the 20 men could have been 20 or 30, or 50 or even 100, and a vacuum could still be created to overpower them. Ottonis de Guericke Experimenta Nova (un vocantur)
cylinder and piston as shown in Figure 5-3. Guericke had prepared a sphere, from which he had already evacuated the air. He connected that sphere to the cylinder via a pipe and stopcock. When the stopcock was opened, the men could not hold back the piston from descending into the chamber. The force that overcame the von Guericke’s men was the 14.7 pounds per square inch of air pressing in on the vacuum inside the cylinder. When the catch was released, the movable piston was pushed into the cylinder. It was not lost on some observers that a force with the equivalent pulling power of this many men had potential to do useful work, and that the commercial economy had some profitable work that needed doing.

To Create a Vacuum

“Water being evaporated by the force of fire, these vapours immediately require a greater space (about two thousand times) than the water occupied before…”

---Sir Samuel Morland

By the late 17th century, the potential pushing power of the atmosphere was known. The question was, how to create the vacuum? If it was to be commercially useful to the developing economy and its expanded the investor’s ability to process energy, the method had to be easy, inexpensive, and able to repeat quickly. Alternate methods were tried. Perhaps the most dramatic attempt was the use of the chemical energy in gunpowder. It was known that an explosion of gunpowder evacuated the air from a chamber. Christiaan Huygens (Dutch, 1629-1695) and his assistant Denis Papin (1647-1712) constructed a cylinder with a piston, and then


239 If we assume one man could provide 200 pounds of resistance, 20 would have 6,000 pounds of resistance. Von Guericke would need a piston about 3 feet in diameter, which would have an area of about 1,000 square inches; if he lowered the air pressure inside the cylinder to 6.7 pounds per square inch, which would have been 8 psi less than the outside air, resulting in a force of 8 X 1,000 = 8,000 pounds overwhelming 20 “homeness robustos”.

fired a charge of powder to exhaust the air in the cylinder through a non-return valve. While the
gunpowder engine was not successful at that time, the use of the cylinder / piston combination
would prove long lasting.\textsuperscript{241}

Denis Papin, who was a French Huguenot, fled to England in 1675. Sometime between
1690 and 1695 he repeated the cylinder-and-piston experiments he had conducted with Huygens,
trying alternate means of creating a partial vacuum. It was known, as the Moreland quote above
shows that water boiled into steam occupies a much greater volume. Papin put a small quantity
of water in a vertical chamber with a piston. He placed a fire underneath the cylinder and
brought the water inside to a boil, pushing the piston to the top of the cylinder. He held it there
using a catch, and then waited for it to cool. As the cylinder cooled, the steam condensed back
into water; since the water occupied a much smaller portion of the cylinder, this created the
desired partial vacuum. When the catch was released, the atmospheric pressure pushing the
piston down could lift a considerable weight.

Papin believed the cylinder and piston arrangement to be impractical. He did not take the
additional step of hastening the cooling process, but instead experimented further with steam
pressure. This was about the point, at least conceptually, where Newcomen took up the work
around the year 1700. Newcomen’s goal was to more rapidly condense the steam to produce a
vacuum.

The Savery “engine”

Before any success was gained in more rapidly condensing steam in a chamber, a man
named Thomas Savery promoted a piston-less pump. In a stroke of marketing genius he termed
his device “\textit{The Miner’s Friend}”, and produced a pamphlet with the same name. As Hill

\textsuperscript{241} The harnessing of the power of an explosion in a cylinder would eventually prove practical in the internal combustion engine of the 19\textsuperscript{th} century.
characterized it, “His treatise, *The Miners Friend*, is an early and excellent example of the salesman’s glossy brochure.”

Savery’s pump operated in two stages. The first stage was not unlike a coffee percolator. By boiling water in a sealed chamber, pressure forced the water up a central tube, passing through a non-return valve. In this he had not made any advance on Heron’s experiments, 1600 years earlier. It was in the second stage that the power of air pressure was utilized.

For the second stage, Savery condensed the newly created steam in a middle chamber by pouring cool water over the receptacle. The steam inside, which had already been used to force some water higher, condensed to create a partial vacuum. This vacuum then drew water up from a lower pipe, again through a non-returning valve.

It may be a measure of just how acute the need for additional pumping power was that Savery was able to secure a patent for his fire-powered pump. His original patent was granted on July 25, 1698 for “Raising water by the impellent force of fire”. In 1699, Parliament extended the original 14-year patent to 35 years, through 1733.

It should not be missed that Savery’s “engine” is in fact a pump, and not a prime mover. Terming this device a “steam engine” is a bit misleading. An engine, a prime mover, would have a number of applications where it could, well, *move* things. Savery’s engine, so often referred to as an early “steam engine”, is really no more than what it claims to be: a device for “Raising water by the impellent force of fire.” Savery and Newcomen, were not trying to invent an engine (a general purpose prime mover), they were, as the patent suggests, seeking to raise water using the thermal power of fire. To suggest anything beyond this is to project onto the activities of those men intentions that they never had. A variation of this thinking suggests that Savery’s

---

242 Hill, p. 16.
243 Rolt and Allen, p.26
patent threatened to stifle innovation because it was too broad in the rights it reserved to him. The implication is that Parliament, in their ignorance, encroached on the development of other engines. This is of course nonsense. No one was “inventing a steam engine”; Parliament wanted to encourage a novel use for thermal energy: raising water.

As with other early high-pressure steam devices, Savery’s engine worked well in the small models he built for demonstration, but was not successful as a full-scale example. Its failure was only partially due to the extraordinary inefficiency of the machine. Its other failing was the high-pressure its first stage required.

“I’ve seen Captain Savery at York Buildings make steam eight or ten times stronger than Common Air; and then its heat was so great, that it would melt common soft Solder; and its strength was so great as to blow open several of the Joint of his Machine: so that he was forced to be at great Pains and Charge to have all his Joints solder’s with Spelter or hard Solder.”

High-pressure, the obvious way steam might provide useful work, was simply beyond the technology of early 18th century Europe. It is possible that materials technology would have been advanced in due time by other developments in the commercial economy. However, when looking for the initial adoption of thermal energy in Britain or elsewhere in the world, it seems a simpler technology would have been more likely to succeed commercially. A successful application of atmospheric pressure would eventually be worked out not by a scientist, but by a practical blacksmith (an “iron monger”) named Thomas Newcomen.

---

244 In addition to its other drawbacks, the second stage of the Savery pump, since it relied on a vacuum rather than powering a pump, it was still subject to the 34-foot limit.

Chapter 6: The Obscure Mr. Newcomen

Thomas Newcomen’s personal history is obscure.\textsuperscript{246} He was christened on February 24\textsuperscript{th}, 1663 at St. Saviour’s Church in Dartmouth, where he would own a house and shop. His father Elias was a Dartmouth merchant, and the Newcomens were Baptists; the family’s Baptist connections would aid him in business. Newcomen described himself as an “ironmonger”, a term applied to a retail trader in iron products. These traders typically would fabricate iron implements in their own shops.\textsuperscript{247} Ironmongers can be thought of as highly skilled blacksmiths, akin to what would later be called a millwright or machinist.

Newcomen’s partner was a man named John Calley. Calley's skills were in plumbing and as a glazier. The pair were not cloistered experimenters, but worldly businessmen. Newcomen’s work made him a frequent visitor to the tin mines of Devon and Cornwall, in the extreme southwestern tip of England. His work certainly would have made him aware of the water-pumping needs in these mines.

Newcomen was familiar with Papin’s work (or at least the concepts involved), where cooling the steam in a cylinder could create a partial vacuum. The resulting vacuum caused outside air pressure to force the piston down into the cylinder, restoring the balance in air pressures. Newcomen sought for a way to harness this reaction to accomplish some useful work. His line of experimenting appears to have been to search for a way of speeding the cooling process. He is believed to have begun experimenting around the year 1700. For an experimental

\textsuperscript{246} The best source on Newcomen’s life is still L.T.C. Rolt and J.S. Allen The Steam Engine of Thomas Newcomen (1977). This text is an update by Allen of Rolt’s life of Newcomen. It has been described by J.W. Kanefsky as the ‘bible’ for information on early engines (personal e-mail communication, May 17, 2011).

\textsuperscript{247} Rolt and Allen, p. 34.
cylinder and piston, he likely used a seven-inch in diameter brass cylinder with a piston, as this would have been the similar to the water pumps he had fabricate for use in the mines.\textsuperscript{248}

**A Rediscovery of Fire**

Perhaps the most reliable description of the course of Newcomen’s work that led to the design of a successful engine comes from the Swedish engineer Marten Triewald. Triewald had traveled to England in 1716, and worked there for 10 years. During this time he worked directly with Newcomen and Calley, initially by assisting in the erection of an engine near Newcastle. Triewald would go on to erect the first steam engine in Sweden.\textsuperscript{249} In his book of 1734, Triewald related the course of Newcomen’s experiments:

“Now it happened that a man from Dartmouth, named Thomas Newcomen, without any knowledge whatever of the speculations of Captain Savery, had at the same time also made up his mind, in conjunction with his assistant, a plumber by the name of Calley, to invent a fire-machine for drawing water from the mines. He was induced to undertake this by considering the heavy costs of lifting water by means of horses which Mr. Newcomen found existing in the English tin-mines. These mines Mr. Newcomen often visited in the capacity of a dealer in iron tools, with which he used to furnish many of the tin-mines.”\textsuperscript{250}

Note that Newcomen was described as frequenting the tin mines, and his motivation for experimenting with fire-powered mechanical power was the cost of organic animal power. “Captain Savery” was the very same Thomas Savery, promoter of *The Miners’ Friend*. Savery’s patent covered any machine for the “Raising water by the impellent force of fire”, and this terminology was broad enough to prevent Newcomen from operating his engines without infringing on the Captain’s patent. To remedy this, Newcomen came to a business arrangement

\textsuperscript{248} Rolt and Allen, p. 41.  
\textsuperscript{249} See Part IV on Dannemora Mine engine.  
with Savery, possibly as early as 1705, where Newcomen would operate under the original patent. Coming to terms with Savery may have cost Newcomen some of his potential profits, but in return he gained patent protection for his engine until 1733, the expiration of Savery’s original patent.\textsuperscript{251}

As a practical man, Newcomen wanted to use as much of the existing infrastructure as possible. Analogous to his willingness to work within Savery’s patent, he sought to develop an engine that could be accommodated within the existing pumping systems at the mines. Rather than invent a new pump, as Savery had, his goal was to replace the prime mover (the horse) that drove those pumps. The driving force for his engine would be air pressure.

Apparently, Newcomen’s experiments took their cue from von Guericke’s piston-forced-by-atmospheric-pressure concept. Guericke had shown the potential power of a vacuum. As for the creation of a vacuum, Papin had shown how steam, when condensed, created a partial vacuum that could lift a significant weight. The flaw in Papin’s method was the long wait for the cooling steam to condense back into water on its own. Newcomen experimented with methods of cooling the cylinder rapidly enough to produce useful mechanical energy.\textsuperscript{252}

In his early attempts he used a cooling-jacket over the cylinder. The jacket, made of lead, surrounded the cylinder, leaving a space for water between the two. Cold water flowed into the jacket, eventually cooling and condensing the steam inside. This caused the piston to descend, allowing the machine to do a useful stroke. Unfortunately, the period between the strokes was still too long.

\textsuperscript{251} Rolt and Allen, p. 39-40.
\textsuperscript{252} Frustratingly little is known about the course of his experiments. How many ideas had he toyed with in an attempt to produce a steady stream of mechanical power? Had he considered multiple cylinders pulling in sequence to shorten the time between strokes? Details are lacking.
Eventually, Newcomen and Calley hit upon the idea of introducing a burst of cold water directly into a cylinder filled with heated steam. This internal cooling produced a much more rapid reaction. A story about the discovery was provided by Triewald:

“For ten consecutive years Mr. Newcomen worked at this fire-machine which never would have exhibited the desired effect, unless Almighty God had caused a lucky incident to take place. It happened at the last attempt to make the model work that a more than wished-for effect was suddenly caused by the following strange event. The cold water, which was allowed to flow into a lead-case embracing the cylinder, pierced through an imperfection which had been mended with tin-solder. The heat of the steam caused the tin-solder to melt and thus opened a way for the cold water, which rushed into the cylinder and immediately condensed the steam, creating such a vacuum that the weight, attached to the little beam, which was supposed to represent the weight of the water in the pumps, proved to be so insufficient that the air, which pressed with a tremendous power on the piston, caused its chain to break and the piston to crush the bottom of the cylinder as well as the lid of the small boiler. The hot water which flowed everywhere thus convinced even the very senses of the onlookers that they had discovered an incomparably powerful force which had hitherto been entirely unknown in nature,-at least no-one had ever suspected that it could originate in this way.”

Note that we do not have to believe it was an accidental discovery to suppose that the reaction (the speed and power of the stroke) would have exceeded Newcomen’s expectations. Whether by accident or design, the introduction of coolant directly into the chamber would have produced a much more rapid reaction than the slow condensation of the steam. The abrupt condensation would have resulted in a much more forceful decent of the piston. This rapid acceleration could have snapped the chain, as Triewald described. Without the chain to hold the piston back, it would likely have smashed the boiler below.

The rapidity of the reaction is only part of the improved functioning provided by water injection vs. slow cooling. The useful work captured would also have been much greater. The reason for this was that the faster condensation would have allowed less time for the inevitable

---

253 Triewald, § 2, emphasis added.
leakages around the imperfect cylinder. A more rapid reaction would transmit a greater portion of the available energy to the system.

Even though 300 years have passed, we can, with only a little reflection, share Newcomen’s elation: He had been experimenting with various ways to speed the time between strokes to harness fire, and now he had it. Newcomen and Calley had re-discovered fire.

**Newcomen Dismissed by the Scientific Community**

Newcomen’s scientific ability was usually described in derisive terms by learned writers of the 18th and 19th. Triewald attributed Newcomen and Calley’s success to direct divine intervention, which he saw as the only possible explanation for how “…ignorant folk who had never acquired a certificate at any University or Academy” could have overcome such technical problems.\(^{254}\) This earlier dismissal of Newcomen, contrasted with the later deification of the scientist James Watt, has tinted the historical discourse regarding the development of the steam engine through the early the 20th century.\(^{255}\) Even today, Newcomen remains a footnote in the development of the “steam” engine.\(^{256}\)

The personal reputation of the two inventors aside, the dismissal of Newcomen adds to the difficulty of developing a proper understanding of the process of mechanization. This pall lasted for hundreds of years. It was not until the 20th century that the retrieval of Newcomen’s history even began. It is a revealing fact that most of the Newcomen engines now known to have existed have been documented only in the last 90 years. Writing as late as 1923, John Lord in

---

\(^{254}\) Triewald, § 3, 1730; see also Desaguliers (1744) or Stuart (1827).

\(^{255}\) This is not to denigrate Watt’s achievements, but he has certainly received his due; see Ben Marsden (2002) for a description of the esteem that the 19th century heaped upon him.

\(^{256}\) On the Smithsonian’s website describing the “Hall of Power Machinery” at the National Museum of American History, Newcomen’s 1712 machine is still (March, 2012) attributed to Savery; they describe the hall as: “…illustrated with several models, including the first commercially useful steam engine, designed by Englishman Thomas Savery in 1712. [http://americanhistory.si.edu/exhibitions/exhibition.cfm?key=38&exkey=48](http://americanhistory.si.edu/exhibitions/exhibition.cfm?key=38&exkey=48) (accessed March 15, 2012).
*Capital and Steam Power* concluded that the Boulton and Watt engine had a near monopoly during the late 18th century.\(^{257}\) In reality, a detailed analysis shows that the Watt engine was not even a majority of the engines *built* between 1780 and 1800, let alone operating during that time.\(^{258}\)

If Newcomen had any deficiencies in his understanding, it was probably as regards the fuel needs of his fire engine in a commercial setting. This can hardly be thought a slight against his abilities: Newcomen was working in an as-yet unknown branch of physics. It would be over 100 years before an understanding of the principles involved in the operation of his engine began to be systematized with the development of thermodynamics.\(^{259}\) Ironically, and possibly part of the reason Newcomen remain obscure, this was after his engines had been rendered obsolete by the advances of Watt and others. In 1710, Newcomen could have had only a vague idea of how efficient his empirical experiments would be in producing mechanical-power using fire.

---


\(^{258}\) Much of this data was gathered through the efforts of the Newcomen Society in Britain, after 1920. See also John Kanefsky and John Robey, “Steam Engines in 18th Century Britain: A Quantitative Assessment”, *Technology and Culture*, Vol. 21, No. 2 (Apr., 1980).

\(^{259}\) For example Carnot’s *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance* was not published until 1824.
Newcomen and the Realities of the Commercial Economy’s Energy Using System

Newcomen had the method he had sought. Fire, a thermal energy source, could be harnessed to do mechanical work. The partial vacuum in his cylinder could perform 10 to 12 useful strokes per minute. Newcomen’s technology would work, but it remained an open question whether it was efficient enough to be economical in practice.

The pumping needs he had observed in flooded mines illustrated that when energy inputs exceeded what could be provided economically, production came to a stop. Newcomen was trying to push back the border of what was “economical”. Potential investors would have been attracted by the prospect that the engine could allow the operation of mines too expensive to pump using previously available prime movers. These mines could potentially be transformed from worthless water pits to profitable producers, but even the boldest speculator would be cautioned by the fact that this lower cost was as yet undemonstrated. They had heard such talk before, from Savery and others, and had been disappointed. It is at this juncture that the role of fuel’s cost and availability, as related to the adoption of thermal power, reveals itself through Newcomen’s first engines.

The location of the first Newcomen engine has been the subject of considerable research in England. Newcomen’s first successful engine was at Dudley Castle in 1712. This was probably not, however, his first attempt. His first commercial attempt was almost certainly in Cornwall, most likely at Wheal Vor (the “Great Work”), at Breage in Cornwall, in 1710. A second was possibly built not far away at Balcoath, near Porkellis, Wendron, also in Cornwall, circa 1710-11.260

---

260 After a careful consideration of the available evidence, Rolt and Allen thought the building of an engine at Wheal Vor in 1710 “very probable”, and one at Balcoath, near Porkellis, Wendron, Cornwall in 1711 possible, but “unconfirmed”; see their Appendix, after page 145; Rolt and Allen cite Bryan Earl, Cornish Mining: The Techniques
That the first attempts would have been in Cornwall is not only perfectly reasonable, upon reflection it seems obvious. It would have been strange if they were anywhere else. Newcomen was from Dartmouth, and was known to ply his iron trade in the tin mines of Cornwall and Devon.\textsuperscript{261} Further these mines were producing a high value commodity, tin; of the many commodities drowned in flooded mines, tin’s high value would have doubtless made its mines relatively more attractive to speculators with capital to risk on novel pumping methods.\textsuperscript{262} Both of these engines were built in tin mines with which Newcomen was familiar. Both of them were failures. Their failure has been variously attributed to technical difficulties, or the inevitable problems with a first attempt, or “…it can be \textit{assumed} that either it (the engine) was not satisfactory or the mine failed…”\textsuperscript{263} This would not be the last early engine whose failure was attributed to some unknown technical problem (or lack of expertise).\textsuperscript{264} However, after a review of successful Newcomen engines in the first half of the 18\textsuperscript{th} century, and an in-depth examination of the case studies to follow, one comes to strongly suspect that the fault was not the technology, but the cost of fueling the engine.

In the case of these earliest engines in Cornwall, coal would have been used to fire the engine’s boiler. For a simple task, such as of boiling water for the engine, or for space heating in the city of London, coal was the preferred fuel as it was cheaper than wood. Unfortunately Cornwall, on the southwest tip of England, lacked local sources of coal. Any coal used there would have been shipped from Bristol or South Wales to a Cornish port. Upon landing, the coal would have been carried to the mine by mules; this hauling would have at least doubled its

\textit{of Metal Mining in the West of England, Past and Present} (2nd ed.) (St Austell: Cornish Hillside Publications, 1994) page 38.
\textsuperscript{261} Hill, p. 22.
\textsuperscript{262} See earlier quote regarding speculators whose pockets were often drained before their newly acquired mines.
\textsuperscript{263} Rolt and Allen, p. 45; emphasis added.
\textsuperscript{264} See Dannemora example below.
landed cost at the port. Exact figures are difficult to pin down, but that coal would cost double or triple the mine-mouth price is uncontroversial. For example, in 1701, coal at the Forest of Dean, a potential source for Cornwall, was 10 shillings per cauldron; for that same year, coal delivered to Kings College was 30 shillings, 3-times as much. This likely understates the cost increase, as Kings College would have likely been serviced by coal from the lower-cost collieries of New Castle. On top of all these expenses, a tax was imposed on “sea-bourne” coal (“sea coal”). It was not until 1741 that coal destined for engines was finally exempted from this tax; it is probably not a coincidence that this exemption was largely due to petitions from the Cornish mine owners.

The problem of expensive fuel was not limited to tin mines. Due to transportation, existing taxes, and assuming the coal mongers would insist on at least a little profit, the fuel for an engine operating anywhere in Britain would pay at least two to three times as much as it cost to produce the coal. Anywhere that is, except at a coalmine itself.

Selling the Engine, 1712

The suspicion that fuel costs were a major stumbling block to a commercially successful application of the fire-powered engine in Cornwall is further strengthened by the fact that, less than two years later, Newcomen was able to convince investors at the Coneygree colliery in the South Staffordshire coal field, near Dudley Castle, to erect an engine. This was the famous 1712 “Dudley Castle” engine, and is regarded as the first commercially successful steam engine in the world. If we contrast the failure at Wheal Vor with the success at Dudley Castle, several

---

265 Nef, Appendix E, pp. 393 and 405.
266 Note that, due to transportation costs, even removing the tax on coal would still leave it costing more than twice as much delivered as it did at the mine mouth.
267 The 1712 engine is usually referred to as the “Dudley Castle” engine, after Barney’s 1719 engraving. However, it should be noted that the exact location of the first engine in Staffordshire has been the subject of debate, with
points suggest that Newcomen was aware that fuel cost was the remaining stumbling block to commercial success, and was actively seeking a solution.

First, the location. The successful 1712 engine was located in the coalfields of England’s Midlands, a considerable 200 miles from Newcomen’s home in Dartmouth.\textsuperscript{268} This was an area where he lacked the experience and contacts of his work in Cornwall.\textsuperscript{269} What prompted this shift in geographic focus? Of course it is possible that he fortuitously traveled to the coal country, or was contacted by ready investors from the Midlands. But these two explanations sound strangely like Triewald’s attribution of Newcomen’s success either to luck or being called by a higher authority.

Second, the relatively short interval of only two years suggests the technology of the engines would have been similar.\textsuperscript{270} The time frame might have allowed for some minor changes, perhaps the automation of the opening and closing of the valves, but any cost saving from these improvements would have been minor.

\textsuperscript{268} The distance to the sites in Cornwall was still a considerable 95 miles by land, but they are just down the coast from Dartmouth, only a few miles inland from the port of Falmouth.
\textsuperscript{269} Rolt and Allen note that Newcomen had religious ties (Baptist) to the area, and through these sources may have been familiar with the Midland’s problems with flooding; even so, these links were much weaker than his Cornwall experience and, curiously, again invoke a religious guidance for Newcomen’s success.
\textsuperscript{270} This point was made by Rolt and Allen, p.44. They also noted that the design of Newcomen’s engine of 1712 quite mature, including automatically operating valves.
Figure 6-1. Newcomen’s England. Modern map showing the relative locations of Dartmouth (Newcomen’s home), the Cornwall mines (Wheal Vor), and “Dudley Castle” (Staffordshire coal fields).

Finally, and perhaps most telling given the profit-oriented nature of venture capitalists, it seems unlikely that Newcomen would have been able to sell new investors on the idea of erecting another engine unless he could explain why they could expect to succeed where their brethren in Cornwall had failed. Perhaps it was for technical reasons, as Rolt and Allen suggested, but this seems unlikely given the short time interval. However, if it were the case that a quick technical fix was all that was required, Newcomen would probably have been able to convince other investors in Cornwall.
If instead we attribute an active role to Mr. Newcomen, a more plausible explanation presents itself. It is much more likely that he identified the voracious fuel use of his putative engine in Cornwall as its critical failure. In a second or third engine, marginal improvements in efficiency could be expected. Unfortunately, the prospects that these would be sufficient to overcome the engine’s energy deficit probably would have appeared dim to a gentleman-capitalist considering venturing his treasure on a fire engine. It seems more likely that it occurred to Newcomen and Calley that they needed to seek out an application where fuel would be more readily available.

In his *Experimental Philosophy* (1744), Desaguliers indicated that Newcomen was already in the Midlands in late 1711:

“…In the latter End of the Year 1711 (they) made Proposals to draw the Water at Griff in Warwickshire; but their Invention, meeting not with Reception, in March following, thro’ the Acquaintance of Mr. Potter of Bromsgrove in Worcestershire, they bargain’s to draw water for Mr. Back of Wolverhampton, where, after a great many laborious Attempts, they did make the engine work; but not being either Philosophers to understand the reasons, or Mathematicians enough to calculate the Powers, and to proportion the Parts, very luckily by Accident found what they sought for.”

The time-line of his decision to take his fire-engine proposals to the Midlands suggests that Newcomen was aware that he did not have a technical problem making the engine work: he had an economic problem of getting the engine to pay for its fuel. His solution to this problem was to take his proven technology where coal costs would be less than half that in Cornwall.

As for his reception in the Midlands, it is extremely unlikely that Newcomen could have convinced the equally cautions mine owners there to try their fortunes on a technology that had just failed in Cornwall unless he could present a plausible scenario in which their results would be different. What would be different? Newcomen had the strong selling point that he could

---

271 Quoted in Rolt and Allen, p. 45. Note how again, since he is not a scientist, Newcomen’s success is attributed to a lucky accident.
reference an earlier Cornwall engine as a full-scale working model that merely lacked the one item produced in a Midland’s coal mine, a low-cost thermal fuel. This would explain the relatively short time between the (economic) failure in Cornwall and his successfully finding new backers in Staffordshire.

**Counterfactual**

Consider for a moment the counterfactual. What if there were no coalmines within Newcomen’s reach? The need for pumping would be no less at the tin mines, but the cost of using an engine to power the pumps would be prohibitive. Additional engines would not be built, at least not at that time. Unable to cross the threshold into commercial activity, the engine with its brass cylinder and other unrefined features would languish.

This is hardly to say that the invention of the steam engine would be lost forever, but its adoption would be at least postponed. Put differently, a thermal energy source needs to be not merely available but also affordable for the adoption of mechanical power to occur. Applying this insight to world history suggests that when looking for other examples of adoption of fueled mechanical power, we should look for it in a commercialized environment, where there is a growing need for primary energy, and available thermal fuel is relatively cheap.

**Description of the engine**

**Operating Principles**

Before presenting contemporary descriptions of Newcomen’s engine, an outline of its operation is in order. These engines are no longer used in commercial settings, although several are operated by museums.
Figure 6-2. Diagram of a Newcomen Atmospheric Engine. Note that the weight of the beam pulls the piston up, allowing the cylinder to fill with steam. The power-stroke begins when the steam condenses.

Figure 6-2 shows the essential parts of a Newcomen engine. From the ground up, they are the firebox (burning wood or coal), a boiler used to produce steam from the fire’s energy, a cylinder to contain the steam, a piston within the cylinder, and on top a water reservoir that provided the spray of cooling water. This reservoir also supplied a steady stream of water to the top of the cylinder; this was to cover the piston, which aided the piston’s gasket in keeping air out of the cylinder. The piston is connected via a chain to one side of the large wooden beam that transfers its motion down into the mine, to operate the pumps.
The engine would cycle as follows. The wooden beam was balanced so that, when at rest, it pulled the piston to the top of the chamber. A valve between the boiler and the cylinder opened, allowing steam to fill and warm the chamber. Once filled with steam, the intake from the boiler was closed; then the valve from a cold-water tank was opened. Figure 6-3 shows the engine just at this point, when cold water is spraying into the cylinder to condense the steam. Note that the cold-water reservoir (the “cistern” in Figure 6-2) was at a higher level than the cylinder; when the valve was opened, gravity forced the spray of cold-water into the chamber, condensing the steam. The condensed steam became water, occupying only a fraction of the volume the steam had only a moment ago occupied. The resulting sudden drop in required volume created a partial vacuum. Since the atmospheric pressure outside the cylinder had not changed it was now at a relatively higher pressure, and pressed in on the chamber. The atmosphere squeezed all sides of the chamber; since it had a movable top – a piston – the piston was forced down into the cylinder, providing the power stroke.

After the power stroke, a valve is opened, allowing pressure inside the cylinder to equal the normal ambient air pressure. Another valve at the bottom of the cylinder opened, allowing the condensed water to drain out (these details are not shown in Figure 6-2). Since the counterweight on the pump side of the beam is greater than on the piston side, once the pressure was equalized, the piston was pulled back to the top of the cylinder. Note that in Newcomen engines, the steam does not push the piston up; gravity pulls the pump-side of the beam down and as the other side of the beam rises it lifts the piston to the top of the cylinder. The valve between the boiler and the cylinder is then opened again, allowing the chamber to fill with steam to repeating the process. These engines would complete 10 to 12 of these cycles (power strokes) per minute.
As noted, a typical installation used a “rocker beam” to transfer the motion from the piston to pumps down in the mine.\textsuperscript{272} The rocker beam was not unlike a child’s seesaw, if a child had a twenty-foot long toy, weighing several tons. The beam had curved arches attached to each end, which served to smooth the transfer of motion. A chain at one end of the beam was attached to the piston. At the opposite end another chain was attached to pumps down in the mine. As for the pumps, they were exactly the same kind as would have previously been worked by a waterwheel or horses (see Figure 4-6).

A fundamental distinction between an engine driven by atmospheric pressure and later high-pressure engines that would use steam as a motive force is the radically different strain on the engines’ parts. Since Newcomen’s engine used only differences in air pressure, rather than pressurized steam, it operated at pressures only slightly different from normal atmospheric pressure. By contrast, even the simplest high-pressure steam engines required steam under pressure many times that of the atmosphere. Recall that Savery’s engine required what they believed was “…steam eight or ten times stronger than Common Air.”\textsuperscript{273}

A second technological benefit is that engines using atmospheric pressure as a driver tend to work better as their size is increased. Even a great increase in size would not involve any increase in the pressure inside or outside the cylinder. In the later 1700’s it would not be uncommon for these engines to have a cylinder 5-feet in diameter and 10 feet long. Although the atmosphere pressing on these giant pistons had not increased, by giving the air pressure a much larger area to push against, it would greatly increase the power of the each stroke. While increasing diameter greatly increases power, the same is not true of length. In this case, power increases only linearly, and so making the cylinder longer would not convey much of an

\textsuperscript{272} Rotary motion would not be developed until the late 18\textsuperscript{th} century. See Hill Chapter 5.

\textsuperscript{273} Desaguliers Experimental Philosophy Vol.II, p. 467.
advantage. Thus Smeaton’s 1772 cylinder for the engine at Chacewater in Cornwall, although at 72 inches in diameter is was well over three-times wider than the 21 inches of Newcomen’s original engine, it was only marginally longer than the nearly 8-foot length of Newcomen’s 1712 machine.  

For an engine powered by air pressure, tripling its diameter makes it 9-times more powerful. This was the reverse of contemporary engines that used steam’s propulsive power. To increase the power of Savery’s engine (and indeed Heron’s engine of circa 100 AD) the pressure of the steam needed to be increased. This was why they worked well as small models or toys, but the crumbled when a full-size high-pressure driven version was attempted.

As a practical matter, Newcomen’s engines do not create a complete vacuum. At sea level, the atmosphere pushes down with a force of about 14.7 pounds per square inch. Newcomen’s condensation of steam dropped the pressure inside the cylinder to about half that. For calculation purposes, the imbalance between inside and outside the cylinder was about 7-pounds for every square inch of the piston. Take for example a piston 24 inches in diameter, which would have an area of just over 450 square inches. At 7 pounds per square inch, the power stroke would have a force of 450 X 7 = 3,150 pounds, or roughly the weight of 380 gallons of water. Heat and mechanical losses etc. would greatly increase the amount of energy needed to accomplish this work, but for the early 18\textsuperscript{th} century this was a prodigious volume of water lifted, per stroke.

---

275 The power of a Newcomen engine depends on the area of its piston, not the steam. Since area increases based on the radius squared, an engine with a piston 2-foot in diameter is 4 times more powerful than an engine with a 1-foot in diameter piston. An engine with a 4-foot piston is 16 times more powerful than the 1-footer.
276 Hill noted that in the 1760’s, Smeaton used 7 PSI as the working force for calculations.
277 In exact figures, a piston 24 inches in diameter would have an area of 452.4 square inches; at 7 pounds per square inch the power stroke would have a force of 452.4 X 7 = 3,166 pounds.
Actual Engine

Again, this material has been expertly covered elsewhere; this section will present a brief recap of the technology involved, as this will be helpful with the case studies to follow. An engraving of the Dudley Castle engine by one Thomas Barney was published in nearby Birmingham in 1719. The full engraving has a key showing in detail the various parts of the engine.

Triewald provided a description of this engine in his 1734 text:

“…Later on Mr. Newcomen built the first fire-engine in England in the year 1712, which erection took place at Dudley Castle, in Staffordshire. The cylinder of this engine measured 21 inches in diameter, and was 7 feet 10 inches high. The boiler was 5 feet 6 inches in diameter and 6 feet 1 inch high. The water in the boiler stood 4 feet 4 inches high and the volume of water was 673 gallons. The machine made 12 strokes a minute and delivered 10 English gallons at a stroke. The mine was 51 yards of 25 ½ fathoms deep.”

Note that the engine (figure 6-3) has two different titles. The most prominent declares it is an engraving of “The Steam Engine near Dudley Castle. Invented by Capt. Savery and Mr. Newcomen. Erected by ye later in 1712.” However, according to the Oxford English Dictionary, the term “steam engine” was not used prior to 1750, suggesting that this title may have been a later addition. The other title, perhaps the original, states “To the Knights, Citizens and Burgess of the County of Stafford.” “This Plate is humbly dedicated by their most humble servant, T. Barney”.

---

278 Triewald (1734), § 4 and § 5 of Introduction.
279 Rolt and Allen, p. 47; they estimate the horsepower of this engine at 5 ½ HP.
Figure 6-3, part 1. Barney’s 1719 engraving of the “Dudley Castle” Engine of 1712. Note anachronistic caption, declaring it a “steam engine”, not a term used in 1719; The different styles of the two titles suggest they were applied at different times.
Figure 6-3, part 2. Key to Barney’s 1719 engraving of the “Dudley Castle” Engine of 1712.
Another engraving, actually published two years earlier in 1717 but not rediscovered until the 1925, was made by the engineer Henry Beighton. The engraving is of the first engine Newcomen built at the Griff Colliery.

Figure 6-4. 1717 Engraving of Engine at Griff. Henry Beighton’s 1717 engraving of the engine built by Newcomen at the Griff Colliery is highly detailed. Note that this caption is original: “The ENGINE for Raising Water (with a power made) by Fire.”

This engraving is interesting for several reasons, most notably for its depiction of self-regulating features. Figure 6-5 is a detail of this engraving, edited to show the principal parts of the engine.
Figure 6-5. Detail, Rendered from Henry Beighton's 1717 Engraving. Seen here are all of the essential parts of a Newcomen engine, including the self-acting gears and wealthy gentleman capitalist.

The detailed operating characteristics of Newcomen’s fire engine have been presented to call attention to a key point: It cannot be emphasized enough how phenomenally inefficient this
engine is. The air in the chamber, and the walls of the chamber itself, are repeatedly heated with steam only to be cooled with cold water. The whole chamber needs to be reheated for each power stroke. The action of the piston is transferred using an overhead rocker arm; add to this friction, heat loss, the questionable gasket sealing the gap between the cylinder and the piston, apply the engineering standards of the early 18th century, and it is a wonder that any useful work could come out of such a machine. Over 100 years later, science would develop various measures of heat conversion such as “thermal efficiency”. Thermal efficiency is a measure of how much of the energy used in an engine is turned into useful work. Newcomen engines have a thermal efficiency between 0.5% and 1.0%. In other words, over 99% of the energy is lost to waste heat and friction.280

The first Newcomen engines were used only as water pumps and limited almost entirely to coal pits. This should not be surprising. Coal is a bulky commodity; shipping it any distance greatly adds to its cost. However, at the head of a coal pit, these handicaps are less of a concern. No matter how much fuel might be required for the fire engine’s voracious appetite, at least it did not need to be shipped. Further, these engines often used “slack” coal, or coals too small to ship profitably. As a result, at a coalmine, and only at a coalmine, fuel was effectively cheap, if not quite free.281 The simple low-pressure technology of the atmospheric engine made it a commercial success in the flooded coal mining industry. Between 1712 and 1733, nearly 100 engines were built. Of these, 89 were known to be in coalmines.282

280 Dickenson, p. 164.
282 Rolt and J.S. Allen, see Appendix; see also Kanefsky and Robey. These figures are examined in greater detail in Chapter 7.
Chapter 7: Technical Improvements and Political Gains

The commercial success of Newcomen’s engine set in motion changes that would further lower the operating cost of the engine itself. These changes included greater skill in building engines, technical improvements collected by engine operators, and political successes. As with other aspects of the development of the “steam engine”, the historiography of these events has a long tradition. This chapter will seek to enlarge upon this body of work by examining the role of energy in this process. Although not obvious at the start of the 18th century, Britain had entered into a period of energy abundance. Previously, they had made some use of coal as a replacement for wood in applications requiring thermal power, such as brick or glass-making, but the primary use was for the space heating of dwellings. Henceforth, coal, a mineral fuel, could become an increasingly important source of primary power.

Precise figures are wanting, but an outline of the increase in coal production is both clear and staggering. Total production of coal in 1700 was 2.5 to 3.0 million tons. Estimates for the year 1800 at from 10 million up to 15 million tons, indicate output was four or five times greater. Yet, even with this historically unprecedented expansion of output, the price of coal remained steady. Some analysts have even concluded that, adjusted for inflation, the price of coal actually declined over the 18th century. It seems that not only did coal provide fuel for steam engines, but also steam engines contributed to lower cost of production at coalmines.

---

283 Richard L. Hills Power from steam (1989) provides the best recent evaluation of the technical issues in the development of the Newcomen engine. Hills’ work with the Mechanical Engineering Department of the University of Manchester Institute of Science and Technology building a one-third replica of a Newcomen engine provides unique insight into the problems faced by Newcomen; see Hills pp. 20-30.
284 Wrigley, pp. 54-55; for the low-end estimate of 10 million tons in 1800, see von Tunzelmann, p. 111.
285 See Gregory Clark and David Jacks “Coal and the Industrial Revolution, 1700 – 1869” European Review of Economic History, 11(1) (April, 2007): 39-72; see especially figure 9. It should be noted that they interpreted the declining real price of coal as evidence that any amount of coal could have been made available, at any time in
history, and so coal was not essential to the Industrial Revolution. Curious. For an opposite opinion, see Landis (1969), pp. 97-100.
The number of fire-powered engines built in Britain in the 18th century is not commonly appreciated. Over the course of that century, nearly 2,200 engines were erected in Britain. “It is, nonetheless, clear that the steam engine was even more important to the 18-century economy than has generally been realized.”\textsuperscript{286} This is not to say that their contribution to the power needs of industrializing Britain were essential, even at the end of the century. Waterpower was the first choice, where available, and the steam engine would not become the dominant prime mover until well into the 19th century. However, viewing the economy as a whole masks how the efforts of the steam engine were concentrated in the mines, particularly the coalmines. The development of iron-coal-steam nexus was a long process requiring not only certain technological advances but also establishing a support infrastructure and the human capital embodied in the engineers of the country. Britain’s lead in these areas in the 19th century owed a considerable debt to its long experience with engines.

Kanefsky and Robey’s “Steam Engines in 18th Century Britain: A Quantitative Assessment” remains the most complete list of machines in Britain for that century.\textsuperscript{287} Drawing together numerous area studies, they were able to compile data on 2,191 engines erected in Britain up to the year 1800. In popular imagination, formed by the historiography of the 19th and 20th centuries, Watt engines were so superior to the Newcomen type that they immediately replaced them. The reality documented by Kanefsky and Roby was that less than 500 of these 2,191 engines were of the Bolton and Watt type, while perhaps 1,400 machines were of the

\textsuperscript{286} Kanefsky and Robey. Their exact count is 2,191.
\textsuperscript{287} Although first published in the 1980’s, their work remains a complete list. Kanefsky has updated the list in preparation for a 2012 publication, but noted in a personal communication that less than a dozen engines have been added to his list of 2,191 machines, and that all of these were from the late 18th century (John Kanefsky, e-mail message to the author, May 17, 2011).
Newcomen type. Even when they were in direct competition, during the last 20 years of the 18th century, more Newcomen engines were built than were Watt engines.\textsuperscript{288} The preference for Newcomen engines may have been helped by the patent Watt held until 1800; the royalty due to Boulton and Watt would have increased the cost of their engine, relative to the “common” Newcomen engine.

**Savery Engines**

Kanefsky and Robey’s research also clarified the history of Savery’s high-pressure engine. The Savery engine, it would seem, was much more important in the scientific writing of the 18th century than they were in any commercial applications. A “very few” early examples were built around 1700, perhaps as many as 4 machines.\textsuperscript{289} These fell into disuse, and only one or two additional experimental versions were built by mid-century. Desaguliers, for example, had experimented with improving the Savery type circa 1740. Late in the century, in the 1780’s and 1790’s, a number of Savery engines were used as “return” engines. In this application, they would return water to the top of waterwheels at textile and other factories.\textsuperscript{290} These applications suited the engine, as the height the water was lifted was generally modest, perhaps 30 feet, and the power needs were small, requiring a 2 horsepower engine.\textsuperscript{291} Even with this spate of building, their numbers were never great: Kanefsky and Robey were able to positively identify 20 Savery engines, and suggested that their total number out of the 2,200 engines of the 18th century was less than 50 (2%). It should be noted that the Savery engines were being pressed into service by the expanding power needs of textile factories.

\textsuperscript{288} Calculated from Kanefsky and Robey, Table 6. 1,480 engines were built between 1780 and 1800; since less than 500 of these were of the Watt type, that leaves nearly 900 machines; allowing for Savery or other type engines still leaves a comfortable majority of the Newcomen type.

\textsuperscript{289} Kanefsky and Robey, Table 2, p. 169.

\textsuperscript{290} Some histories cite the use as a return engine as the end-evolution of the low-pressure atmospheric engine, but Kanefsky and Robey estimate that only 150 to 200 engines were used for this purpose.

\textsuperscript{291} N. von Tunzelmann, p. 48-49.
Table 7-1. 18\textsuperscript{th} Century Engines in Britain, by Industry

<table>
<thead>
<tr>
<th>Industry Group</th>
<th>Up to 1733 (engines)</th>
<th>Up to 1733 (% of Known)</th>
<th>1733 to 1780 (engines)</th>
<th>1733 to 1780 (% of Known)</th>
<th>Total Up to 1780 (engines)</th>
<th>Total Up to 1780 (% of Known)</th>
<th>1781 to 1800 (engines)</th>
<th>1781 to 1800 (% of Known)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalmines</td>
<td>79 85%</td>
<td>376 66%</td>
<td>455 68%</td>
<td>373 26%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Other Mines</td>
<td>10 11%</td>
<td>106 18%</td>
<td>116 17%</td>
<td>120 9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textiles</td>
<td>0 0%</td>
<td>1 0%</td>
<td>1 0%</td>
<td>468 33%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal Working</td>
<td>1 1%</td>
<td>51 9%</td>
<td>52 8%</td>
<td>211 15%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foods</td>
<td>0 0%</td>
<td>5 1%</td>
<td>5 1%</td>
<td>107 8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misc.</td>
<td>3 3%</td>
<td>34 6%</td>
<td>37 6%</td>
<td>130 9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>98</strong></td>
<td><strong>613</strong></td>
<td><strong>711</strong></td>
<td><strong>1,480</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment No data</td>
<td>5</td>
<td>7</td>
<td>12</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-total Known Use</td>
<td>93</td>
<td>573</td>
<td>666</td>
<td>1,409</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Count of engines taken from Kanefsky and Robey “18\textsuperscript{th} Century Steam Engines by Industry, p. 181. Note total for all three periods is 2,191 engines.

The years between 1712 and 1780 were a crucial period of development, during which over 600 Newcomen engines were built. The simple low-pressure technology of the atmospheric engine made it a commercial success in the flooded mines of the coal industry. We can consider this the coalmine as the incubator of the atmospheric engine. In general, Newcomen engines were used to drive water pumps and, for the first few decades of the 18\textsuperscript{th} century, they were limited almost entirely to coal pits.
In their analysis, Kanefsky and Robey noted that, for all known engines in Britain up to 1800, pumping water at mines was the most common use of an engine. The survey the whole century and note that coalmines were important, but not critical, as they were the location of only 38% of all engines. However, looking at the entire 18th century understates the extent to which a coalmine was the destination of most of the earliest engines. The dominance of coalmine-use is shown by examining two key periods: up to 1733, which was the year Savery’s original patent expired, and the period 1733 to 1780. These two periods are prior to any serious competition from the Boulton and Watt engines, which were first used commercially in 1776.

By their reckoning, 98 engines were built up to 1733. Of these, 5 were experimental, leaving 93 engines at work. By far the most common use was pumping not just in mines, but specifically in coalmines: 79 engines (85%) were at work in coalmines. For the period 1734 to 1780, another 633 engines were built. Of these, 66% were in coalmines. This tendency was not due to a lack of imagination or a willingness to try the engine in other applications. It was linked to the marginal energy rent.
The Shifting Border: Feedbacks

These uses for the earliest Newcomen engines show the borderline between organic and mineral energy; between positive and negative energy rents. The very first successful engines were in the collieries. The lack of success in areas like Cornwall reveals that there was a relatively thin margin between success and failure, and that border was determined by fuel prices. As it happened, the border was shifted in favor of positive energy rents by a series of improvements. As a result “only” 66% of the engines erected between 1733 and 1780 were in collieries. These improvements allowed the atmospheric engine to take its first steps out of the coalmines, as the border marking off the applications with negative energy rents receded.

It is true that, during the first crucial decades after 1712, the Newcomen engine had little usefulness outside of the coalmines. However, at these mines, the energy rents from atmospheric engines were satisfactory enough, relative to organic power sources, to result in the building of a hundred engines. This proved to be a sufficient number to allow technological improvements to accumulate. In general, a new technology, once it is established, is able to collect a series of incremental improvements from “learning-by-doing”. Taken together, these improvements lowered both capital and operating costs. While these improvements did not add any new energy source to the operation of the engines, they lowered costs to the extent that projects, which may have been unprofitable given the best practices of 1720, were possible circa 1740.

Capital Costs

The single largest initial expense for an engine was its cylinder. The first cylinders were cast in brass, and could cost as much as all the other engine parts combined. By the 1720, after perhaps 20 engines had been built, experiments began with using cast iron for cylinders. Improved casting techniques with this cheaper material would eventually lower the cost of
engines. The potential savings in capital costs, which were not trivial, were documented in the work of K. H. Rogers. An archivist, he published an analysis of the account book of one Thomas Goldney (1694 - 1768) of Bristol. Goldney acted as an agent for the Coalbrookdale Company, a manufacturer of iron cylinders used for Newcomen engines. Rogers estimated that Goldney alone sold 60 engine cylinders in Southwestern England in just the 22 years between 1744 and 1768. Iron cylinders allowed for a significant savings. Farey, in his *History of the Steam Engine*, cited a bill for an engine cylinder 29 inches in diameter, made of brass, costing 250 pounds in 1727; by contrast, the larger 30-inch cast iron cylinder for an engine at Paulton, Somerset, cost only 49 pounds 15 shillings in 1745, less than one-fifth as much.

Goldney’s account books also provide insights into how the business of erecting an engine was conducted. Rogers notes that most of the parts and plumbing could be done locally; what Goldney shipped to the mines were the specialty parts, those beyond the abilities of localities to produce. Principally, this was the engine’s cylinder and piston, and certain specialty valves. With these key parts, local artisans would, under the guidance of an engineer, erect the machine. As engineers gained experience, they achieved, and usually shared, other improvements such as better seals for the piston, and especially more efficient boilers.

**Operating Costs: The Self-Regulating Machine**

Operating costs were also reduced through practice. For example, the regularized movement of the engine allowed for automatically operating valves. These are clearly shown in the drawing of 1717 by Beighton of the Griff engine (see Figure 6-6). Even if we put aside the greatest technical innovation of Newcomen’s career, which was injecting water directly into the

---

293 Both figures cited in Rogers, p. 11.
294 Rolt and Allen, Chapter 5; improvements in boiler efficiency translated directly into fuel savings.
cylinder to increase the rapidity of the engine’s stroke, his development of self-activating working gear to run the engine would have earned him a niche in the inventors’ hall of fame. In the 21st century, the idea that a machine can use monitor its environment to pace its own operation is obvious. People rarely consider the humble thermostat on the wall, monitoring the air temperature so that it can signal the furnace (or air conditioner) when to operate, and when to stop. In the early 1700’s this concept was unknown.295

The cycle of the engine (described in Chapter 6) requires the opening and closing of a series of valves and stopcocks in a specific sequence. In Newcomen’s original experiments, these would have been operated by hand. By 1717 at the latest, as shown in the Henry Beighton engraving of that year, the engine had self-acting gears.296 Via a series of rods and gears, the movement of the beam, through its up-and-down of the cycle, was made to operate the necessary valves. This simplified the operation (read: reduced the operating costs) of the engine. Alas, the 18th and 19th century historiography of these developments slight Newcomen. Stuart and Farey both attribute the invention of the self-acting gear to Beighton.297

Learning-by-doing also reduced costs as the engine operators experimented with various pressures and number of strokes per minute. Later analysis showed that Newcomen operated his first engines with a relatively high vacuum, reducing the pressure in the cylinder to 9.4 PSI below atmospheric pressure.298 Since the atmospheric pressure is 14.7 PSI, this means he reduced the pressure inside the cylinder to 5.3 PSI. This provided for a more powerful stroke, but increased the time between strokes because it required injecting a greater volume of water into the cylinder to drop the pressure as rapidly as possible. As a result, it required more time

295 George P. Richardson Feedback Thought in Social Science and Systems Theory (Waltham, Massachusetts: Pegasus Communications, System Dynamics Series, 1999), see Chapter 2 on concept of applied feedback.
296 The Barney engraving of 1719, of the 1712 Dudley Castle engine, also shows these self-acting gears.
297 Rolt and Allen, p. 89.
298 See Hills, p. 28-29.
between strokes to heat the cylinder. It was soon discovered that using less of a vacuum, perhaps only 7 or 8 PSI below atmospheric, was more economical. Although it lifted somewhat less with each stroke, the reduced cooling water allowed for more strokes per minute.

**Buoys will be Boys (according to Desaguliers)**

It has already been noted that the scientific writers of the 18th century slighted Newcomen’s contribution to his engine. Their efforts to diminish his achievements in the development of self-acting gear produced a garbled story that, as eventually related by Adam Smith, is as humorous as a Newcomen engine anecdote is likely to get.

Newcomen applied the concept of self-regulation to several parts of the engine’s operation, including the production of steam. The earliest engines were limited in their ability to work due to the inefficient boilers then in use. Even though the steam did not provide propulsive power, the boilers required time to replace the steam drawn-off into the cylinder. If the cooling water were to be injected before sufficient steam was built up in the cylinder, the result would be an insufficient vacuum. This would produce either a weak stroke, or bring the engine to a stop all together. To avoid this problem, Newcomen devised a buoy, contained in a tube protruding from the boiler’s top, which rose as the boiler filled with steam. This buoy governed the valve that permitted cold water from the injector pipe into the cylinder: the shot of cold water was delayed until, as gathering steam in the boiler lifted the buoy, a rod attached to the buoy lifted a catch that released the cold water valve.299 Thus, sufficient steam *had* to be present before the cold-water injector could operate. The engine might operate more slowly, but would not stop.

Newcomen’s ingenious solution, which made the machine draw on information about the state of its boiler to regulate its movements, proved to be only temporarily necessary.

---

299 Rolt and Allen, pp. 93-94.
Eventually, improvements in boilers designed specifically for engines allowed for the production of ample steam, rendering the buoy redundant. However, this series of technical developments in the application of automation gave rise to a popular story, eventually cited by no less an authority than Adam Smith. In discussing how the division of labor leads workmen to improve the operation of their machines, Smith stated:

“In the first fire-engines, a boy was constantly employed to open and shut alternately the communication between the boiler and the cylinder, according as the piston either ascended or descended. One of those boys, who loved to play with his companions, observed that by tying a string from the handle of the valve which opened this communication to another part of the machine, the valve would open and shut without his assistance, and leave him at liberty to divert himself with his playfellows. One of the greatest improvements that has been made upon this machine, since it was first invented, was in this manner the discovery of a boy who wanted to save his own labour.”

It seems that Smith did not invent this story, as an earlier version can be found in Desaguliers. Note that were Smith described the valve as controlling steam from the boiler, in Desaguliers’ version, it correctly states that the valve controlled cold water from the injection pipe; less plausible is Desaguliers’ suggestion that Newcomen had somehow failed to notice that the boiler had twice as much steam as needed:

“They used before to work with a buoy in the cylinder enclosed in a pipe, which buoy rose when the steam was strong, and opened the injection, and made a stroke; thereby they were capable of only giving six, eight or ten strokes in a minute, till a boy, Humphry Potter, who attended the engine, added (what he called scoggan) a catch that the beam Q always opened; and then it would go fifteen or sixteen strokes in a minute.”

Thus, Desaguliers not only denied Newcomen any credit for developing the automatic mechanism, he would have it that the design was so inept that a mere boy was able to greatly

--- Smith, pp. 9-10.
improve upon its operation. Condensed in Desaguliers’ garbled version of events are at least two developments that lowered the operating costs of the machine. First, the advances in automating the machine; second, the improvement in boiler design that provided more steam for more strokes per minute.

**Political Feedback**

Parliament had early on established a tax on mineral coal, which they called “seacoal”.

Seacoal was the expression used in Britain and its colonies to refer to mineral coal. Coal was an excellent source of tax revenue for the crown: Its bulk made it difficult to smuggle; it came from a few concentrated areas, such as Newcastle; and demand for it was in growing throughout Britain. The need for coal meant that even if it were more expensive, it would still be bought. In the early 18th century, this tax was five-shillings and five-pence per cauldron (“5s 5d”).

As more engines were built, they gained acceptance and allies among interest groups. This set in motion political feedback that would reduce the cost of operating these engines. As noted in Chapter 6, both transportation and taxes added to the cost of coal in Cornwall. Although that area had valuable mines with significant flooding problems, the Newcomen engine was virtually unusable in the southwest tip of England due to fuel costs. In 1740, only 3 engines were working in Cornwall. Even these had tenuous commercial existences: “…the engine at

---

301 The origin of the term seacoal is somewhat obscure. On the one hand, it appears to refer to mineral coal that typically arrived at its destination by sea. However, following Nef, the likely explanation is that some of the first coal actually came from the sea, washed ashore from veins off the coast of Northumberland. After the 15th century, at the latest, the term was applied to all mineral coal in England, whether shipped by sea or not. See Nef, Appendix P. The use of the term seacoal makes sense: it would have avoided confusion with charcoal made from wood, which was already commonly referred to as “coal”.


303 Rolt and Allen, p. 108. In brief, there were 12 pennies to one shilling, and 20 shillings to the pound, thus 240 pennies to the pound. The abbreviations of “d” for a penny is said to be based on the Roman denominations of “denarius”.

304 Ibid, pp. 108-109; see also Rogers, 16.
Wheal Rose is said to have been so expensive to run that the adventurers drove a mile-and-a-half adit so that they could discontinue it.”

As early as 1730, acts that would exempt engine fuel from the coal tax were proposed. Finally, in 1741, an act was pushed through Parliament, largely through the political influence of the mine owners in Cornwall, to remove the tax on any coal that was used as a fuel for fire engines. Thoughtfully, they limited this exemption only to engines used in Cornwall.

In an Act of Parliament of 1741:

“An act for granting to His Majesty the sum of one million out of the sinking fund, and for applying other sums therein mentioned, for the service of the year one thousand seven hundred and forty one: and for allowing a drawback of the duties upon coals used in fire engines for draining tin and copper mines in the county of Cornwall: and for appropriating the supplies granted in this session of Parliament: and for making forth duplicates of exchequer bills, lottery tickets, and orders, lost, burnt, or otherwise destroyed: and for giving further time for the payment of duties omitted to be paid for the indentures and contracts of clerks and apprentices.”

The tax had been perhaps 20% of the cost of coal in Cornwall. Its removal, along with the lower capital and operating costs that had been developed since 1710, would appear to have made the use of engines in Cornwall practical. Only 3 engines were operating there in 1740; 20 years later in 1760 there were an estimated 60 steam engines operating in Cornwall. It is not a heroic assumption that the lowering of the cost of coal per cauldron helped to turn the energy rent positive.

**Smeaton and the Chacewater engine**

---

305 Rogers, p. 16; again, the dividing line between negative and positive energy rents.
306 Parliament of Great Britain (London: John Baskett, printer to the King’s most Excellent Majesty, 1741), emphasis added.  
http://books.google.com/books/about/An_act_for_granting_to_His_Majesty_the_s.html?id=WdiHHAACAAJ (accessed March 17, 2012).
By the second half of the 18th century, the existence of hundreds of engines, and their growing importance to at least part of the economy, had the effect of focusing research on improving these engines (again, read: lowering their costs). It was the engineer John Smeaton who took the Newcomen engine to what was probably its peak of possible perfection. Smeaton conducted a series of experiments with a model Newcomen engine, identifying ways of improving its operation. Using insights from his experiments, in 1775 he built an engine with a 72 inch in diameter piston at the Chacewater mine in Cornwall. It is estimated that this engine developed 72 horsepower.\(^{307}\) Perhaps even more impressive than the engine’s sheer size was its efficiency. The earliest Newcomen engines had efficiencies of 0.5% to 0.7%; that is to say, over 99% of the energy burned in the furnace to produce steam was lost in the process. Smeaton’s engine was nearly 1.5% efficient.\(^{308}\) This means that it required less than half the fuel of an earlier Newcomen engine to do an equivalent amount of useful work. This level of efficiency would not be bettered until Watt’s separate condenser was added to the atmospheric engine.

**Mr. Watt’s Wonderful Condenser**

Earlier, it was noted that the historiography of the steam engine passes quickly over Newcomen, and exults James Watt. This was not intended in any way to diminish Watt’s achievements. Born in 1736, not far from Glasgow, Watt became a nautical instrument maker who excelled in fine metal work. In the 1760’s, as Smeaton had, Watt sought ways to improve upon the Newcomen engine by carefully measuring it operation, and he too conducted a series of experiments. Watt focused on determining the latent heat, heat capacity, and losses of heat through conduction. In this way he addressed a great weakness in the design of the earliest engines: a lack of understanding of the relation among fuel, heat, and the engine’s efficiency.

\(^{307}\) Hill, p. 37. The name “Chase-water” speaks for itself.  
\(^{308}\) N. von Tunzelmann, p. 67.
Watt was seeking to reduce to a minimum the amount of fuel required. This was, again, not a theoretical pursuit: he hoped to make considerable profit. With the mental and material thriftiness for which the Scotch are, on occasion, remarked, Watt reasoned that one-cylinder full of steam should be all that was necessary for each stroke of the engine. However his experiments and calculations revealed that for each stroke of work, a Newcomen engine consumed a volume of steam 3 or 4 times greater than the volume of the cylinder. In other words, 3 or 4 times more fuel was consumed than would be in a “perfect” engine. From his observations, he found that the spray of water that condensed the steam also cooled the cylinder; thus additional steam was required to heat it again. His solution, which he hit upon by 1765, was to use a separate condenser to cool the steam back into water, leaving the cylinder hot.\textsuperscript{309} He patented the idea of the separate condenser in 1769, but it took until 1776 to build a successful commercial engine.\textsuperscript{310} This was 11 years after he first conceived the idea, and 64 years after Newcomen’s first commercial success.

With the separate condenser, the atmospheric engine would use perhaps only a third of the fuel to do the same amount of work as the Newcomen engine. Watt’s other improvements, such as capping the top of the engine and using a steam jacket to insulate the cylinder, would eventually lower this to about one-fifth the quantity of coal, again for the same amount of work. It should not be surprising that some of the most eager customers for Boulton-Watt engines were the mine operators in Cornwall, where the expense of coal had held back engines for so long. Among Watt’s first engines was the one at Tingtang, near Redruth (1776), and another at Wheal Busy (1777). By 1800, there were 55 Watt engines in Cornwall.\textsuperscript{311}

\textsuperscript{309} Marsden, pp. 58-59.  
\textsuperscript{310} Hills, pp. 51-53.  
\textsuperscript{311} Marsden, p. 102.
The prize of fuel efficiency was what drove Boulton and Watt. The separate condenser was not a conceptual goal, but a way to save money by reducing fuel consumption, thus increasing the energy rent. In a testament to their understanding of this concept, Boulton and Watt arranged for fuel consumption to directly determine how much they were paid: In return for allowing a business to use an engine of their design, they received a royalty that was based on the fuel savings, over what would have been used in a “standard” Newcomen engine. They were paid $\frac{1}{3}$ of the savings. In a backhanded compliment to Smeaton, Watt made it clear that the “standard” engine was not the improved Smeaton type.\textsuperscript{312}

Watt specifically targeted organic-based prime movers when marketing his engine, seeking to replace horses as prime movers. As part of his marketing strategy, he devised a simple equivalent between his engine and an abstract horse: Watt coined the phrase “horsepower”. He reasoned that an “average” horse might do 22,000 foot-pounds of work per minute for several hours. To show prospective customers that he was more than fair, Watt increased this by 50%, and chose to use 33,000 foot-pounds per horsepower for his engine.\textsuperscript{313} This is still the equivalent of one horsepower.

\textsuperscript{312} Ibid, p. 104.
\textsuperscript{313} McShane and Tarr, p. 3.
Coal Mine as Incubator

Why must my stupid Fancy e’er admire
The way of raising Water up by Fire?
That cursed Engine pump’d my Pockets dry,
And left no Fire to warm my fingers by.

--- The Broken Stock-Jobber: Epilogue by a Loser (1720)\textsuperscript{314}

As the above lament from 1720 relates, the operation of an engine could prove more expensive than it was worth. Significantly, the lament complains that no fuel is left to warm the fingers of the unwary investor. Fuel, again. To properly assess the historical evolution of the steam engine, it is important to consider just how restricted these engines were in their initial applications. The first Newcomen engines were creatures of the coalmines. A common Newcomen engine had a thermal efficiency in the vicinity of 0.75%, with over 99% of the energy lost to waste-heat and friction. It was not at all obvious that such a machine could succeed commercially. The example of the Savery engine is instructive. In retrospect, Savery’s machine was truly propelled by the power of steam. From the vantage point of 300 years later, we might consider this innovation of great importance because of what followed. However, it was even less efficient than the Newcomen engine, while its high-pressure steam made it more difficult, and dangerous, to operate. At the time (1700), perhaps 4 machines were built, and then it fell into disuse. The commercial revolution had its dictates: a task that was not profitable would not be undertaken. Absent the need for a pump at a coalmine, the Newcomen engine may have suffered the same fate of a few test machines, and then disuse.

It had long been known that the heating and cooling of the cylinder for each stroke wasted a great deal of energy. Smeaton and others were working to improve these engines, and

\textsuperscript{314} Quoted from Rolt and Allen, p. 70.
had cut its fuel use in half by 1770. Finally James Watt hit upon the idea of a separate condenser, building the first commercial example in 1776. However, this was more than 60 years after Newcomen’s first successes. It should not be missed that both Smeaton and Watt had model Newcomen engines to work out their theories and improvements. Their generation of engineers had hundreds of examples before them because Newcomen engines had been commercially successful, principally in the collieries.

How obvious was this process at the time? For a contemporary view of the significance of these events, we could do worse than consulting the keenest observer of the British economy in the 18th century, Adam Smith. Bear in mind Mr. Smith was most likely acquainted with his fellow Scotsman and resident of Glasgow, Mr. Watt. Writing in 1776, Smith in his *The Wealth of Nations* mentions “fire engines” only once as part of a general discussion of machinery. He does discuss coalmines, but here his emphasis is their high capital requirements. His silence on the topic suggests that, if he thought about the mechanical engines at all, he did not see the atmospheric engine as having a significant impact.

Watt’s 1776 engine was still an atmospheric fire engine, but its thermal efficiency was four or five times better than Newcomen’s. With this improvement in efficiency, a major threshold had been crossed. The frontier of negative energy rents, which had been slowly receding, suddenly evaporated. The whole realm of productivity was just as suddenly a playground of ripe energy rents. It is little wonder the adventure capitalists of the early 19th century deified Watt.

Where the first Newcomen engine needed the nearly free fuel of a coal pit to be successful, the first Watt engine cost less than an equivalent number of horses, provided the coal

---

315 Smith, 9.
316 Ibid, 263.
317 Marsden, p. 194, notes that a larger than life marble bust of Watt was displayed in Westminster Abby!
did not need to be shipped too far. These lower operating costs threw open the range of potential commercial applications for the atmospheric engine. Of the 496 Boulton and Watt engines, only 164 (33%) were pumping engines, while 308 (62%) were used to drive machinery, mostly in the textile industry.\footnote{Hills, p. 70.}

It is no accident that fossil fuel engines were first economically feasible in a coalmine. It is also not an accident that any meaningful non-pump use of a fire engine had to wait until Watt’s improved engine. It is momentous that among the first “non-pump” engines was one at an iron forge at Wilkinson’s foundry. Coal was now (1776) used to power the blast furnaces that would make more iron more cheaply; this iron could be used to make more (and less expensive) engines; this would expand the demand for coal to run these engines; expanded mining of coal would of course employ more engines, producing a greater volume of coal, which kept its price from rising. Mechanization was out of the nest with the expansion of the Watt engine.

These chapters have focused on the successes of the Newcomen engine. However, the early failures of Newcomen engines also provide insight into how demand for primary power was linked to fuel costs. As already discussed, Newcomen built an engine in Wheal Vor, Breage, Cornwall about 1710, and perhaps a second at about that time, neither of which were successful. It has been speculated that their failure was due to Newcomen having to yet perfect his design. A similar suggestion of technical problems was put forward for the engine Marten Triewald built in Sweden in the late 1720’s. This engine, constructed at the Dannemora iron mine, was also a failure, as the mine operators chose to return to using horses to pump the mine shaft just a few years after the engine was built. In the case study that follows, this engine will be examined in detail to assess the actual causes of its failure.
Part VI: A Newcomen Engine at an Iron Mine: Dannemora, Sweden 1727

In 1727, a short 15 years after the first commercially successful engine began operation, a Newcomen engine was erected in Sweden. The circumstances of this engine are unusually detailed, as its erector, one Marten Triewald, wrote a book in 1734 about fire engines in general and his machine in particular. His text (in Swedish, translated into English in the 1920’s) provided a complete, if biased, overview of his engine. The details known about this engine’s career were greatly enhanced by the research work of Svante Lindqvist (University of Uppsala) in the 1980’s.

The Swedish engine at Dannemora was a failure. Its failure, however, may provide considerable insight as to what made the fire engine successful elsewhere. It will also, not incidentally, elucidate the role of energy in the industrialization process. The nature of mining compelled operators to harness, often literally, successively greater quantities of primary energy. Whether they desired it or not, they were on the frontier of energy using technology.

This case study will be the first of two that examine the building and operation of a wood-fired engine at an iron mine. Both of these engines were cast and operated in a non-British enterprise: One in Sweden, the other in colonial New England. These case studies will be used to explore if coal was a necessary element for the engine to succeed, or if coal was merely the readily exploitable energy source available in Britain.
Chapter 8: Energy Demand at the Dannemora Iron Mine

One of the earliest engines built outside of England was constructed at the Dannemora Iron mines in Sweden. An examination of the career of this engine provides further evidence that fuel availability (cost) was a make-or-break factor in the adoption of mechanical power.

The outline of this engine’s story is easily told.\footnote{See for example Rolt and Allen, pp. 76-78.} By the 1720’s, the iron mines at Dannemora had been having serious difficulties with water for the better part of a century. Their deepest pit, the “Nora Silverberg” shaft, had been shut since 1709 due to flooding. In the late 1720’s a Swedish engineer named Marten Triewald offered to erect a Newcomen-type engine to pump out the deepest shaft. Triewald, by virtue of having assisted in the building of several engines in England over the previous ten years’ time, was among the most experienced engineers in the world. Construction of the Dannemora engine was undertaken in 1727 and it began operating in 1728. Unfortunately, the engine was run only intermittently; by 1731 it was the subject of a lawsuit between Triewald and the mine directors. In 1734, the owners instructed the operators to mothball the engine and resumed pumping at the Nora Silverberg shaft using horse whims.

The story of this engine is known through a book written by Triewald in 1734: \textit{Kort beskrifning, om els- och luft-machin wid Dannemora grufwor} (“A short description of the fire and air machine at Dannemora Mines”). Triewald was not a disinterested observer when he wrote this book. Not only was he the builder, who might be expected to have a paternal inclination toward his creation, he was at that time defending himself against a lawsuit assessing blame for the engine’s failure. As a party to this adversarial legal procedure, he judiciously chose not to dwell on any reasons for the engines shortcomings.
The Swedish text was not translated into English until the 1920’s. In the introduction to that translation, Rhys Jenkins suggested that the likely reason for the failure of the engine was the lack of engineering expertise:

“It was not a success (probably it was difficult to get men competent to work it and to effect repairs as necessity arose) and a few years after the book was published the mine-owners reverted to the use of horse whims for pumping…”\(^{320}\)

Sweden’s mechanics in the 1720’s, so the explanation went, simply lacked the technical sophistication then available in Britain.

Jenkins’ suggestion was taken as fact by subsequent authors until the 1980’s. At that time Svante Lindqvist, of Uppsala University, published his research on Marten Triewald and the introduction of the air-fire engine into Sweden. As part of his doctoral dissertation, Lindqvist undertook extensive research in the records of Swedish mining companies. His work eventually made this material available to non-Swedish scholars (a group, Lindqvist himself readily admitted, that is somewhat larger than the audience of Swedo-phones).

The surviving company records from iron mining at Dannemora are extensive. When Lindqvist was undertaking his research, the mines at which Triewald had worked nearly 300 years earlier were still in business.\(^{321}\) As Lindqvist put it:

“In the company archives of the numerous Swedish ironworks, the accounts have been kept in immaculate order for hundreds of years. It is not uncommon to find shelf after shelf of account books, one volume for each year, in consecutive order from the seventeenth century to the present day… The vouchers, the minutes of board meetings, and the correspondence are likewise kept in good order, and seldom is any volume found to be missing.”\(^{322}\)


\(^{321}\) The mine’s operator, SSAB, subsequently closed Dannemora in 1992; the de-industrialization begun in the last quarter of the 20\textsuperscript{th} century has cast a long shadow.

\(^{322}\) Lindqvist, pp. 246-247.
Lindqvist’s excellent history focused on the social aspects of the technology transfer attempted by Triewald. As part of his research, Lindqvist provided a great deal of data concerning how the mine’s operators had previously dealt with water, as well as details about the engine’s operating characteristics. He used his research to demolish the accepted narrative that it was a lack of technical expertise that rendered the engine untenable. In its place, Lindqvist presented an incisive analysis of the social relations in the Swedish mining industry, and how these factors contributed to the failure of Triewald’s attempted “transfer of technology”.

This current case study will use Lindqvist’s basic data to take the analysis in a different direction. Piecing together a reconstruct of the economics of the engine’s operation, this analysis will focus on the engine’s fuel availability and cost within the context of the iron mine. Lindqvist documented the mine directors growing hostility to the engine. He attributed this hostility to the low social position of the engineers, who were challenging the existing social structure within the mining operation. This analysis will show, however, that an alternate interpretation can be found within the data: the mine managers’ hostility stemmed from the alarming fuel consumption of the machine. These managers then used their social position as a tool to block further development of the engine. In this interpretation, the uncertainty of sufficient fuel being available at a reasonable price was the fundamental reason for the failure of the engine, while their higher social position was the method they used to derail it.
Background on Dannemora

Dannemora is located on the Uppland Peninsular, near Sweden’s coast on the Gulf of Bothnia. It is about 47 kilometers north of Uppsala, which by the year 1700 boasted an established college. The country’s capital of Stockholm is 112 kilometers to the south. Iron had been mined in the area for centuries. In the early seventeenth century, activity was greatly intensified by Dutch businessmen who moved into the Uppland peninsular, bringing know-how and their business organization to Swedish iron making. Swedish bar iron would henceforth be a commodity.

Perhaps 200 people, men and women, worked the mineshafts at Dannemora. The mines made use of prisoners of war, particularly Danish and Russian soldiers captured during the Great Northern War (1700-21). The Danes were exchanged in 1713, but the Russians were not released until the war’s end in 1721. The date of 1721 is significant, as it implies that the repatriation of prisoners would increase the demand for labor at the mines. The operators would need to intensify use of other sources of power: water, wind, horses, and the locally available human labor.

Gender and Mining

At the Dannemora mines, circa the 1720’s, not only were women regularly employed, it would appear that they were worked much the same as male laborers. This may be significant, as it will be seen that this is in contrast to the labor use at the iron mine in Cranston Rhode Island.

323 Note that this is part of the commercialization of commodities. Lindqvist, p. 215.
324 Lindquist, p. 223.
Lindqvist related an incident in 1726 at the mine. It began when the mine operators put into effect a scheme to remove the results of a rock fall in one of the pits by an example of what Marx would later term “primitive accumulation”. Previously, each windlass at the mine had typically been worked by 8 people, their labor raising barrels of rock from the pits. To remove the rock fall, the mine operators set up 2 windlasses to be worked by 11 laborers, but substituted barrels approximately twice as large as the old ones. In response to the heavier labor, over the next three days the 22 workers assigned to the 2 windlasses slowed down work. They protested to the bailiffs, and, in the bailiffs’ later testimony “…became recalcitrant, and with abusive expressions left the windlasses.”

Following the labor practices of the day, all 22 all were eventually rounded up by the mine operators and imprisoned in “the coffin”, the mine’s lock up, which consisted of a pit dug in the ground with a wooden hatch over it. The name and marital status of each of the 22 workers was listed in the official court proceedings: 9 were men working as miners; 5 were solders assigned to the mines; and 8 were women working as miners (2 married women, 2 widows, and 4 unmarried women). The punishments handed down varied. The instigators received 15 strokes with a pair of lashes while suspended in manacles; those who had followed along, refusing to work, were punished with 2 or 3 days in the coffin with nothing by bread and water. The women received the lesser punishments, but it is not clear that this was because of their lesser crimes or gender.

---

326 Lindqvist, p. 224. The incident is recounted from pp. 223-227.
Energy Environment

Unlike England, 18th century Sweden lacked significant coal resources. Their only deposit of coal, in northwest Skane, allowed for only small-time mining. Even if Skane’s coal resources had been extensive, it was located on Sweden’s opposite coast, over 300 miles from Dannemora. For thermal power, Sweden was dependent on wood.

Although Sweden is heavily forested, it would be an anachronistic mistake to project the 21st century’s detailed knowledge of their northern forests onto decision makers of 300 years ago. Fuel, which in 18th century Sweden meant wood fuel, was actually a source of anxiety. “It was a common belief in eighteenth-century Sweden that there would soon be a shortage of timber.”\(^{327}\) The problem was the availability of timber that could be easily cut, dried and transported to the areas where iron blast furnaces operated. Wood fuel equaled charcoal, which equaled iron, the iron that was a significant contributor to Sweden’s political power.

This was not casual worry about an insignificant industry in a marginal kingdom. Sweden in the 17th and 18th centuries was the dominant power in the Baltic Sea area, with provinces extending as far eastward as Estonia and Livonia. In retrospect, the Great Northern War would mark a turning point in Swedish history. During the course of this struggle the coalition of Russia, Denmark, and Saxony succeeded in breaking Sweden’s dominance of the Baltic Sea area.\(^{328}\) Again, none of this was obvious as the 18th century began.

Further, iron was as essential for Sweden’s finances as for their military. In the 18th century, bar iron represented 70% of Sweden’s exports and, for the decision makers in a mercantile economy, maintaining exports was a primary goal. The production of iron, it should

\(^{327}\) Ibid, p. 34.  
\(^{328}\) Lisk, Part VII
be noted, is extremely energy intensive, requiring extensive amounts of wood for charcoal. The kingdom was dependent on iron for export revenue; the steady supply of iron was in turn dependent on wood fuel for their blast furnaces.

This dependence fed an anxiety that there might not be enough wood to sustain Sweden’s financial and military needs. This anxiety about a lack of timber, expressed in the term “skogsodande”, was intimately linked to the kingdom’s most significant export, high quality bar iron. A contemporary observer noted

“…many large areas of the realm are in danger of soon becoming desolate because of the shortage of timber and that the mines and towns in many parts of the country are threatened for the same reason, with a ruin that cannot long be delayed…”

In direct contrast with the coalmines of England, the iron mine at Dannemora did not operate in an energy rich environment. Instead, as commercialization progressed, they would find themselves competing for available fuel supplies. This competition was intensified by the fact that the iron mine at Dannemora was operated independently of the many blast furnaces it supplied, and they all demanded extensive amounts of wood fuel. A sense of the extensive energy demands in the vicinity of the mine can be gleaned from Figure 8-1, which shows Dannemora and 17 ironworks that used its ore.

---

329 See Chapter 11 on Hope Furnace for detailed description of the production of charcoal and iron production.
330 Lindqvist, p. 37. There may be something in the regional character that causes the Swede to dwell on anxiety. The 18th century had its “skogsodande”; one is tempted to draw parallels with anxiety in 20th century Swedish cinema (Bergman) or automobile design (Volvo), but that is outside the purview of this paper.
331 Lindqvist, p. 37, emphasis added.
Figure 8-1. Iron Works Around Dannemora Mine. This map shows the seventeen iron works producing bar iron from Dannemora’s ore. Note each is located along a waterway, as they require waterpower to drive their bellows. Reproduced from Lindqvist, page 216 (yellow highlighted notes added).

Note that the thermal energy from wood is only a portion of the energy inputs needed to process iron. A close inspection of Figure 8-1 reveals that each ironworks is located on a waterway, as sufficient waterpower was essential to the power the bellows that provided the air blasts for each furnace.

In England, coal was a key commercialized commodity; in Sweden, it was bar iron. As a commodity, Swedish iron ore had been subjected to accelerating exploitation under the commercialization described in generic mine model.\textsuperscript{332} As the demands of commercialization drove the mines deeper, it created greater demands for mechanical power. As with coalmines in

\textsuperscript{332} See Chapter 3.
England, so with the iron mines in Sweden: it was no accident that mines producing a
commercialized commodity felt the demand for additional power most keenly.

**Commercialization – Intensification – Flooding**

Dannemora presents, in a microcosm, how the constrained availability of prime movers vexed emerging industries in the 17th century. Operators were driven to ever-greater expenditures to control greater amounts of energy. Beyond just abstract energy, they needed useful work: they needed to control when the power was available (temporal control) and where (spatial control). As elsewhere in the world, these mine directors living in the Uppland Peninsular would try to augment muscle power with waterpower, wind power, and even by reshaping the environment.

Lindqvist documented the evolution of Dannemora’s struggle with flooding. It is recounted here for two reasons: 1) it provides a striking example of the generic model of energy demand in a commercial environment, and 2) the procession of energy types employed will be repeated, albeit on a smaller scale but in greater detail, in the 1770’s at the iron mine in Cranston Rhode Island.\(^{333}\)

In the early eighteenth century Dannemora had the greatest water difficulties of any mine in Sweden.\(^{334}\) Its extensive veins of high quality iron had the misfortune of being located adjacent to a mountain lake, where the mine openings were actually lower than the level of the lake. Water in the mine had been a concern as early as the mid-1600’s. In 1656, the partners operating the mine had left a substantial wall unexcavated, to limit the potential for flooding.

The initial seepage of water into the mines was met with horse power. Horse whisks lifting water out of the mines were employed to keep the water at bay. However, as Agricola had

---

\(^{333}\) See Chapters 11 and 12 below.

\(^{334}\) Lindqvist, p. 229.
noted over one hundred years earlier, dealing with any serious incursion of water requires more power than can be conveniently provided by horses. Grappling with these needs prompted the mine’s directors to seek greater primary power. In 1680, they commissioned Olof Hidersson Trygg (1629 – 1699) to supervise the building of a waterwheel. The mill wheel was 10 meters in diameter and cost 10,000 copperdaler to construct.

Unfortunately, the operators could not take full advantage of the wheel’s power. The stream was not convenient to the mine mouth, but was 1.5 kilometers away. To transfer the power to the mine, the operators constructed a stangenkunst. The stangenkunst, which is a series of poles connected by pivots, represented an early attempt to expand the spatial flexibility of waterpower as a primary energy source. The pivots mechanically transferred power from the wheel to the mine. This system was, of course, subject to extensive power losses through friction, and so it is perhaps not surprising that the waterwheel proved to have insufficient power to drain the mines.

The following decade, the mine operators turned to wind power as a prime mover. In 1691-1692, at the cost of 9,000 copperdaler, they constructed a windmill to augment the efforts of the horses and the waterwheel. This proved a yet another disappointment. The intermittent nature of wind power – that is, the lack of temporal control over when it may be used – resulted in a mismatch between when the power was needed, and when it was available.

---

335 Agricola, page 195.
336 Lindqvist, p. 230
337 See Reynolds *Stronger Than a Hundred Men*, pp. 118-19
Figure 8-2. Overhead View of Main Works at Dannemora. The pits shown here are north and east of “Silverberg” shafts (Silverberg shafts, not shown, are to left and down slightly from this view). Compare position of the windmill in Elias Martin’s landscape painting of 60 years later. Note the circles along the pits, which represent horse whims. Reproduced from Lindqvist, page 228, with highlighted titles added for clarity.
Figure 8-3. “Dannemora” watercolor by landscape painter Elias Martin, after 1780. Note windmill to left and tubs for ore. The “Silverberg” pits, with Triewald’s engine house, would be in the background of this scene, off to the left.
By the late 1690’s, the directors decided on the extreme step of altering the environment in an effort to cut off the source of water flooding the mines. In 1697, at the tremendous expense of 30,000 copperdaler, a dam was completed between the lake and the minesshafts. “It consisted of piles driven to a depth of 4 ½ meters and faced on the lake ward side with planking and compacted clay.”

At long last, the mine was dry, but alas only for a short time. Initially the digging was pursued with renewed vigor, but as a result, a direct result, the water problem was not long in returning. In 1709 the deepest mine shaft, known as the Norra Silverberg Mine, had to be abandoned due to the difficulty of keeping it clear of water.

Figure 8-4. Overhead view of “Silverberg” shafts at Dannemora. “Nora Silverberg” shaft is at right, marked “Z”. Note the circles along the pits, which represent horse whims. Reproduced from Lindqvist, page 230, notation added.

The recurring problem of flooding in the mineshafts at Dannemora is an eloquent exposition of the feedback that spirals between

1) Success in removing water from a mine, followed by

2) Intensified digging, resulting in

3) An even more severe flooding problem.

With the limited primary energy sources available in an organically powered industry, the “flooding-pumping-increased flooding” spiral does not take too long to reach equilibrium. In the case of Dannemora’s deepest shaft, it was only 12 years from a radical altering of the landscape, via a dam in 1697, to a steady-state equilibrium in 1709. Unfortunately for the mine operators, the stable equilibrium was reached when the pit was flooded beyond hope.

Figure 8-5. Profile of “Silverberg” shafts at Dannemora. “Nora Silverberg” shaft is at far right, marked “Z”; note also the shading, indicating that it is flooded (a stable, if unwelcomed, equilibrium). Original map by Olaf Trygg in 1721, reproduced from Lindqvist, page 231.
Marten Triewald’s Engine

Marten Triewald was born in 1691 into a family of German immigrants to Sweden. His father was successful blacksmith, what Thomas Newcomen might have called an ironmonger. In 1716, at the age of 25, Triewald traveled to England and, while in London, attended lectures given by the scientist J.T. Desaguliers. In 1717-18, he had the opportunity to assist young Samuel Calley, the 17 year-old son of Newcomen’s partner, in the building of the first engine at the Byker coal pit at Newcastle on Tyne.\(^{340}\)

Between 1717 and 1723 Triewald assisted in the building of as many as four engines at the collieries around Newcastle. He was acquainted with both Newcomen and Calley, and his 1734 text *Kort beskrifning, om eld- och luft-machin wid Dannemora grufwor* contains an account of the development of the engine that Triewald quite possibly heard from Newcomen himself. Although Triewald had learned from Newcomen’s work, he considered himself, as a scientist, superior to the inventor. Triewald had been trained at the University of Uppsala and would later be a member of the Royal Society. In his 1734 book, Triewald was one of the earliest contributors to what would become the standard 19\(^{th}\) century historiography that it was not Newcomen but scientists such as himself and later Watt that were the true fountainheads of steam power. He entitled a section of his 1734 book “How foolishly those behave who attempt to create artifices without a true knowledge of mechanics and its laws.”\(^{341}\) In contrast to Newcomen’s ignorance of the machine’s operating principles, Triewald immodestly stated “…I, however, as soon as I saw the machine at work, conceived a more complete theory of it than the

\(^{340}\) See Rolt and Allen, Appendix; this was one of the first dozen engines built in the world. Triewald described young Calley as “…a quick youth, 16 years of age.” (Introduction, § 7). Note that Triewald’s book is divided into two parts, an introduction followed by a discussion “Concerning the Power” of the engine; these two are broken into subsections, each designated with a “§”, using a sequential number Triewald’s original listing of sections is used here references.

\(^{341}\) Triewald, “III The Usefulness”, § 44.
inventors themselves possessed down to the very moment of their death.”\footnote{Triewald, Introduction, § 9.} This storyline would be continued by Triewald’s English friend and correspondent, Dr. Desaguliers. During in the 19\textsuperscript{th} century, this interpretation of events would become the dominant narrative of the invention of steam engine, rendering Newcomen an obscure figure until the 20\textsuperscript{th} century.\footnote{See for example Farey’s \textit{A Treatise on the Steam Engine} (1827). It is significant, as noted, that most of the Newcomen engines documented today were unknown 100 years ago.} 

Triewald’s high opinion of himself was not completely unfounded. With the combined benefit of his family training as a blacksmith and his experience on four engines, Triewald would have been one of the world’s few engine experts in the mid-1720’s. In 1726 he carried his engineering expertise back to Sweden, where he was keen to apply what he had learned in England. He sought a suitable project, and settled on the Dannemora mine. This was a sensible choice, ripe with opportunities for an ambitious young man seeking entry into royal scientific circles: the mine’s difficulties with water were well known; the waterpower available for pumping was known to be insufficient; and the mine was producing a strategically important commodity. This commodity was essential to the local blast furnaces as an input, just as the bar iron produced from it was essential to the kingdom as an export. Triewald was 35 and the opportunity to secure his place both professionally and socially was in his grasp.

**Building the Engine**

Triewald did not shrink from the challenge. In 1726, he proposed to the Partners in the Dannemora Mines to build a fire and air machine (“\textit{eld- och luft-machin}”) to pump out their deepest pit, the 67-meter-deep Norra Silverberg mine, which had been filled with water since 1709.\footnote{Lindqvist, p. 231.} He estimated the construction would cost 24,000 copperdaler, or about two-and-one-half times the cost of the waterwheel. As to operating expenses, he estimated 200 copperdaler
for annual repairs and 600 for an operator. Triewald hired as his assistant Olof Hultberg, a student of mechanics who had studied at the University of Uppsala.\(^{345}\)

Not unlike contractors since then, Triewald’s estimate of construction costs proved to be only about half their ultimate total. As we shall see, this cost overrun for a novel technology was not wholly unexpected by the mine’s directors. Where he went furthest astray however was in his estimate of the fuel required. For fuel, he projected the engine would burn only 300 stafrum of wood annually (about 480 cords).\(^{346}\) Note that a stafrum equates to a little less than 6 cubic meters, or about 1.6 cords of wood. Elsewhere, Lindqvist cited documentation that stated a stafrum of wood suitable for the boiler would cost 3 copperdaler each, meaning Triewald had projected 900 copperdaler annually for fuel.\(^{347}\) At 900 copperdaler, fuel would cost only a little more than operations and repairs.

Construction of the engine was to begin in the spring of 1727, and it was expected to be in operation later that year. In the event, the project was subject to delays, the most significant of which was due to problems with the cast iron cylinder. Triewald had contracted for the engine’s cylinder to be cast in England. However cast iron cylinders were still relatively new in 1727, and the size of Triewald’s, at 36 inches in diameter, posed a challenge.\(^{348}\) The first two castings failed, and by the time a successful third casting was ready in November it was too late in the year to ship it safely to from England to Stockholm.\(^{349}\)

For a cylinder, Triewald turned to the Royal Gun Foundry in Stockholm. In early 1728, they were able to produce a 36-inch in diameter cylinder of brass. Note the similarity between

---

\(^{345}\) Lindqvist, pp. 251-252.

\(^{346}\) A stafrum was a cubic stack of wood that was 3 Swedish ells per side; Lindqvist notes there is some local variation, with a stafrum equalling “approximately 6 cubic meters” (note 9, p 356). An ell is 0.6 meters, and so a stack 3 ells on the side would be 5.7 cubic meters.

\(^{347}\) Triewald quotes 3 copperdaler per stafrum in 1733 or 1734; this was several years later, but we can assume the price was about the same in 1727. Quoted in Lindqvist, p. 296.

\(^{348}\) The cast iron cylinder would have cost a fraction of the brass.

\(^{349}\) Lindqvist, p. 254. Lindqvist noted the difficulties posed by the Swedish winter.
the skills needed for casting cannon, and those for casting an engine cylinder.\textsuperscript{350} The cylinder was made of 100 parts copper to 10 parts tin (“gun metal”).\textsuperscript{351} The engine’s cylinder was 36 inches in diameter by 9 feet long. The engine house, which is still existent, is two and a half stories high. The original large semi-circular opening for the boiler has been filled in, but is still readily discernable.\textsuperscript{352} The boiler to produce steam and other large parts were produced in Sweden, but certain special parts of the engine were shipped from England. These arrived at Stockholm in September of 1727 aboard the \textit{Elizabeth}.\textsuperscript{353}

Hints about the relative scarcity of hardwoods, such as oak, are revealed in the details of the engine’s construction. The heavy rocking lever that transmitted the engine’s down-stroke to the pumps was not made of oak but rather a composite of pine and oak. Instead of a single log\textsuperscript{354}, the beam was made up of six pine logs for most of its length; only the curved quadrants on the ends were made of oak.

“The great beam, 30 feet long, made of 6 pine-balks, firmly joined together, with their quadrants of oak; on one of the said quadrants within the house is a strong iron-chain 4 inches thick, on which the piston-rod is hooked fast.”\textsuperscript{355}

The substitution of the softer pine for oak suggests that hardwood was pricey enough to cause the builders to avoid it where possible. When used as a fuel, hardwoods have approximately twice the energy content of softwoods such as pine; we will have cause to return to the lesser energy in a given volume of pine timber below.

\textsuperscript{350} This foreshadows how the Brown’s ability to cast a cylinder in 1783 was based on the experience they had gained casting cannon for the Revolution.

\textsuperscript{351} Rolt and Allen, p. 76.

\textsuperscript{352} In his masterful analysis of this building, Lindqvist “reads” this artifact as if it were a text; Chapter 12.

\textsuperscript{353} Lindqvist displayed a photo of the bill of landing, Figure 13.1, p. 254.

\textsuperscript{354} A “single massive oak timber” was described as typical by Rolt and Allen, p. 97. Alternatively, two such beams joined together, p. 97. Two joined oak beams were used in the case of the Brown engine in Rhode Island.

\textsuperscript{355} Triewald, item “h.h.” in his “Explanation and Interpretation of the Copper Plate”.
Outline of the Engine’s Operation

The engine first ran on July 4th, 1728. Triewald, never one to miss an opportunity to ingratiate himself to royalty, had selected this date, as it was the name day of Queen Ulrika Eleonora.\textsuperscript{356} Details about the actual operations of the engine are sketchy, but a time line can be reconstructed. From July 1728, the engine ran but was subject to problems, the principal of which was inadequate cooling water. The injection pipe leaked, as did the cold-water tank that supplied it. As a result, steam in the cylinder would not always condense properly, causing the engine to stop. Further, there were problems with the pumps in the mines. Triewald had originally specified iron pumps, but the ones employed were of elm wood; as a result, the pressure from the great depth of the mine caused the pumps to fracture and then split, resulting in further delay.

Although the engine first ran on July 4\textsuperscript{th}, 1728, by the fall it was idled awaiting improved pumps for the deep shaft. In the spring of 1729, the improved pumps allowed work to resume, but the problems with the water tank persisted, and the engine only ran intermittently. By the fall of 1729, it was decided to sheath the tank in lead.\textsuperscript{357} Finally, in October 1729, Hultberg was able to keep the machine running at the rate of 18 strokes per minute, a much brisker pace than the 10 to 12 strokes typical for a Newcomen engine. This suggests a relatively efficient boiler was in use. By late November 1729, the engine had been able to remove all but 3 fathoms of water from the deepest pit, but then stopped again and did not start for several weeks.\textsuperscript{358}

As of March of 1730, it had been 20 months since the engine had first run, but it had not shown itself able to drain the mine. The second half of 1728 had been spent working out

\textsuperscript{356} Lindqvist, p. 257.
\textsuperscript{357} Decided at a meeting of the Mine Partners, September 15-17, 1729. Cited in Lindqvist, p. 263.
\textsuperscript{358} Ibid, pp. 266-67.
engineering weaknesses, but even in 1729 it apparently ran only a few months to any good purpose. During much of this time, Triewald had been away from Dannemora, leaving the work to Hultberg. Unfortunately, the relations between Hultberg and the mine operators, particularly mine Bailiff Thomas Kroger, had been deteriorating. At some unspecified point during the winter of 1729-30, Hultberg quit for good.359

In March of 1730, under the direction of Mine Inspector Bellander, both the partners operating the mine and Triewald were summoned to a meeting to determine what was to be done going forward with the engine. Triewald, sensing trouble, declined to attend. Instead of preparing for the 1730 mining campaign, he and the Partners exchanged a series of letters trading accusations for the delays, cost over-runs, and failure of the engine to have yet drained the mine. From testimony that would follow, it appears that the engine did not run at all in 1730.360

A hearing was convened in September of 1731 to hear testimony from the Partners and Triewald. The Partners claimed to have spent 52,254 copperdaler, a little more than twice the original estimate, but the pit was not yet drained. Triewald countered that many of the delays, such as the problem with the pumps, had been beyond his control. These had idled his engine for many months. He stated that the engine had shown itself capable of draining the mine, having once run for 5 straight days, lowering the water from 27 or 28 fathoms to 5.361

In September 1731, the Board of Mines handed down a judgment in favor of the Partners, and ordered Triewald to repay them the cost of the engine. They cited the engine’s unreliable operation as the cause of the failure. The inescapable fact was that, in the four years since the

359 The exact departure date is uncertain, but Hultberg was already working in Stockholm in early 1730; see Lindqvist, p. 308.
361 Lindqvist’s review of the Hearing’s proceedings; pp. 273 to 278.
agreement had been signed, the engine had failed to actually drain the mine, as Triewald had originally proposed.\textsuperscript{362}

**The 1734 Test of the Engine**

Early in 1734 the Swedish Board of Mines (an advisory group) suggested to the Partners who ran the Dannemora mine to make another attempt at trying the engine. The Partners countered that the engine “…would be sure to prove as unreliable as before and would only cost them large sums for wood fuel unnecessarily.”\textsuperscript{363} Note that the operators based their refusal specifically because of the “large sums for wood fuel”.

Eventually the Partners conceded to a test. Triewald ran the machine for two weeks, May 17\textsuperscript{th} to the 30\textsuperscript{th}, 1734. During this trial, it ran a total of 185.25 hours in 14 days; its longest run was 5.5 days, the shortest just 3 hours. It was able to lower the water 15.5 meters (26 Swedish ells).\textsuperscript{364} For its fuel, the engine consumed 69 *stafrum* of wood, for an average of 8.9 *stafrum* per 24-hour day.\textsuperscript{365}

The test in May of 1734 marked the last time the engine was ever run. The Board of Mine Directors suggested further tests, but neither side was interested. Triewald, his name made as a scientist, had other projects; the Partners operating the mine petitioned for permission to dismantle engine. In the event, the Operators set up horse whims again at Nora Silverberg mine, and began pumping on May 12, 1736. The slowness of this process is demonstrated in their progress: three months later on August 18, there was still 10 meters of water the mine. It was not emptied until November 11\textsuperscript{th} fully six-months after pumping began.\textsuperscript{366}

\begin{footnotes}
\item[362] See Lindqvist pp. 273-279; footnote 14 from Chapter 14 dates the decision as of September 28, 1731.
\item[363] From a mine report in 1733; see Lindqvist, pp 279-80.
\item[364] Note that the Swedish ell is equal to 0.58 meters.
\item[365] Lindqvist, pp. 280-1.
\item[366] Ibid, p. 283.
\end{footnotes}
Chapter 9: Energy’s Role in the Failure at Dannemora

Having recounted the engine’s history of operation, we can now examine the reasons for its failure. Lindqvist’s analysis will be summarized and critiqued, and then the issue of fuel and its cost will be examined for its complicity in the failure.

Lindqvist’s Analysis

Lindqvist began by demolishing the “lack of engineering expertise in Sweden” argument, as suggested by Rhys Jenkins. He traced the history of this interpretation, showing that it was based on earlier Swedish sources that were biased and unreliable. The factor Lindqvist returns to throughout his text is that of the social context of 18th century Sweden (see especially chapters 5, 7 and 11). He sees the history at Dannemora as a cautionary tale that a transfer of technology will not succeed unless it fits with the social structure of its new environment. In contrast to these chapters, Lindqvist makes only scattered references to the role of fuel costs as a factor in the engine’s failure. For Lindqvist, “The average official in the Board of Mines in the period 1715-1736 is the central character in this study.”

Lindqvist, in his summation, reviewed five factors that he believed contributed to the engine’s failure:

- Technical (technical expertise, level of technology)
- Geographical (climate, natural resources, strained natural resources of wood)
- Economic (external financial backing, reproducing cost effectiveness)
- Social (adaptation to the existing social order, integration of the immigrant mechanics)
- Cultural factors (utilitarian ideas, place of the scientist)

Technical

---

368 Lindqvist discusses fuel as a subset of the economic difficulties of the engine, see page 296; he mentions the link between the Newcomen engine and coal on pages 114, 166, and 171.
369 In addition to Triewald himself; Lindqvist, p. 100.
370 Ibid, chapter 15.
In Lindqvist’s view, the technical problems stemmed from the engine’s large size. He states that, at 36 inches in diameter, it was at that time the largest in the world, 90% larger than typical engines in England. As a result, Lindqvist believes the injection pipe was undersized, and perhaps the boiler as well. Lindqvist points to Triewald’s ego, and his desire to build the largest engine in the world, as the source of trouble.\(^{371}\)

**Geographic**

Lindqvist noted how the cold climate contributed to the difficulties of erecting the engine. For example, the cylinder could not be shipped from England after September, as it was deemed too late in the year to safely traverse the North Sea and into the Baltic. Also under “geographic” Lindqvist noted the constraints on natural resources (wood). The harsh climate certainly contributed to the operational difficulties.

**Economic**

Lindqvist does not dwell on the cost of operating the engine. He notes cost effectiveness was an issue, but devoted only a page to this (p. 295). He believed the greatest economic difficulty for the engine was the lack of external financial backing. The financing of the engine came from the operators of the mine, who were not the owners. Unlike an owner, the operators had a much shorter time frame for results. They were not interested in long-term benefits, but were required to produce ore promptly for the dependent furnaces. As a result, the engine had only a short period to prove itself. I believe there is much more to this economic analysis, and will expand on it after reviewing the Lindqvist’s social and cultural factors.

**Social organization**

\(^{371}\) Ibid, pp. 263-64; see also p. 294.
In his analysis of the mine’s ownership structure, Lindqvist detailed the how the arrangements of the mines’ production reflected contemporary Swedish society, and how that structure impacted decision makers at different levels. As organized, the mine supplied ore to the blast furnaces on what was essentially a time-share basis. The quantity of ore a blast furnace received was dependent on the activity at the mine during the weeks it was producing for them. A blast furnace’s specific weeks had been contractually determined well in advance. As a result, any disruption of the mine’s production, even if temporary, could be disastrous to an individual blast furnace. This made decision makers sensitive to prompt production of ore, rather than overall annual production. If, for example, the mine’s output was curtailed because the lone-engine was off-line undergoing repairs during certain weeks, any blast furnace dependent on production during those weeks would suffer the full loss.

In contrast to the all-or-nothing work done by the engine, horse whims provided a diversified and steady, if weaker, power source. The failure of any one whim would not halt all work at the mine while it was being repaired. Overall production might be lower, but no single individual would see a total loss.

Cultural

The social and cultural problems of technology transfer occupied the greater part of Lindqvist’s analysis. Culturally, the mining industry in Sweden was hierarchically based. A clear power structure placed the aristocratic owners at the top, and the laboring peasants who dug and lifted the ore, and cut the wood, at the bottom. In between were the directors, bailiffs, and technical experts who had been retained by the nobility for the task of operating the mines. Lindqvist believed the fundamental problem that undermined the engine’s potential was that not only Triewald, but especially his assistant Hultberg, were outside of this structure. As a result,
they drew the hostility of the middle group, the managers. In trying to introduce the new technology, so this explanation goes, Triewald ran afoul of the established order, the members of which then effectively blocked him out.

For Lindqvist, the principal villain of the piece was mine Bailiff Thomas Kroger. In his position as Bailiff, Kroger wrote a series of reports on the engine’s progress. Lindqvist depicts Kroger’s hostility as emerging shortly after construction of the engine began, and increasing until the engine was dismantled and stored away. Lindqvist goes so far as to project Kroger’s emotions when he was granted permission to dismantle and store away the machine:

“It was no doubt with great satisfaction that Mine Bailiff Kroger obeyed his orders. (in March of 1736)… to close the door on the hated machine for he last time and symbolically turn the key on the new technology.”

**Fuel Costs as the Fatal Flaw**

Lindqvist makes some excellent points regarding the difficult climate, the awkward ownership structure, and the cultural challenges inherent in technology transfer. However, as further analysis will show, fuel costs were perhaps at the root of these difficulties.

*Technical Factors*

Lindqvist faulted Triewald for wanting to build the largest engine in the world. He saw this expression of Triewald’s ego as a serious mistake because “…one cannot increase just one parameter of a technological system without being confronted with a series of difficulties.”

Lindqvist states that the 36-inch cylinder was 90% larger than the typical engine in England; he

---

372 Lindqvist, p. 282.
373 Ibid, p. 292; emphasis in original.
suggested that if Triewald had built an “average” engine, he would have had a better chance of success.

Triewald’s ego is clearly shown in his writing, but the “technical-problem” argument is weakened when one considers not the average engine in England, but the several with which Triewald was specifically involved. For example, the second engine at Byker Colliery in Newcastle, erected in 1722, was 33 inches in diameter by 9-feet long; Rolt and Allen note that Triewald was involved with the engine, and the actual builders were possibly himself and young Samuel Calley. The Dannemora engine, at 36 inches and 9-feet long, engine would be less than 10% larger than this engine.

The “technical-factors” argument is further weakened by the details of improvements in the engines operation. Recall that by the fall of 1729, Hultberg was able to keep the machine running at the rate of 18 strokes per minute. Since this is more than the 12 strokes typical for a Newcomen engine, the boiler and injection pipe must have been of more than sufficient size.

Granted, perhaps these problems would have been resolved more quickly for a smaller engine, and the technical trials and tribulations chronicled by Lindqvist certainly must have been exasperating for the mine operators. However these difficulties were hardly unusual for a process so ground breaking. Significantly, the Mining Board’s published comments suggest that they had anticipated difficulties and cost overruns, as should be expected of any novel engineering project. As part of their rulings in the lawsuit between Triewald and the Operators, the Board decision implied that allowances needed to be made for these unanticipated difficulties: while they did find against Triewald for failing to keep the engine running, the Board excused him for the cost overruns. In their findings, they stated that

---

374 Rolt and Allen, p. 148, note that while the builder is not definite, Triewald offered to build the engine and had an agreement to split the profits with the other partners. Triewald (1734) discussed this engine, Introduction, § 10.
“It is not unusual that on building works, cost often exceed estimates, which is all the more to be pardoned in moving machinery, as one cannot foresee all the difficulties encountered.”\textsuperscript{375}

In other words, they were not overly concerned about sunk costs; it was the ongoing operation that was the area of contention.

**Kroger’s Hostility: Cultural Factors or Fuel Costs?**

Lindqvist characterized Bailiff Kroger as unrelentingly hostile to the engine. However, an examination of the timeline of his reports suggests that it was rather the engine’s alarming fuel use that was the source of his contempt for the machine. Interpreted this way, social hierarchy was not the source of his hostility, but a tool Kroger used to strengthen his hand in opposing further use of the engine.

Relations between Kroger and Hultberg did deteriorate, as Lindqvist’s scholarship relates, until they ultimately exchanged charges at a mine board hearing in September of 1729. However, their relationship had not always been so poisoned. Lindqvist noted of Bailiff Kroger “At first his reports were neutral in tone…”. Kroger’s neutral comments were in a report from June of 1728:

“\textquote{And as far as Directeur Triewald’s engine is concerned, work proceeds with it daily, and it is intended to be ready except for the hoisting machine for the nex (sic) Court of Mines. He had some trouble this week with the tank or water cistern, as this had not been made watertight as he desired, but this difficulty has finally been overcome so that the tank and boiler are now full of water.\textquote{}}\textsuperscript{376}”

Note that this was the month before the engine was first run on July 4\textsuperscript{th}, 1728. In other words, although the engine was nine months behind Triewald’s original schedule, and was already subject to higher than expected construction costs, none of these factors prompted a negative

\textsuperscript{375} Lindqvist, p. 278.

\textsuperscript{376} Lindqvist’s and Kroger’s quotes are both from Lindqvist, p.257.
report from Kroger. Kroger and his predecessors had earlier overseen the construction of a windmill, watermills, and a major dam. As a by-product of these innovations, they had probably seen their share of the inevitable project delays and cost overruns. The neutral June report also speaks to the social relations: by the time of this report, Kroger had been working with Hultberg for over a year. The neutral report suggests that he had been taking the young engineer’s social status in stride.

Kroger’s first overtly negative report comes in August of 1728, the month after the machine’s trials had begun. In this report, he refers directly to the quantity of wood that is being consumed by the machine. Kroger stated that the machine used 10 stafrum of wood per day, and that “…it has already wasted 57 stafrum of wood.” He complained that the cost of the wood used by the engine was “no little loss for the company”.377 The timing, and his specific mention of fuel, suggests Kroger’s “hostility” to the engine grew out of his concrete concern for the expense of its fuel consumption, not some abstract notion of social position.

Fuel Use per Day

Climate, organizational structure, and technical difficulties: all these worked against the engine’s success. However the fatal flaw was its operating cost, and the bulk of this cost was fuel. To run for a full year, the engine would have needed roughly 6-times more fuel than Triewald’s original estimate of 300 stafrum.

Triewald’s Estimate

Lindqvist does not speculate about how Triewald could have been so far off in his original estimate of fuel requirements, but several factors may have been involved. In his 1734

---

book about the engine, Triewald shows a lack of understanding regarding fuel requirements. In a parenthetical explanation, he states:

“(However big may be the difference in power between 24, 25, 26, 28, 33 and 36 inches cylinders, the cost of keeping these very different machines going will, as far as wood is concerned, be found to be almost the same, for I have found the machine in Hungary, which is only half the size of that at Dannemora, consumes almost the same amount of wood).”

It is possible that Triewald is deliberately inaccurate in an attempt to support his claims for Dannemora, but it is also possibly that he simply lacked the tools to estimate the fuel required. His error in understanding the additional fuel required was essentially the same mistake made by John Stewart in the 1760’s in his proposal to use extra steam from the sugar boilers in Jamaica. Rolt and Allen noted that early Newcomen engineers were “…men, who were quite ignorant of the nature of steam or the laws of thermodynamics…” Little wonder, as the first statements of thermodynamics were over 100 years in the future.

We can gain some insight into Triewald’s conception of the fuel required to produce steam via his comments on Newcomen. When a 33-inch engine had been proposed, Newcomen and Calley believed it impractical because “…so large a cylinder could not be supplied with sufficient steam.” Triewald believed them mistaken:

“The cause of this (Newcomen’s) conclusion was the false principles concerning the steam which the inventors harboured in their minds, thinking that the steam rises from or is generated by the boiling water in proportion to the quantities of water. In consequence of these false principles they made their boilers very high, as can be easily seen from the Stafford machine, the boiler of which they made of greater height than width, thus not knowing that they should give the boiler a suitable shape. Neither did they then possess the knowledge of the great importance of letting the fire play all around the sides as well as at the bottom of the boiler- not to mention

378 Triewald, “III The Usefulness” § 28.
379 Rolt and Allen, p. 89.
380 Ibid, p. 90.
many other improvements which a sound theory concerning the fire-machine seems to suggest and demand.”

In other words, Triewald believed that Newcomen’s boilers, being taller than they were wide, were inefficient. In this he was correct. He also believed that by selecting the optimum boiler shape, the quantity of steam from a given quantity of fuel could be greatly increased. In this he was also quite right: Over the course of the 18th century, empirical trial and error would do much to improve efficiency of Newcomen engines, roughly doubling the efficiency (halving the fuel requirements) by the 1760’s. Much of this gain came from improvements in boiler shape. Where Triewald went astray was in overestimating his own ability to improve the efficiency, circa 1728.

In addition to his expectation that he could greatly improve steam production, Triewald’s lack of concern for fuel may have been reinforced by his experience with the engines that he had built and operated in England. These engines had, of course, been fueled using coal. His error may have been one of confounding volume with heat content. Apparently, Triewald did not have any prior experience with wood-fired engines. It is unclear to what extent Triewald’s estimate allowed for the differing heat content between coal and wood. From the vantage point of the 21st century, we know with certainty that a given volume of coal has roughly 3 and a half times the heat content of hard wood, but it is not clear what Triewald’s understanding may have been.

The heat content of coal vs. hard wood may only have been part of the uncertainty. It is possible that the wood supplied to the boiler at Dannemora may have been softwood pine, rather

381 Triewald, Introduction, § 10.
382 For example the characteristic “haystack” boiler would be developed.
than hard wood. Recall that the rocker-beam of the engine had been constructed of a composite of pine and oak, with the stronger oak used only for the ends. This suggests that the wood fuel supplied to Dannemora may have been less expensive soft wood, such as pine. This is only speculation, but as noted above, the design of early atmospheric engines was hampered by just this difficulty in understanding heat content. If softwood had been used, it would have further increased the volume of wood required, as pine has only half the heat content of oak.

By the Numbers

We have sufficient detail about the engine to cross check its fuel use. A Newcomen engine 36 inches in diameter with a cylinder 9 feet long would have developed something between 14 and 19 horsepower. What volume of fuel would it require? That would depend on the type of fuel (hardwood or softwood), and how efficiently it converted the wood energy consumed by its boiler. At that time, the 1730’s, the efficiency of Newcomen engines would have been in the 0.6% to 0.8% range. In other words, less than one percent of the energy consumed at the firebox was converted to useful lifting power.

For pine wood fuel, at the rate of 6 stafrum (approximately 9.5 cords) of wood per day, the engine’s efficiency would have been in the 0.5% to 0.7% range. This would be typical for a Newcomen engine, although at the lower end of the range. At the higher consumption rate of 8.9

---

383 Only the contact points of the beam were hardwood, the bulk of it being made up of soft wood.
384 It may only be a coincidence, but the heat content differential between a cubic foot of coal and one of pinewood is sufficient to explain the error in Triewald’s estimate of 300 stafrum of wood per year. In heat content terms, the equivalence of 1 bushel of coal, to 3 of oak, to 6 of pine could explain the difference. Where 1 volume of coal per day would provide sufficient steam, 6 units of pine would be needed. Triewald’s original 1727 estimate, made before he built the wood-fired engine, was 300 stafrum, the equivalent of 1 per day for 300 days. Experience would prompt him to revise this figure to 6 per day in his estimate of 1733, after he had worked with the engine. Further research is needed to clarify the type of wood used at Dannemora, to see if this 1-to-6 ratio has any significance.
385 This assumes the 36-inch piston had a working power stroke of 6 or 7 feet at the rate of 10 to 12 strokes per minute.
386 Newcomen engines would achieve an efficiency of greater that 1.5%, but that was not until the time of Smeaton, in the 1770’s.
stafrum, the efficiency would have been less, on the level of 0.4% to 0.5%. This would be a quite poor efficiency, but given that the engine had not run for some time, not unexpected. Triewald would have been justified in expecting he could reduce this to the 6 stafrum of his estimate.

Cost of Operation

From the engine’s operating history, we can tease out several citations that provide details about its fuel use and efficiency. Kroger stated that the engine used 10 stafrum per day. This was during the first month of operation, and so probably overstates the fuel needs. Still, as Bailiff Kroger was expecting to use only 300 for an entire year, this rate was probably something of a shock.

During the 1734 test, the engine used 8.9 stafrum per 24 hours of operation. Since this had been a carefully monitored test, we can have some confidence in this figure while still suspecting it to be a bit high. The engine had been idle for some time prior to the test and was probably not in the best of repair. Added to this, it is likely that the efficiency would have been improved upon, had operation continued. While a new technology is prone to cost overruns, it eventually benefits from learning-by-doing, which tends towards improvements in operation.

For his part Triewald, in his 1734 book, avoided discussing the economics of his engine’s operation. Instead, he cited a letter from Jacob Leopold discussing an engine erected in Hungary, and by comparing the relative size of the two machines, projected the operating characteristics of his engine. This circumspection on his part is probably attributable to the fact he was at the time still party to a lawsuit regarding his engine. Elsewhere, Lindqvist

---

387 These efficiency estimates also suggest the fuel was a soft pinewood. If the fuel used for the test had been a hardwood oak, the greater heat provided by this fuel would imply even greater losses, with the efficiency equating an abysmal 0.24% to 0.32%.

uncovered an estimate, which he believes Triewald made in 1733 or 1734, projecting annual operating costs for the engine (figures in *copperdaler*).\textsuperscript{389}

```
<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Fuel</td>
<td>6,570</td>
</tr>
<tr>
<td>One engineer</td>
<td>600</td>
</tr>
<tr>
<td>Two operators:</td>
<td>576</td>
</tr>
<tr>
<td>Repairs</td>
<td>1,164</td>
</tr>
<tr>
<td>Triewald’s royalty</td>
<td>1,200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10,110</td>
</tr>
</tbody>
</table>
```

(Note wood fuel is figured at 6 *stafram* per day, 3 *copperdaler* each, $6 \times 3 \times 365 = 6,570$)

Fuel, then, would make up two-thirds of the operating budget. The company could arguably dispute the second priciest item, Triewald’s royalty, but fuel was unavoidable. To put this 10,110 figure in perspective, Lindqvist cites an August 17, 1726 report of the Partners that the cost of keep the mines clear of water “…have risen to nigh on 9,000 *copperdaler* a year, and that only for keeping the water away, and not counting the cost of drawing up the ore.”\textsuperscript{390} Note that this figure does not include the Nora Silverberg, which was still flooded at that time.

The amount of fuel required per day was possibly as low as the 6 *stafram* put forward by Triewald. However, even at the 6 per day figure, that would still equal 2,190 *stafram* per year (just under 3,500 cords of wood), for a cost of 6,570 *copperdaler*. From the Directors’ point of view, they would probably have used the 8.9 *stafram* per day rate, from the 1734 trial. At 3 *copperdaler* per day, they could expect fuel alone to cost them 9,746 *copperdaler* for a 365-day year, plus additional repair and operation costs.\textsuperscript{391} Based on what they had experienced, the Directors could be expected to select the lower cost option of horse-powered whims to drain the mine.

\textsuperscript{389} Lindqvist, p. 295.  
\textsuperscript{390} Translation quoted in Lindqvist, p. 251.  
\textsuperscript{391} This is the same reasoning used by Lindqvist, pages 295-6, where he notes both that the operators were unlikely to pay Triewald’s royalty, and they would probably have used a higher fuel use per day figure.
Triewald’s 1734 book is illustrated with an engraving of the engine at Dannemora drawn by Eric Geringius. In Chapter 14 of his book (pages 283 to 290), Lindqvist provided an insightful analysis of the imagery used in this engraving. He observed that the picture is not a literal image of the machine, but intended to inform the viewer about the engine. He further noted the inaccuracy of the proportions. The cylinder, for example, although only 9 feet tall appears three to four times taller than the workers tending it. He attributes this to a desire to better emphasize the machine’s size and power. Continuing the line of analysis elsewhere in his text, Lindqvist interpreted the engraving as showing the engine’s place in Sweden’s social structure.

The engine is the focus of the image, but there are also six people depicted in various relations to the engine. Lindqvist interprets these six as illustrative of the mining district’s social structure. The three figures inside the engine house show the ease of operating the engine. At a window the engineer is shown relaxing, smoking his pipe; the engine-operator studiously works some valves, while at the lowest level (socially and physically) the stoker tosses several logs into the firebox.
Figure 9-1. Engraving of the engine at Dannemora, made by Eric Geringius to accompany Triewald’s book of 1734. Reproduced from Lindqvist, page 284.
Three additional figures are observing the engine from outside the building. They are: a wealthy man (accompanied by a dog), an excited boy and a stooped old man, whom Lindqvist identifies as a miner. Lindqvist’s analysis of the engraving reveals its intention to reinforce the existing social structure, but perhaps does not go far enough. He passes over in silence the tremendous amount of wood stacked up outside the engine.\textsuperscript{392} As with other aspects of the engine, I would suggest that by examining the fuel, additional insights about the engraving might be gained.

Five stacks of wood are shown leading up to the building. Note the standardized size of each of the logs. Their uniformity gives them the appearance of a manufactured input: the natural variety of tree that produced the wood has been altered and standardized to facilitate the industrial process.\textsuperscript{393} The logs are laid lengthwise, with four of them to the row between three uprights that hold them in position.

Although the stacks of wood, like the people, are not shown in proportion, it is possible to estimate how much is depicted in the engraving. Recall that a “stafrum” of wood is a cube whose sides are 3 Swedish ells in length. Since an ell is slightly less than 0.6 meters, a stafrum contains 5.7 cubic meters, or 1.58 cords of wood.\textsuperscript{394} One stafrum then is approximately 202.0 cubic feet.

\textsuperscript{392} This is not to say he ignored the engines technical aspects. Lindqvist provided more than adequate coverage in Chapter 12, examining the engineering drawings prepared for the engine and engine-house. These drawings had miraculously survived, unnoticed for centuries, in the Dannemora archives until they were identified in the 1970’s.

\textsuperscript{393} This, not incidentally, is an excellent early (1730’s) example of how industrialization tends to organize and standardize its inputs.

\textsuperscript{394} Several citations by Lindqvist confirm this equivalent length of the ell; see for example note 9 on page 251 or page 281.
Returning to an examination of the wood fuel depicted in the engraving, consider the detail of the engraving showing the old man, identified as a miner, standing next to one of the wood stacks. The old fellow can be used to approximate the volume of wood in the adjacent stack. Since the stack comes up to the waist of the stooped miner in the foreground, it is depicted as being perhaps 3-feet tall (a little less than 1-meter). For the length and width, if a life of hard work in the pits has left the stooped miner, say, five and a half-feet tall, then by proportion each stack of wood nested between the upright posts appears to be on the order of 8 by 8-feet. Using these rough measures, a stack 3-feet tall, 8 feet long, and 8 feet wide would contain on the order of 192 cubic feet. This is close to the 202 cubic feet estimated per stafrum, which the stack may represent. Granted, the suggestion that the stack is a stafrum of wood may be based on rough measurements, but we have no reason to suppose that an engraving, which has been so carefully composed in all its other elements, would have a random quantity of wood in
the foreground. It is not much of a stretch to suppose that each stack depicted is meant to represent one Swedish *stafrum* of wood fuel.

Note that by the time he was writing his book about the engine (1734), Triewald had revised his estimate of its daily fuel needs to 6 *stafrum* of wood per day. In light of this, we can suppose that the five stacks of wood in the foreground depict one *stafrum* each. The sixth is already inside the engine house, where the stoker is shown feeding the last half-dozen or so logs from the day’s first *stafrum* into the flue “A”. Upon reflection, one would expect the engraving to usefully display a day’s worth of fuel for the engine, 6 *stafrum*.

Lindqvist noted that the perspective of the drawing was altered to make the cylinder appear more dramatic (p. 284-85). I would suggest this artistic license extended to the depiction of the fuel, which has been made to look less dramatic. Although the stacked wood is in the foreground, it is confined to the lower right hand corner of the picture. Perspective has also been employed: the stacks become smaller the deeper into the scene they are depicted. The effect is to make the stacks near the building appear insignificant in size. Consider that the cylinder, although only 3 feet wide, dwarfs the 8-by-8 foot stack of wood nearest the building.

Geringius’ engraving was not intended as a blueprint, but to inform the reader about the technical aspects of the engine. For this reason, it is not too surprising that the engine is depicted out of perspective, relative to the people and other embellishments. By including the fuel among the “embellishments”, the overall impact is to disclose the quantity of wood required to operate the engine for 24 hours, while at the same time minimizing its significance.
Summary and Conclusion

The attempt by Marten Triewald to transfer the technology of the Newcomen engine faced a number of challenges. As Lindqvist has show, cultural and climate factors conspired against its success. Further, Triewald himself may have seen the engine merely as a means to an end: His goal of establishing himself among the elite Swedish scientists of his day. Once Triewald had made a name for himself by demonstrating he could build a working engine, the engine would have served his purpose. Further, only he and his assistant Olof Hultberg were trained to run the engine, and Triewald was often away. Lindqvist asserted, “…the Newcomen engine at the Dannemora Mines stood or fell with Olof Hultberg.”

While climate, culture, and lack of trained operators all presented difficulties, none of them were insurmountable. The climate, although harsh, had not prevented other energy technologies from being applied to pumping at the mines, and the culture was grounded in the mine as a profitable enterprise. As for potential engine operators, where there was one tech student who could be trained, there would be others: Triewald could have, in short order, trained as many operators as he needed. The fatal problem that could not be addressed was fuel costs.

The Uppsala Peninsula in the 18th century was an energy-constricted zone. True, a great volume of wood fuel was available, however this source was already being employed to supply the iron smelting furnaces that surrounded the Dannemora mine. For its fuel requirements, Triewald’s engine needed to enter into competition with the 17 established iron furnaces in the vicinity. As a result of this competition, fuel was relatively expensive. Even at the 6 stafrum per day rate, the fuel alone would cost 6,570 copperdaler annually. To put this sum in perspective, it cost 9,000 copperdaler to operate all the other existing horse whims, the windmill, and the

395 Lindqvist, p. 311. Curiously, this is not too different from Jenkins’ parenthetical suggestion about how it may have been “…difficult to get men competent to work it (the engine)…”, a suggestion Lindqvist flatly rejected.
Once repairs, operation and maintenance was added into the equation, the mine operators concluded that the engine would not provide any price advantage over their current “best-practices”. They chose horse-powered whims to drain the Nora Silverberg shaft.

From this failure of a wood-fired engine, it may be tempting to draw the conclusion that the Newcomen engine could not function outside a coalmine. Lindqvist gave voice to this conclusion when, at two different points in his text, he quoted Graham J. Hollister-Short, who asserted that the Newcomen engine was

“…so symbiotically linked to the mining of coal that (...) it could not in any significant or lasting way break clear of the technological matrix in which it had first come to maturity”\(^{396}\).

However, as a further case study will show, coal may only have been the particular historical realization in Britain.

Perhaps the engine failure can most clearly be understood in its overall energy-using milieu. Seen this way, the experiment with the engine can be seen not as an experiment in technology, but as an expression of the desire to control and convert additional energy. The operators at Dannemora were driven by just such a desire. They had been expanding their energy menu since the mid-1600’s. In the 1720’s, they wanted to control additional energy to drain their deepest pit, the Nora Silverberg. Their choice was to try to exploit the thermal energy in wood, as transformed by fire and air, or *eld- och luft*, as they would have said. In this they were frustrated due to the cost of the fuel required, and so the operators resorted to using additional horse powered whims to drain the pit. Their intensified use of animal labor should not

obscure the fact that they were pursuing their goal of converting additional energy, as long as it had a positive energy rent.

In an energy rich environment, one where the engine could provide access to additional energy rather than compete with existing users, the Newcomen engine should be expected thrive whether the thermal source is coal or wood. A following case study, which also deals with an engine at an iron ore mine, will test this proposition. Rather than a part of Europe where existing energy sources were already the subject of intense competition and worry, this mine was situated in the relatively energy-rich environment of Colonial America.
Part V: Newcomen in North America

Chapter 10: The First Engines in the Americas

This chapter will briefly review the history of several of the earliest atmospheric engines established in colonial America. The standard historiography states that, in general, the “American colonies provided neither the deep mines nor the large urban waterworks which would have made steam engines economically attractive.”\(^{397}\) The actual history of the Newcomen engine shows that this was not entirely the case. Not only did proprietors on the western side of the Atlantic show interest in the Newcomen engine, at least several examples were actually built and operated commercially. Although their numbers were not great, their uniqueness itself may prove enlightening. Why was it, given the relative abundance of other power sources, that certain productive activities were interested in mechanical power?

**First engine: Schuyler Copper Mine in North Arlington New Jersey**

The first documented engine in the British colonies was erected in 1755, a quarter century after the engine at Dannemora. It should not be surprising that it was located at a mine, in this case a copper mine run by John Schuyler in New Barbadoes Neck. This area today is part of North Arlington, New Jersey, less than 10 miles from the Hudson River, opposite Manhattan. The land had been deeded to Peter’s father, Arent Schuyler. In 1713 or 1714, a large stone found on the property proved to be relatively rich in copper ore; mining followed, beginning some time between 1715 and 1719.\(^{398}\)


The history of this mine up to 1750 would have seemed familiar to the supervisors at the Dannemora mine. In its early phase, the mine’s minerals were easily recovered. Through 1731, the deposit produced nearly 100 tons per year through drift mining. This type of mining is accomplished by digging into the side of a slope, between the lower meadows and the high ground. When Arent died in 1730, his son John took over management of the mine. During the early 1730’s drift mining was no longer able to access the copper ore. The easy ore, it would seem, was exhausted. Some time around 1735, the surface mining became shaft mining; their first shaft would eventually become known as the “Victoria shaft”.

The digging appears to have been vigorous, as the shaft was over 100 feet deep by 1743. A notice in a New York newspaper provides both an indication of the depth of the pit, and the dangers of mining:

"We hear from Newark, that on Saturday, the 26th of March last, one Malachi Venderpoel unfortunately fell into one of the mine pits near that place [the Schuyler mine] upwards of 100 feet deep, by which his whole body was so bruised, and many bones broken, that he died immediately."

The inevitable problems with water were not long in making themselves felt in the deep shaft. By 1748, the mine had been idled due to flooding. Ben Franklin, who visited the mine in 1748 or 1749, noted in a letter to his friend Jared Eliot both the flooded state of the mine and their intent to purchase an engine. “I was at it last fall, but they were not then at work. The water has grown too hard for them, and they waited for a fire-engine from England to drain their pits. I

---


suppose they will have it at work next: it costs them one thousand pounds sterling.”

Thus, the arc this mine’s existence conformed to the pattern of new – mature – flooded, as see at other mines. As a remedy, John Schuyler, now Colonel Schuyler of the New Jersey militia, decided to purchase a fire engine from Britain.

In 1747 or 1748, Schuyler (or more likely his agent in London) struck a deal with Jonathan Hornblower to cast an engine in England, and ship it, along with a trained engineer, to the mine. Jonathan and Josiah Hornblower had previously been working in the collieries of the Midlands; they moved to Cornwall in 1745, after the removal of the coal tax stimulated demand for engines there. In this they were carrying on the family business. Their father, Joseph, had been an associate of Newcomen’s. The engineer eventually selected to accompany the machine to the colonies was the younger brother, Josiah.

Due to various delays, the engine was not ready to be shipped until mid-1753. The circumstances are murky. Certainly the export of technology was frowned upon, which may have contributed to the length of time it took to prepare the engine and spare parts. It is possible that Colonel Schuyler had sufficient influence with the Governor of New Jersey to allow him to import an engine. We do know that the engine and engineer were transported in an American ship, the Irene. The crossing, hampered by bad weather, took from June 6 to September 9th. From New York, the engine was transshipped up the Passaic River to the mine. From its arrival in September, it was another year and a half until it first ran in March of 1755.

The engine followed the standard Newcomen design. The cylinder was made of brass and while its exact measurements are uncertain, it was recalled as being 34 ½ inches in diameter

---

403 Nelson, p. 15.
and 8 feet long. The boiler that serviced it was 8 to 10 feet in diameter, and as tall. The boiler was fired using wood. The firebox, boiler and engine were all housed in an engine house built of stone and wood. Protruding from one side of the house was the rocker beam, used to operate the pumps in the mineshaft.\(^{405}\) It was estimated that the engine could have lifted as much as 8 hogsheads of water per minute, 720,000 gallons per day; however it was known to have worked a 10-inch diameter pump (circa 1794), which could have managed no more than 200,000 per day (Nelson’s estimate, p.21).

The engine was noted by travelers, such as the English Reverend Andrew Burnaby, but in his case only in passing:

> “From hence I returned, and in my way crossed over the river to colonel John Schuyler's copper-mines, where there is a very rich vein of ore, and a fire-engine erected upon common principles. After this I went down two miles farther to the park and gardens of this gentleman's brother, Colonel Peter Schuyler.”\(^{406}\)

Apparently, the English Reverend found nothing worthy of recording about an engine “erected upon common principles”.

Following the course of the engine’s operating history, its record was somewhat less than stellar. The engine was originally set up to empty the 100-foot deep “Victoria” shaft. However it proved unable to keep up with the water, and was instead put to work in other shafts. In 1760 a new brass cylinder arrived from Britain. Perhaps encouraged by this, the following year (1761) Hornblower and a partner John Stendall leased mine from Schuyler, agreeing to pay one-seventh of the ore in rent. Their activities were cut short when, in March of 1762, the engine house burned down. Fortunately, the engine itself appears to have been little damaged.

\(^{405}\) Nelson, pp. 18-22.
Hornblower and Stendall were joined by Philadelphia partners, and worked the mine again during 1765 and 1766. The mine then was idle in 1767/1768 when, in October of 1768, the engine burned down again. This fire idled the engine for 25 years, until 1793. Thus, up to 1793, the engine appears to have run for some period between 1755 and 1760, plus a total of not more than 4 years after that. The derelict engine was observed by Lieutenant Isaac Bangs of Massachusetts in 1776.

“In the afternoon Lieut. Wheeler, Makepeace, & myself visited Mr. Schuyler… An old Man accompanied us as a Pilot, & in our Way he shewed us the Copper Mines belonging to Mr. Schuyler; the Work which we could perceive had been done in them was sufficient to astonish any Man who had seen so little of the World as I had. Nothing had been done in these Mines for 4 Years, the Engine for throwing of the Water having been burnt about that Time. This cost about 3 Thousand, sterling, & would cast out of the Earth 80 Hogsheads in a Minute. This was actuated by Fire, & from fire it had its only Motion; & it was constructed upon the same Principles & much in the same Form as that of N. York for watering the City; but (from necessity) the Works of Mr. Schuyler were greatly superior in Magnitude to those of the City, of which I could judge by the incombustible Matter which was still remaining.”

Bangs’ observations are interesting on several levels, not least of which is the how he justifies the historian’s caution regarding an “eyewitness”. The old man “Pilot” who guided Lieutenant Bangs would appear to have exaggerated the engine in several particulars, most notably the “80 hogsheads” per minute-rate of pumping would be about 10 times the rate of the actual engine.

In 1793, Philip A. Schuyler, Jacob Mark, and Nicholas I. Roosevelt reorganized the mine as “New Jersey Copper Mining Association”. They contracted with Hornblower, by then about

---

407 Note that the Revolution cannot have been the sole reason for the engine’s idleness; while it may have been a contributing factor, the Revolution did not begin for 7 years after this fire, and had been over for a decade before the rebuild was attempted.


409 The works “of N. York for watering the City” refers to an engine built there in 1775; this engine, which is discussed below, had been visited by Bangs earlier in April of 1776.
63 years old, to rebuild the engine for a third time. For this version, they used an iron cylinder. A clipping in the *New-Jersey Journal* (published September 10, 1794; p. 3, vol. XI, iss. 569) stated that the mine was being worked and that “The water is discharged from the Mine by a Steam Engine which completely answers its purpose.” This was not the view of the proprietors. For them, this incarnation of the engine did not meet their expectations, and the following year (1794) they broke their contract with Hornblower. Again paralleling the Dannemora experience, they filed a lawsuit against him for the engine’s poor performance.

**Evaluation**

The Schuyler engine had been built professionally in Cornwall by highly experienced engineers. This should have made it a reliable engine as “The engines built in Cornwall were of a higher standard than those in the north of England, for fuel economy was all-important…”.

The engine was also professionally erected and run. Josiah Hornblower was 26 years old when the engine first ran in 1755, and had been in the family’s engine business his whole life. Unfortunately, the details as to cause of the engine’s poor performance have not yet come to light. It is unclear if the idleness was something inherent in the engine or stemmed from other problems at the mine. One is led to suspect fuel, but this is only a guess based on circumstances.

The reasons for the proprietors’ disappointment with the engine’s rebuild in 1793 are also unclear. Certainly the proprietors were familiar with the work of Boulton and Watt; they named their works at the mine, which included a machine shop, “Soho” in conscious imitation of the Boulton and Watt shop in England. They may have expected the engine’s performance to have more in line with the Watt type engine. Perhaps the rebuild had gone poorly, but against this supposition is the newspaper report of September 1794 stating that it “…completely answers its

---

410 Rolt and Allen, p. 109.
If it was adequately draining the mine, where else may the problem have lain? Again, one may suspect fuel, but further research is required to see if this suggestion has any merit.

**A colonial-built engine: Colles’ water-works engine in New York City**

An engine that may have been the third erected in Britain’s Atlantic colonies was built in New York City. While this engine has the distinction of probably being the first colonial-built machine, its short-lived career was even less impressive than the Schuyler engine. In 1774, Christopher Colles, an Irish immigrant, proposed to build a pumping engine to supply water to the growing city. He came to an agreement with the city fathers. In an interesting financial innovation, notes were issued to raise money for New York Waterworks. These notes featured an excellent depiction of a Newcomen engine, complete with the technical detail of the water tank that supplies both the condensing spray of water to the cylinder and the sealing water to the top of the piston. The design appears sound, perhaps more sound than the notes themselves.

The engine cylinder, small for a Newcomen engine at only 18-inches in diameter and 10-feet long, was cast in February of 1775 by Peter Curtenius, as related in the *Pennsylvania Evening Post* (page 51, vol. I, iss. 13 Publication Date: February 13, 1775, emphasis in original).

> “On Friday last, at Mess. Sharp and Curtenius’s furnace in this city, a CYLINDER was cast for the steam engine of the WATER WORKS now carrying on here, being the first performance of the kind ever attempted in America, and allowed by judges to be extremely well executed.”

---

411 Chronologically, at least one engine had been built in Jamaica (British Caribbean) earlier than 1775; see section on sugar plantations, below. Since they were built less than an dozen miles from each other, the Schuyler and New York engines are here dealt with together.

412 Mr. Curtenius will turn up later as a business associate of the Brown brother of Providence, Rhode Island; see Chapters 11 and 12.
Figure 10-1. Engraving of Colles’ New York City Engine. The notes issued to raise money for the New York City Waterworks featured a Newcomen engine, complete with the square cold water reservoir, to the upper left; the pipe delivering water from the tank to the cylinder can be seen (see also Purcell, p. 8). The machine is flanked by fountains of pure, fresh water.

The engine was apparently at work the following year, as related by the *New York Gazette and Weekly Mercury* in March of 1776 (page 3, iss. 1274. Publication date March 11, 1776):

“We can with Pleasure assure the Public, that the Fire Engine of the Water Works was work’d many Days last Week, greatly to the Satisfaction of vast Numbers of People who went to see it. This Engine carries a Pump of 11 inches diameter, and 6 Feet Stroke,
Which contains, 29 Galls.
Makes 10 Strokes in a Minute, 290
In one Hour, 174 Hogsheads, 17400
In 12 Hours, 2088 ditto 208800
In 24 Hours, 4176 ditto 417600
The Well is 30 feet diameter, and 30 deep, contains 8 Feet depth of Water. The Water is inexhaustible, for the Pump, tho’ s continually work’d, cannot lower the Water more than two Feet. A Cord and ¼ of Wood will work the Engine for 24 Hours.

** It is proposed to work the Engine for some Days longer, for the further Inspection of the Public, of which Notice will be given by hoisting a Flag.”

The engine pumped water up to a reservoir, from which it was distributed via wooden pipes. This news article usefully reports the engine’s fuel consumption at 1.25 cords per day. From this and the other details about the length of stroke and strokes per minute, the engine’s horsepower was likely 4 to 4.5 HP. Using 1.25 cord of wood to do this amount of work implies an efficiency of about 0.6%, assuming good hardwood was used. This level of efficiency was on a par with the early common Newcomen engines, which gives us some faith in its accuracy of these reported figures.

Lieutenant Isaac Bangs visited the engine in April of 1776. This was his first view of a fire engine, as he would visit the Schuyler mine later in the year. Although it was not in operation when he was there, it is worth quoting Bangs’ description at length, as he provides a description of the major structural pieces of the engine.

“I visited, and took a full view of the Waterworks that are making to convey Water through the City… These Works were began about 12 Months since at the City Expence, to defray which they issued Bills that are current as other Money. A Dutchman undertook the Jobb for a certain sum, & hath already performed the most difficult part of the Work, **the not with that success that was expected by the Citizens, as they say**. He saith he hath done as well as he promised. The Work that is already done (the most difficult part) is to convey Water from the side of an Hill nigh a Pond to the top of the Hill, which being higher than any part of the City, the Water is to be conveyed in Pipes through the City.

As the Man that attended spoke very broken English & the Machiene was not at Work, it was with great Difficulty that I understood the Construction of the Machiene; & to pretend to give a perticular discription of this Work would be folly
in me, as I could by no means do it Justice… (description of the well, reservoir, and distribution pipes)…

All of this I could easily understand; but the grand Question was how was the Machihe in the Well first actuated & continued its motion? This I was surprised to find was wholly done by the Power of Boiling Water.

It was a long time before I could discover even by seeing the Works how this could be effected, & the Man who shewed the Works could give me no satisfaction as to this till at length I found that by Means of a large Copper (which is kept boiling when it is requisite for the Works to be set in Motion) the Steem or Vapour of the Water is conveyed from thence into a strong Copper Tube of about 18 Inches Diamiter & about 10 Feet Long (the cylinder), which stands perpendicularly. The lower part or end of this Tube is tight; but the upper End hath in it a moveable Stopper (the piston) which may move upwards or Downwards with as much ease as possible, and at the same time to keep any of the Air from without from entering into the Tube & to keep it as tight as possible another part of the Works constantly supply the Top of the Tube above the Stopper with a small stream of Water (the standard method of sealing the piston of a Newcomen engine).

…the Stopper is kept in constant Motion by the Means of Steam or Vapour, & to this Stopper is fastened a stout Wooden lever by a bar of Iron. The Lever is Fastened in the Middle upon an Axis; and as the Stopper of the Tube moves upwards and downwards, it moves the Lever, which worketh the Engine (water pump) in the Well, which forceth (as I before described) the Water into the Pond at the Top of the Hill.”

Bangs describes the cylinder of a rather small Newcomen engine. He also noted that the project was not the “success that was expected by the Citizens”, but this may have been a problem with distribution rather than the engine, as the “most difficult part” of raising the water had already been accomplished.

The works were in operation in 1776 with Christopher Colles in charge, but shut almost immediately: “Owing, however, to the insufficient supply furnished, and the confusion caused by the Revolution, the whole enterprise was soon abandoned.” While it is true that British forces under General Howe occupied the city in September of that year, one would expect that

---

413 Bangs, entries for April 20, 1776, pp. 25-27, emphasis and parenthetical editorial explanations added.
the thousands of troops stationed there would have benefited from a steady supply of fresh water. However, nothing further was done with the engine, and it does not appear to have been used subsequent to 1776. While well described, this machine’s short career precludes it from providing much insight into the relation between fuel and an engine’s success. It does show, however, that the Americans had the technical skill to produce and engine locally.

Sugar and Steam

When looking beyond its use as a pump in the mines, the dominant narrative of mechanization usually involves textiles. However, on the western side of the Atlantic, a different group showed much earlier interest in the potential of steam power. In the colonies of the Americas, the owners of slave-sugar plantations were among the earliest enterprises outside of the mines to seek out thermal-powered prime movers.

Slavery, as an institution that focuses on the exploitation of human labor, is sometime thought of as inimical to technological progress. Slaveholders are characterized as technologically conservative, if not regressive. To step outside of this storyline, consider for a moment the position of the plantation owners in the slave-sugar complex. From the standpoint of extracting surpluses from energy use, the planter class is in the vanguard: they took the exploitation of human labor to its logical, horrifying, extreme. The suggestion that the planter-class was indifferent to the cost of labor is an inadequate, one-dimensional view of how they manipulated energy.

Planters showed a keen interest in supplementing human labor, when and where it could provide a better energy rent. An example of this was in the selection of prime movers to drive the mills that crushed the sugar cane at harvest. Originally, these mills were turned by slaves.

---

415 Satchell’s work contains a discussion of this historiography; see Satchell, p. 520.
By the 18th century, they were generally powered by cattle because, for this task, animals provided a greater energy rent than using human labor. After the mid-18th century planters, keen to maximize their returns, were eager to replace animal power with mechanical power, if it would allow them to capture a greater energy rent.

Seen in this light, their wealth, need for primary power, and even temperament, made the sugar planters likely candidates to seek out the steam engine. Successful sugar planters were the super-wealth venture capitalists of their age, which afforded them the financial resources to potentially purchase an engine. At the same time, their power needs during harvest, as will be reviewed, were not merely extensive, they had to be available during the limited window of time when the cane was ready. The temporal weaknesses of wind and waterpower were familiar to the planters. Finally, their temperament: A planting sugar was an enterprise with large payoffs if things went well, but the possibility of quick ruin; anything a planter could do to increase the flexibility of the power sources available at harvest would increase the chances of success.

The planters understood that controlling the flow of power, whether it was human, animal, and/or mechanical, was required to transform cane into raw sugar. They took ruthless advantage of the spatial and temporal flexibility of human labor. To succeed, they concentrated this labor in an enterprise destructive of human life, even by the standards of slavery elsewhere in the Americas. They supplemented this labor-power with less flexible, but more powerful, wind and water mills. It was not lost on them that if they could reduce the uncertainty of power (increase its flexibility), there would be one less risk of potential ruin.

---

416 See Williams for a discussion of this topic, Chapter 1.
417 Financial ruin is presented as the worst-case scenario for a planter; still, the lot of a ruined sugar planter does not seem nearly as grim as that of a successful slave on a sugar plantation. The industrial nature of sugar production is discussed in Richard Follett *The Sugar Masters: Planters and Slaves in Louisiana’s Cane World, 1820-1860* (Baton Rouge: Louisiana State University Press, 2005).
A review of the physical process that transforms cane plants into raw sugar reveals its
time-sensitive demands on potential primary energy sources. Once cut, the juices in the cane
begin to ferment. The stalks must be crushed in a mill within a short time or the juice will sour.
The work was organized along military lines in what was essentially an industrial enterprise. It
is difficult to overstate the physical demands made on the slaves to concentrate the power of their
labor. To say that planting and harvesting sugar cane was “difficult” or “backbreaking” only
seems to trivialize how destructive these tasks were to the people forced to do them.418

Slaves cut the cane, striped it of its leaves, and transported it to the sugar mill. There the
cut cane was passed through the rollers of the mill, squeezing out the juice. The earliest mills
were turned by slaves, and then by animals, typically oxen or donkeys. The juices obtained by
grinding were then heated in a series of four kettles, a carefully controlled process. The sugar
thickened as it passed to each successive kettle, until it was “struck”, and allowed to cool. After
that, as solid raw sugar, it was packed into wooden kegs, the molasses drawn off, and it was
shipped to a sugar refiner. Once the harvest was begun, the cutting, crushing, and boiling will
continue without pause for from morning until night for months.

Two elements should be noted from a primary-energy point of view. First, the amount of
energy required for crushing was intensive. The primary energy source needed to be
concentrated, to squeeze out the maximum possible juice. This was a problem for human labor,
which is difficult to intensify, even involuntarily. Second, it needed to be prompt: Unlike
grinding grain, the process could not be paused. Waterpower was an obvious choice, but the
areas of sluggish river marshes that favored sugar production did not always provide sufficient
running water. Windmills, which were widely used for grinding grain, were unsuitable for
grinding sugar cane. Their poor temporal flexibility was at odds with the prompt energy needs

418 For a brief overview of the process, see for example Follett, pp. 12-13, 37-38.
of the sugar production process. Typically, where waterpower was not available, animal powered mills were used.

Figure 10-2. A Typical Animal-powered Sugar Mill. The cut cane would be fed between the rollers in the center.
Early Fire Engines in Jamaica

Veront Satchell has studied technical innovation among the sugar plantation owners in Jamaica in the late 18th and early 19th century. 419 He has documented the early interest in steam power, and concluded it was arguable “…that the diffusion of steam power was well underway in the island before the advent of the Watt engine.” 420 His research has shown that engines of the Newcomen type were not merely discussed among the sugar plantation owners on the island: in 1768, in Jamaica, John Stewart (also known as Robert Rainey) sought a patent for a sugar mill driven by an atmospheric engine, which he had brought with him and intended to erect on the island.

Stewart appears to have been aware of the ravenous fuel consumption of the engine, and as part of his patent proposed a clever solution. He planned to avoid fuel costs altogether by using the heat that boiled the cane juices to also provide steam to an atmospheric engine that would drive the cane-crushing mill 421. The more recent term for this process, where the same heated steam is used sequentially in an industrial process and a steam engine, is called “co-generation”. A Committee of the Jamaican House of Assembly was sufficiently impressed to advance Stewart the sum of 343 pounds sterling; following up on his activities in 1770 they reported that he had erected the fire engine for grinding sugar canes at the Greenwich plantation and “…the power of said fire engine is found to be sufficient for the grinding of canes…” 422

421 John Stewart, A Description of a Machine or Invention to Grind Sugar Canes By the Power of a Fire Engine: Such as are used in Raising Water Out of Mines &c. (1768), cited in Satchell 1995/96.
In Jamaica, interest in fire engines for sugar mills grew during the last quarter of the 18th century. Satchell cited several more individuals who proposed steam powered sugar mills or actually built proto-types. In the 1780’s and ‘90’s, various planters corresponded with Boulton and Watt, seeking terms and conditions for using the improved Watt engine. There is also evidence that a number of penny-wise planters, who were too impatient to wait out the expiration of the Boulton and Watt patent in 1800, erected pirated Bolton and Watt machines on their estates. Satchell believes that it was the eventual improvements in the atmospheric engine in England that discouraged further independent experimentation on Jamaica, as it became easier to simply import the machines from England.

An opportunity to gain energy as part of the sugar production process involved the waste that remains after the cane was crushed. The resulting crushed cane is called “bagass”, or sometimes “bagasse” (a French term, from out of the Spanish, for “dregs”). When dried, this material could be used to fire a boiler to produce steam. Satchell notes that bagasse reduced reliance on imported coal; “…bagasse and local wood became the chief sources of fuel for engines operating in the island (Jamaica).”

**Louisiana Sugar**

The application of steam power on the sugar plantations in the United States belongs to a slightly later period, after the age of the Newcomen engine. It merits a brief mention here as it highlights how the need for spatial and temporal control of a prime mover created demand for steam engines, in this case well outside the dominant narrative of industrialization.

---

423 A machine built by Bateman and Sherratt was shipped to one of Lord Penrhyn’s estates before or during 1796. Satchell, p. 523.
The primary sugar cane growing area within the United States was in Louisiana. In the lower reaches of the Mississippi, the time element at harvest was even more critical than in the Caribbean. Unlike the planters in Jamaica, those in Louisiana had to be on the watch for frost, which could ruin a crop. Yet, they wanted to let the cane grow for as long as possible. This constricted the time element in planters’ calculations, which prompted them to intensify the harvest; this led them to seek out the most reliable form of primary power.\footnote{In addition, the topography of southern Louisiana precluded using waterpower.} In 1812, a Louisiana sugar planter approached engineer Benjamin Latrobe seeking an engine for a sugar mill. In anticipation of servicing this and other markets, Latrobe established his works in Pittsburgh, advertising to build engines “upon the principles of the celebrated WATT & BOLTON”\footnote{Meaning the engines would be low-pressure atmospheric engines. Advertisement in the \textit{Pittsburgh Gazette}, April 9, 1813, quoted in Purcell, p. 64. Note that Watt received top billing over “Bolton” (sic).}. Latrobe’s and other engine shops would ship their machines down the Ohio River, to the Mississippi, and thus to the sugar plantations of the South.

Sugar plantations provided a surprisingly large market for stationary steam engines. Rather than technologically retrograde, certain slave plantations were among the earliest adopters of steam power. In 1838, the Secretary of the Treasury was instructed by Congress to survey the states with a series of questions regarding the use of steam engines, both locomotive and stationary, within their states. For stationary engines, the state with the most steam engines was, not surprisingly, Pennsylvania with 383, 21\% of the total. The surprise was the state with the second-most: Louisiana, with 274 engines (15\%), had the second greatest number, well ahead of Massachusetts in third place with 165 (9\%).

A further surprise is found in terms of installed horsepower: Louisiana led the country with an estimated 7,794 hp installed, 21.5\% of the total. Pennsylvania was second with 7,448 hp.
(20.5%) and Massachusetts third with 2,244 hp (6.2%). In other words, the average engine in Louisiana was larger than the national average, while in Massachusetts they tended to be smaller.

The 1838 report stated, rather matter-of-factly, that in Louisiana, “The sugar mills and cotton gins are used but a few months in a year, with scarcely ever an accident, and the engines are generally worked by slaves.” Neither were these engines late arrivals. Among the machines for which more detail was provided, a half-dozen of those were low-pressure engines built by “Fawcett & Co., Liverpool” that had been in operation since at least 1821. A low-pressure engine still used for a sugar mill at “Souve” in Jefferson Parish was described in the table as “Very old, being about the first in Louisiana”, sometime before 1820. Note that this was not a list of engines built up to 1838, but a listing of those that were in operation for commercial purposes as of 1838.

It is possible that the figures reported to the federal government in 1838 may even have underestimated the number of engines at work in Louisiana. Figures compiled for a special publication of De Bow’s Review indicate a higher number of engines for sugar plantations alone. Table 10-1 show the summary of growth of three types of prime movers on sugar plantations: human labor, steam powered mills, and “horse” powered mills.

---

427 Levi Woodbury, Secretary of the Treasury, Steam Engines: Letter from the Secretary of the Treasury, Transmitting, in Obedience to a Resolution of the House of the 28th of June Last, Information in Relation to Steam Engines, & C (U.S. Treasury Department, December 13, 1838), Table on p. 379.

428 Woodbury, p. 305, emphasis added.

429 Woodbury, pp. 305-8.
Note that Forestall refers to the slaves working on the sugar plantations as “Manual power”, in the same category as steam mill or “horse” mills. By Forestall’s estimate, the number of slaves working on sugar plantations increased by over 140% between 1828 and 1840. The number of horse mills peaked, and then declined, while the number of steam mills steadily increased.

### Seeking Energy Rents

The number of Newcomen engines erected on the western side of the Atlantic pales in comparison to the hundreds, perhaps 1,500 machines erected in Britain. However, the engines that we can identify follow a consistent pattern of energy use. Engines were sought out where

---


---

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Estates in Operation</th>
<th>&quot;Manual power&quot;* (slaves)</th>
<th>Steam-Powered Mills</th>
<th>Horse-Powered Mills</th>
</tr>
</thead>
<tbody>
<tr>
<td>1828</td>
<td>308</td>
<td>21,000</td>
<td>82</td>
<td>226</td>
</tr>
<tr>
<td>1830</td>
<td>691</td>
<td>36,000</td>
<td>282</td>
<td>409</td>
</tr>
<tr>
<td>1842</td>
<td>668</td>
<td>50,670</td>
<td>361</td>
<td>307</td>
</tr>
<tr>
<td>1844</td>
<td>762</td>
<td>50,670</td>
<td>408</td>
<td>354</td>
</tr>
</tbody>
</table>

* Forestall notes that the number of slaves in 1828 and 1830 are an estimate, while the figure used for 1840 and 1844 was “as ascertained by the last federal census” (1840).
they could supply a significant energy rent, and tend to emerge in areas where their flexibility is an asset. We turn to the next case study where a Newcomen engine was erected at an iron mine, not in Sweden but in Cranston Rhode Island. This was a “colonial built” engine, as the New York City waterworks machine had been. This engine’s much longer career, and the circumstances of how it came to be built, provides an archetypical example where commercialism created the demand for greater primary power, and entrepreneurs - with an inclination towards controlling energy - succeeding in exploiting that opportunity.
Chapter 11: Hope Furnace and the Cranston Iron Ore Pits

The third documented installation of an atmospheric engine in what would become the United States was at “Providence Plantation” under the direction of Joseph Brown. This engine was built in 1783 to pump water out of iron-ore mining pits in Cranston, Rhode Island. These ore beds had already been providing iron ore for Hope Furnace in Situate Rhode Island, 4 to 5 miles away. Both the ore digging operation and the furnace had been established in 1765 by a group of investors led by the Brown brothers of Providence.431

After 1775, the demands of the Revolutionary war intensified activity at the furnace, and thus the ore mine. This not only increased demand for existing energy supplies, it created completely new dimensions of opportunity for energy conversion. That the Browns were eager to step into these new roles, and why they succeeded, is the story of these chapters. It is significant that they early on resorted to locally mined mineral coal, “sea coal”, to supplement wood fuel at the furnace.

At the ore pits, the greater demands meant digging would work deeper in pursuit of seams of ore. As in mining elsewhere, intensified extraction made it increasingly difficult to keep the ore pits clear of water. The Browns followed the generic pattern observed at other mines.432 First, they sought to avoid the problem by digging in water-free areas. After exhausting these opportunities, they resorted to naturally-provided power on site, in the form of a water-powered mill wheel to operate pumps to drain the pits. Further intensification increased

431 The standard history of Hope Furnace is still James Hedges The Browns of Providence Plantations, Colonial Years (Cambridge Massachusetts: Harvard University Press, 1952), see Chapters 6 and 13. More recent scholarship has focused on the Browns and the slave trade; see for example Charles Rappleye’s well-researched Sons of Providence, the Brown Brothers, the Slave Trade, and the American Revolution, (New York: Simon and Schuster, 2006). For a history focusing on the furnace itself, see Discover Hope Village: A National Register Historic District In Scituate, Rhode Island (Providence: Rhode Island Historical Preservation & Heritage Commission, 1996).

432 See Chapter 3.
the demand for power beyond what the water wheel could supply. Their solution was to build an atmospheric Newcomen engine at the ore beds in 1783.\textsuperscript{433} This engine, designed by Joseph Brown and cast at Hope Furnace under the direction of Seth Keith of Bridgewater Massachusetts, would operate at the ore beds until the demand for pig iron from the furnace waned, around the year 1800.

A case study of the Brown’s engine project would naturally be of interest, as it was one of the few Newcomen-style engines built in the Americas. What makes this case even more significant is that the activities establishing the iron foundry from 1765 onward are well documented, something rare for an 18\textsuperscript{th} century enterprise.\textsuperscript{434} The documentation shows that, although it was amateur-built, the engine remained in constant operation until falling demand for the furnace’s products ended the need for iron ore. This stands in contrast to the Schuyler engine which, although professionally built and operated by an experienced engineer, found itself idled for most of the years it was in place at its copper mine. It is also in direct contrast with the experience at the Dannemora iron mine in Sweden, which was another professionally built engine, erected by and experienced engineer.

A key factor in the successful operation of the Brown engine was that it operated in the “energy rich” environment of Hope Furnace. By comparison, the engine’s fuel needs were quite modest in the overall scheme of energy consumption at the furnace/ore pit complex. Prior to the building of the engine, the furnace managers had had over 17 years experience planning for the voracious fuel needs of the blast furnace. In the overall scheme of furnace operations, the engine represented no more than 6\% of the wood fuel needs.

\textsuperscript{433} Hedges was unable to determine the date of the engine’s construction from the documents available to him: “Unfortunately, it is impossible to date it precisely; but as Joseph built it to operate the pumps which he made in 1780, it must have been contemporaneous with them.” p. 277; this 1780 date has been commonly cited by subsequent authors.

\textsuperscript{434} Hedges was of the opinion that it was one of the best-documented enterprises in the American Colonies, p. 123.
Perhaps what will most clearly be laid bare by this case study is how decisions to expand energy-use were essential steps in the broader historical process later termed the Industrial Revolution. Mechanization of production – which greatly expands the consumption of energy as part of production – was an essential feature of the industrialization of society. The building of the Brown’s engine is an expression of their desire to control productive power. Tracing its history is not so much a case study of a steam engine, as a succinct microcosm of the broader story about the how the appetite for mastering energy sources can feed-back upon itself. The 24-hours per day, “Sundays not excepted”, nature of work at the furnace (and at the ore pit, once water pumping was required), presented energy conversion options that the Browns seized.

As this study hopes to show, it was not by chance or serendipity that the Browns were first drawn to the industrial nature of a blast furnace, and later a fire-powered engine. While they would not use these terms, the Browns and their partners had a proclivity for focusing on energy flows, with a keen eye for opportunities to control and convert primary energy inputs. Either overtly or intuitively, they readily grasped the advantages of controlling the primary energy embodied in a mechanized converter, just as they had previously sought control over water power (mills), wind power (sailing-ship trade), wood fuel (at the blast furnace) and human labor (slavery).
The Production of Bog Iron

“My power is great, greater than you think, and I have gold and silver in abundance.”
– Iron Hans (“Der Eisenhans”), the rusty-skinned man who, per the Brothers Grimm, could be found at the bottom of a pond.435

To put this energy-intensive activity into context, it is useful to present a brief sketch of the methods used to production of “pigg iron”. By its nature, and iron furnace, even in the mid-1700’s, was already an industrial enterprise.436 Once begun, the “blast” was carried on 24 hours per day, 7 days per week, for as long as possible, generally more than six months at a time. While iron is the most common element in the earth’s crust, distilling these deposits into usable iron is an energy-intensive activity. It is useful to think of the resulting merchant bars of iron as energy rendered into a solid form.

Iron is found two primary places: mountain iron deposits, and bog iron. Bog iron was commonly used at the many colonial furnaces along the Atlantic Seaboard, and was the source for Hope Furnace. Bog iron is formed in wetlands and stagnant pools by percolating water that carries the iron to the surface; there, oxidation crystallizes it into nodules, forming deposits of iron.437

Prior to Agricola’s De Re Metallica in the 16th century, little had actually been written about smelting iron. The method of using fire to coax useful iron out of bog ore was learned from a master of the craft. The mythic dimension of this-iron-out-of-water process was

436 E.N. Hartley Iron Works on the Saugus (University of Oklahoma Press, 1957; Eastern National reprint, 2007), Hartley presents a vivid picture of colonial iron smelting; see also Michael Robbins The Principo Company: Iron-making in Colonial Maryland, 1720-1781, (New York: Taylor and Francis, 1986). The first books in English on iron production were not published until the 19th century; for contemporary 18th century works, see Courtivron et Bouchu, “Art des Forges et Fournexaux a Fer” in Descriptions des Arts et Metiers (Paris: Desaint and Saillant, 1762).
437 J.A. Starkey, Jr. The bog ore and bog iron industry of south New Jersey (Baltimore: Johns Hopkins Press, 1962), pp. 5-8.
expressed in the German folk tale of “Iron Hans”. Hans, a shaggy wild man made of rusty iron, who lived at the bottom of a pond, would grant unlimited help to those who would release him.

To render the ore into useable iron, to release Iron Hans, the impurities need to be removed. Iron ores were first worked by what is termed the “bloomery” process. In this method, the ore is heated on an open hearth, while repeatedly hammered to drive out the impurities. The result is a malleable wrought iron that is flexible. Bloomery iron production was practiced in China, perhaps 2,000 years before the current era (BCE), by 1,000 BCE in Africa, and about the same time in Europe. Iron smelting was unknown in the Americas, although bronze was produced.

**Blast Furnace Technology**

While the bloomery method produces a flexible iron, it is tedious and difficult process for producing complicated shapes. If the iron is heated to the melting point, it is possible to “cast iron” items directly. Although more brittle than wrought iron, cast iron is more resistant to rusting and can easily be made directly into complicated useful shapes such as pots and kettles. Perhaps more importantly for a market economy, once a mold has been made, any number of items can be cast in that shape.

To attain temperatures high enough to produce molten iron required a blast furnace. The “blast” refers to the blast of air used to raise the temperature inside an enclosed furnace. The blast furnace was hot enough so that the carbon from burning charcoal would combined with the oxygen in the iron ore to form a carbon monoxide gas; this removal of the carbon left behind pure molten iron as it reached the bottom of the furnace.438

---

438 The literature on blast furnace technology is extensive. For a good example, see Robert Gordon *American Iron, 1607 – 1900* (Baltimore: John Hopkins University Press, 1996).
The high temperatures inside the furnace were reached by a combination of wood energy, concentrated in the form of charcoal, and a pair of large bellows constantly blowing on the fire. These bellows, while identical in principal and design to the bellows used for home fireplaces, were ten to fourteen feet in length. While ironsmiths working at open bloomery forges had long used small hand-operated bellows, the driving-power required for a blast furnace’s bellows was beyond what could economically be provided by human or animal power. For this reason, furnaces were located near a stream that had sufficient power to turn a water wheel to work the bellows. The earliest blast furnaces assisted by water power were in China, about the first century of the current era.\textsuperscript{439} By the 1300’s, iron founders in the Flemish regions of Europe had adopted the higher temperature blast furnace method. This method would be used with little change down to the early 19th century, and was the process used at Hope Furnace in Rhode Island.

The material and energy needs to produce iron are considerable; North America, with its ample woodlands and untouched ore deposits, provided these in abundance. Just prior to the revolution, Britain’s North American colonies were the third-largest exporters of pig iron in the world.\textsuperscript{440}

A typical American Colonial blast furnace, of which there were perhaps 82 in operation in 1776, could be expected to produce 600 tons of pig iron annually. Operating a furnace to produce 600 tons pig iron would require 30 weeks of “blast” (production) using:

- 2,400 tons of ore;
- 1,800 loads of charcoal (roughly 260,000 bushels, or 3,000 tons);
- Sea shells to provide lime, a fluxing agent;
- Laborers to feed material into the top of the furnace, 24 hours per day;

\textsuperscript{439} Needham (1986), p. 370.
• Skilled founders drawing and casting the pig iron at the furnace.441

A typical blast furnace was essentially a 25 to 40 foot tall chimney. The materials that fed the furnace required a coordinated supply chain for the three main ingredients of iron ore, charcoal and a flux. These materials were fed into the top of the chimney.

Figure 11-1. A typical mid-18th century blast furnace. (Reconstruction of the charcoal-fueled blast furnace at Duddon, Cumbria, built in 1736).442

441 This summary of requirements to produce 600 tons of iron is derived from an inquiry made by Nicholas Brown to John Relfe, an iron master in Pennsylvania. Source: John Carter Brown Library, Box 177, Folder 5 (abbreviated: “JCB: B.177, F.5”); see also JCB: B.179, F.10 for a summary of Relfe’s response; a version of the questions is also found in JCB, B.179, F.11.
442 Illustration from Metals & Metalworking: A research framework for archaeometallurgy (First Published in UK by the Historical Metal Working Society, 2008), p. 61.
As shown in Figure 11-1, the prepared ore, charcoal, and flux were wheeled into the second story (upper left), to be loaded into the top of the furnace; the “blast” was provided by bellows driven by the water wheel (lower right); the slag (dark material, in front of worker in center) was drawn-off separately. The molten iron was tapped and drawn into a series of bars (“piglets”, to the left), to cool. To ease the delivery of materials into the chimney 25 feet or more above the working floor where the iron was drawn, furnaces were usually built into the side of a hill.

The blast began with a fire in the furnace to burn off any moisture and to raise the temperature within the furnace. After that, the first charges of iron ore, charcoal fuel, and flux were fed into the top of the chimney. As the molten material descended, the non-iron material would be drawn off by the flux to form a lighter “slag” that would float over the heavier pure iron. At the base of the furnace, the founder would tap the melting chamber at different points to draw off the slag and iron separately. The slag was discarded while the molten iron flowed into a channel in the sand the founder had prepared. The main part of the channel was termed the “sow”, and several smaller branches, the “piglets”. When cooled, this pig iron was then ready to be worked at a forge into useable iron implements. Alternatively, the iron pigs could be sold directly, or hammered into rectangular “merchant bars”, again for trade. A more skilled molder (“moulder”) could cast the molten iron directly into molds shaped in the form of a desired cast iron implement.

A great deal of time, effort, skill, and charcoal was used to bring the furnace to the point where it could be tapped for the season’s first pigs of iron. After that, the blast would be sustained for as long as materials, fuel, and manpower were available; typically, this was around the clock for at least six months at a time.

See Hartley, pp. 165 to 184.
**Energy Needs** “…Sundays not excepted,”

An ample supply of energy was critical at each stage of the process. The entire operation required a relatively large, skilled, and disciplined labor force. Including seasonal woodchoppers, the furnace required the labor of perhaps 75 workmen\(^{444}\). The demands of the supply chain tend to promote an integration of the separate branches of the business. Consider the energy needs for each of these steps in the production of iron. The energy inputs to produce 1 ton of pig iron included:

- *Mining laborers* to dig 2 to 4 tones of iron ore (depending on the iron content); the ore needed to be mined, washed, broken to a proper size, and transported to the furnace. Deeper mines needed an energy source for water-pumping.

- *Wood fuel:* cut wood, transformed into charcoal, 300 to 400 bushels of charcoal were needed for each ton of iron produced.

- *Water power* to turn a mill wheel that would work the furnace’s bellows to provide the blast;

- *Furnace laborers* to fill the furnace chimney, skilled molders to draw the molten iron;

- *Carting transportation* (usually provided by ox carts) at each step of the process to gather the materials and deliver the iron.

The operators of a forge had to carefully balance each energy need, if their enterprise was to succeed. Adequate supplies of each of the above energy inputs needed to be available in a timely fashion or the blast would not be successful. Each of these challenges was met by the Brown’s as they established Hope Furnace.

---

\(^{444}\) Hedges, p. 154.
Labor

Labor was needed to dig the ore, chop wood, transport materials, feed the furnace, and draw the pig iron. Even before the blast began, labor was required seven days per week; as the manager at Hope Furnace reported in March of 1767: “We shall begin to cart wood to gather this week. The wood choppers are in number between 30 and 40 every good day, Sundays not excepted.”

Blast furnace work itself required heavy labor, 24 hours per day. After only two years of operation, workers were reluctant to return to the operation under the same terms, prompting Nicholas Brown to complain about the “… difficulty in discussing with the people about the terms of their work.”

It should not be surprising that furnace operators would resort to coerced labor, if not outright slavery. An interesting example occurred at one of the earliest blast furnaces in the English colonies at Saugus, Massachusetts. This furnace used Scottish prisoners of war, taken by the English at the battle of Dunbar in 1650. Similarly, over one hundred years later, some of the labor at both Hope furnace and the source of its ore in Cranston would be performed by slaves. These are not isolated examples: elsewhere in the iron industry, slaves were worked at foundries for as long as slavery was legal.

An additional difficulty for Hope Furnace, and many other colonial furnaces along the eastern seaboard that utilized bog iron sources, was the difficulty of digging in wetlands.

---

445 March 8, 1767 letter from Rufus Hopkins to Nicholas Brown and Company; JCB: B.177, F.11.
Keeping the water out of the ore pits would prove a recurring problem, as will be seen as regards the ore beds at Cranston.

**Wood Fuel**

Charcoal had its own obvious energy needs. Charcoal is desired because it will burn much hotter than its parent wood material. Its production required time and the work of a skilled “collier”. The wood was first cut and seasoned; after that, the collier would construct a mound, using alternate levels of wood and dirt. Burning wood in this reduced-oxygen environment produces a charcoal that concentrates the energy of the wood.

Depending on the iron content of the ore, 300 to 400 bushels of charcoal were needed for each ton of iron produced. To put the wood fuel needs in perspective, 1 cord of seasoned wood produced 30 to 40 bushels of charcoal, depending on the collier’s skill; this means 10 to 13 cords of wood were needed for each ton of iron ore. Since a wooded acre yields 20 to 22 cords of wood, when clear-cut, the production of each ton of pig iron consumed at approximately half an acre of woodland.

While wood is a renewable resource, it does require approximately 20 years for a stand of wood to grow to sufficient height for cutting into wood to make charcoal. Some furnace operations would seek to provide for their long-term needs by purchasing acreage of suitable wood, harvesting it in turn. To produce 600 tons per year of pig iron, the amount planned by the Browns, would require clear-cutting perhaps 300 acres of suitable trees annually. Given the 20-year re-growth, Hope Furnace needed the use of 6,000 acres of wood lots. As the correspondence will show, securing wood and wood lots was a constant concern for the furnace operators.

---

449 300 acres would produce 6,000 to 6,600 cords of wood.
Water Power

A furnace needed to be located along a stream or river with a strong, reliable flow. The ability to store potential water energy in a millpond could provide some temporal control over the release of the energy. However, without sufficient water flow, the high temperatures from the blast of the bellows would be lacking, and the furnace would fail to melt the iron ore. An early colonial attempt in (1645) to establish a blast furnace in Braintree, Massachusetts failed after a short time because the brook upon which it was located lacked sufficient force: “It seems doubtful, nevertheless, if a pond created by damming Furnace Brook could ever have stored enough water adequately to power the furnace water wheel.” 450 Securing sufficient waterpower would be among the Brown’s first tasks.

Transportation

Transportation limitations in the 18th century made cartage of even a modest distance by land prohibitively expensive. Thus the decision about a furnace’s location was absolutely crucial to its success or failure. In addition to being located along a sufficiently powerful stream, the site needed to be:

1) Relatively near to the source of iron ore, typically within a few miles;

2) Near the source of wood for its charcoal, and

3) Not too distant from the market for their iron (or water-borne transport).

When researching the iron smelting business in 1765, Nicholas Brown inquired of founders in Pennsylvania the distances they carted ore and charcoal, and how far they were located from their market in Philadelphia. In response to his letter, he received information on

450 Hartley, p. 108. The area today is in Quincy, Massachusetts.
the inputs required and distances traveled for 15 Pennsylvania foundries. He found that the
distance to their market was much less a factor than the location relative to the material inputs.
While all of the furnaces were at least 39 miles from the city, they were all between 1 and 7
miles from their charcoal, and approximately the same for their ore.\textsuperscript{451}

Each step of iron production has key energy needs. As this case study will illustrate, it is
this demand for primary power that places the owners of iron mining/smelting operations in the
vanguard of those seeking additional power sources. A careful coordination of these energy
sources was required to successfully produce iron. The potential payoff was that the business
that could control all these energy sources would be successful, and its owners would have “gold
and silver in abundance.”

\textbf{The Browns as Energy Masters}

Had they never entered the iron business, the Browns would still have been a leading
family of colonial Providence. Prior to turning their hand to iron production, generations of the
Brown Family had already been successful merchants and businessmen in the colony of
Providence Plantation. The family began business as merchant sea captains trading goods, and
sometimes slaves. In 1770, they were instrumental in founding a college that would eventually
bear their name.

In the 1730’s, James Brown, a successful merchant, was the head of the family. James
had four sons, all of whom would be part owners of Hope Furnace:\textsuperscript{452}

- Nicholas Brown (b. 1729 – d. 1791), who would become a successful businessman. His

\textsuperscript{451} The results for these 15 foundries were summarized in a table, a fascinating early use of the “spreadsheet” as a
decision tool; see JCB: B.177, F.5 for the table; Hedges discusses this data, p. 129.
\textsuperscript{452} These brief sketches are drawn from the work of Hedges.
Furnace for the years 1765 to 1782. In the Colonial Census of 1774, Nicholas’ household is recorded as including 2 slaves.

- Joseph Brown (b. 1733 – d. 1785), the least business-oriented of the four, Joseph’s activities would come to light again and again in circumstances that called for mechanical ingenuity. Joseph was the driving force behind the various efforts to drain the iron ore pits of water, which would culminate in a steam engine. In the Colonial Census of 1774, Joseph is reported to own 4 slaves.

- John Brown (b. 1736 – d. 1803); John has been characterized as the archetypical hard-headed, rapacious businessman. His desire for an unrestrained hand at profit-making would sometimes express itself as a fiery patriotism, as his leading role in the burning of the revenue sloop Gaspee in 1774 will attest. His patriotism burned brightest when it aligned with profit making, as when he enthusiastically turned to privateering during the Revolution. John was the principal force pushing the construction of the air furnace, which was necessary for the production of cannons during the revolutionary war. In the Colonial Census of 1774, John’s household is listed as including 2 slaves.

- Moses Brown (b. 1738 – d. 1836); the youngest son, he would become a Quaker who was active in the anti-slavery movement, and Moses would at one time sue his brother John under an anti-slavery law. After the death of Nicholas in 1791, he would become more involved in the family businesses. It should be noted that Moses was a partner with Samuel Slater in the founding of Slater’s water powered textile manufacturing mill in the 1790’s. In the Colonial Census of 1774, Moses did not own any slaves.

---

Rappleye provides lively portraits of both John and Moses Brown in his *Sons of Providence*. **453**
By the mid-1700’s, the Browns had accumulated sufficient capital to turn from trade to industry. They had already established a manufacturing business that successfully produced spermaceti candles.\textsuperscript{454} In the 1760’s this generation of Browns decided to move into the iron foundry business.

It is unlikely that they would ever have articulated it in this fashion, but first and foremost the Browns masters at extracting an energy-rent.\textsuperscript{455} They understood the importance of controlling energy inputs to the success or failure of a business. For example, in their merchant activities that took the form of trading voyages, they used wind power to move goods to the areas of greatest profit. The Browns were also ready to avail themselves of opportunities for coerced labor, both by their slaving-voyages and by the direct ownership of slaves.\textsuperscript{456} Their fine appreciation of controlling energy resources would be brought to bear on the highly profitable iron smelting business at “Furnace Hope”.

\textbf{From Merchants to Manufacturing}

Hope Furnace and its problems of production were the same faced by iron producers all over the colonies and early republic. There was nothing unique about their furnace or the iron ore pits that supplied it. Indeed, the Browns were latecomers to iron production; by the last third of the 18\textsuperscript{th} century, iron production had largely come and gone from New England.

The original group of partners who formed the Furnace Hope project consisted of Israel Wilkinson, Stephen Hopkins (Governor of Rhode Island), Job Hawkins, Calib Arnold, and the four Brown brothers: John, Nicholas, Moses and Joseph. This group quietly acquired the rights to the iron ore at two known but undeveloped deposits of bog iron, one in Cranston and the other

\textsuperscript{454} Hedges devoted a chapter to this business.
\textsuperscript{455} In the sense that Beaudreau uses the term.
\textsuperscript{456} Except of course for Moses. See Rappleye, chapter 3, for a detailed description of the slaving voyage of the \textit{Sally}. 
in Glocester, Rhode Island. Tests of their ore at nearby Furnace Unity in Cumberland, Rhode Island showed that it was of sufficient quality to produce good pig iron.\footnote{Hedges, p. 130.}

In May of 1765, Israel Wilkinson contracted with Jeremiah Burlingame for the mineral rights to the ore on a certain parcel of Burlingame’s land.\footnote{See Hedges, pp. 126-8.} In July of that year, Wilkinson transferred the rights to a partnership formed with Steven Hopkins, John, Nicholas, Joseph and Moses Brown, Caleb Arnold and Job Hawkins to establish an iron foundry. The mineral rights were to a parcel of land described as

“…lying in said Cranston being the same Land which he” (Burlingame) “then dwelt on bounded easterly on a small piece of land belonging to Captain Israel Gorton, on the South by a Brook called the great Brook until it comes to where Daniel Burlingame’s Land (gaps?) the Brook, Westerly on the said Daniel Burlingame’s land and Northerly on a Highway. With full liberty of him the said Israel Wilkinson to dig and raise such iron ore within any part of parcel of the same land…” (the purchasers) “…engage to pay for every ton of ore that should be dug and carried from this the said Burlingame’s land the sum of six pence Lawful money.”\footnote{July 9, 1765 “Articles of Co-partnership”; JCB: B.177, F.5.}

The “Furnace Hope” that they established in 1765 was not much different from the furnaces that had been active in New England for over 100 years. The Saugus Iron Works, established 1648, had used a combination of iron ore, charcoal and flux in the same type of blast furnace to produce raw pig iron.\footnote{See Hartley, Chapter 9 “Hammersmith – The Technology”.} The Brown’s furnace was located along the north branch of the Pawtuxet River in Scituate, Rhode Island, about 12 miles from Providence waterfront. While not far by modern reckoning, in the 1760’s it was far enough that the Browns could not visit it regularly. The day-to-day operations of the furnace were under the direction of the manager, Rufus Hopkins, son of Governor Stephen Hopkins.\footnote{Rufus Hopkins became manager in 1767, a position he would maintain for the rest of furnace’s existence.} Hopkins was a sea captain who had
conducted trading voyages for the Browns. Although he lacked technical experience, his management skills would prove essential to the success of the furnace.

At first glance a sea captain may seem out of place in charge of smelting iron ore, but in truth the two tasks have much in common. A sea voyage, like the “blast” at a furnace, is a 24-hour per day activity. A crew needs to be assembled and organized; tasks need to occur in a coordinated way for the work to proceed; and the captain needs to secure sufficient supplies to see the organization through to the end of the task, if it is to prove a success.

For the historian, Hope Furnace provides a rare window into the details of an industrial activity during the 1700’s. Although only 12 miles from the Brown’s base of activity in Providence (see map), a trip to and from the furnace was not a casual undertaking in the 1760’s. Given the ceaseless nature of the blast, Hopkins could not travel to consult with the partners. At the same time, since the project involved substantial investment, Hopkins was keen to seek the partners’ input when things did not go as planned. These factors induced Hopkins to keep up a regular correspondence with the Browns in Providence, principally with Nicholas Brown. Nicholas would respond with letters conveying the partners’ decisions. This body of correspondence over the years 1765 to the 1790’s provides a vivid mosaic of an 18th century industry. To the extent possible, I will let the participants speak in their own words.

**An Obsession with Energy**

Hedges, in his assessment of the founding of Hope Furnace, elaborated on the care the Browns took in providing for the project’s energy needs: “In no respect did the proprietors display their entrepreneurial ability to greater advantage than in their maneuvering to **obtain an adequate fuel supply** for an industry located in the midst of a settled agricultural
Further research into the furnace’s operation has shown that this was an ongoing obsession with the partners who operated the furnace.

Figure 11-1. Modern Map of Providence, Cranston, and Scituate. Note that the locations of Hope Furnace and Ore Pits are connected by “Hope Road”.

\(^{462}\) Hedges, p. 132, emphasis added.
From the beginning in 1765, the furnace owners focused on having a sufficient amount of charcoal fuel in their supply chain. Iron foundries require a great deal of wood to produce charcoal, and eastern Rhode Island was not the treed wilderness of Pennsylvania; they were concerned that the expense of wood could render their foundry unprofitable. When negotiating where to locate the proposed furnace, the Browns had extracted energy concessions from landowners. The local landowners were enticed by the prospect that their properties would increase in value, if an active industry such as a furnace were built nearby. What the Browns wanted in return from the landowners was a certain quantity of firewood for fuel. They talked with over 30 area landowners seeking contracted pledges for cords of wood before selecting their furnace site.  

Hedges declared “This threat, so prophetic of the methods employed by railway promoters of a later day to make or break towns, appears to have brought the desired results.”

Thus in 1765, before the ground for construction of the furnace was even broken, the owners collected subscriptions for 5,000 cords of wood. Half of this amount was pledged by just the four largest subscribers: Mathew Manchester (1,300 cords); Charles Lippett (625 cords), plus another 300 cords each from Rich Seares and a Mr. Lippett. Seen in this light, the furnace emerges as a way of transforming wood - cut and delivered at bargain prices by local landowners - into working capital. The Brown brothers knew how to extract an energy rent.

Nor was wood energy the owners’ only concern. The owners of the furnace did not hesitate to use their influence to secure all available waterpower. This brought them into conflict with those who relied on the Pawtuxet River for fish. Native Americans, farmers, and others depended on the fish that would come up river to spawn. Since dam building could potentially

---

463 Rappleye, pp. 94-95.
464 See Hedges, p. 130-132, for several references from contracts with local landowners for cut wood.
465 Account of wood subscribed for furnace; JCB: B.179, F.10.
interfere with this, colonial law (the “Fish Act”)\(^{466}\) required dams to have fish ladders, and provide for release of water during the dry summer months. However, this sharing of the river would reduce the waterpower available to the Browns as furnace operators. The Browns were keen to have at their disposal all the energy the river could provide. With their partner Governor Hopkins, they did not hesitate to use their political influence to exempt their project from both of these two restrictions.\(^{467}\) It should be noted that this was not only a cost-savings measure, it was consistent with seeking the maximum amount of energy from a given source.

**Charcoal**

Their true fixation on energy would be embodied in the work of the manager Rufus Hopkins. In conventional histories of Hope Furnace, Hopkins appears as a minor player. However, when considering the foundry within its energy context, Hopkins’ unrelenting emphasis on securing wood energy emerges as perhaps the key factor leading to the iron foundry’s long-term success. In one of his first letters to Nicholas Brown and Company (December, 1766), Hopkins noted that while he had a “hill” of ore, additional charcoal (“coal”) needed to be hauled as soon as possible:

> “Since Mr. JB (Joseph Brown) was up at the coal pitts we have got thirty four loads in, (and) a hill of ore… (the snow) is very deep and drifted which will make it difficult getting the way Brook to the Pitts, but expect to begin about it (mid January)”\(^ {468}\)

During the more than 30 years he oversaw the furnace, the availability of fuel in the form of charcoal would never be absent from Hopkins’ concerns. Early in the furnace’s history,

\(^{466}\) Discover Hope Furnace, p.3, cites the act of the General Assembly, 1735; see also Rappleye, p. 95.


\(^{468}\) December 20, 1766; Rufus Brown to Nicholas Brown and Company; JCB: B.177, F.9.
Hopkins wanted to go beyond the company’s reliance on pledges of cordwood. In a number of letters, he advocated outright purchase of the land itself to be used as wood lots. He would show himself to be an avid shopper. In a letter dated January 14th, 1769, Hopkins confirmed purchasing a wood lot from David Brayton; Hopkins estimated the land would produce 20 cords per acre.\footnote{January 26, 1769; Rufus Hopkins to Nicholas Brown and Company; JCB: B.178, F.4.} A secondary concern was the distance the wood lots were from the furnace. In a follow-up letter dated January 26th, 1769, Hopkins discussed the measurements of the lot, and included discussion of other wood lots. A letter written a dozen years latter (February 4, 1781) would be almost identical, stressing the importance of securing yet an additional wood lot.\footnote{February 4, 1781; Rufus Hopkins to Nicholas Brown and Company; JCB: B.179, F.2.} This concern for securing his upstream source of fuel would be a constant theme, and contributed to his successful management of Hope Furnace.

Hopkins also dealt with the other energy needs of the furnace. His need for animal power to provide transportation was expressed in a letter of May 10th, 1769 to “Nicholas Brown and Company”. Hopkins described how he had been juggling his available teams of oxen to keep the furnace provided with materials. His concern was that he had only 6 days of “coles”, and 4-days of iron ore even though “…we have had six & seven tons ore bro’t up dayle.” He urged that the company buy oxen, if they at all got the chance. Without them the furnace would run out of stock, and have to shut-in. Just over a month later (June 12th, 1769), he reiterated in a letter to Nicholas Brown and Company that he need teams of oxen to keep the “coles” coming, and urged Brown to keep his people to their contracts no matter how much they complained.\footnote{June 12, 1769; Rufus Hopkins to Nicholas Brown and Company; JCB: B.178, F.4.}

The fine balance of price, distance to cart, and timing are expressed by Hopkins’ in a letter of January 29th, 1783. This letter is quoted verbatim to give the flavor of Hopkins’ staccato
style of writing. He is not composing a formal letter, but presenting a summary of activities to
business partners:

“I am offered about two hundred load coal at four dollars per hundred, should wish
to know whether you approve giving that price. See but little …getting any quantity
under, I mentioned to you could load about 500 cords at 2 per cord at 3 ½ miles
distance,
it is high time to begin chopping the wood, weather nice for begin to chop the two
little parcels on Lippett, Remmington and Sarla lots, I suppose 5 or 600 cords that on
the parcel lot I had reserved for the timbor for that works that on the Lippett plow
another young and is all the wood on the lott…”

The securing of a sufficient store of wood was part of the annual preparation for the blast.
Three items, all dated January 22\textsuperscript{nd} of 1784, show three of the phases of land (wood for charcoal)
acquisition. The first item was a letter from Christopher Lippitt offering some well-wooded land
parcels along “Furnace Road” in Situate. Hopkins was not slow to respond, as their location
along the Hope Furnace Road would simplify the delivery of the wood and the resulting charcoal
to the furnace. That very same day he wrote to Nicholas Brown, reporting that he had examined
the land offered and found some well wooded, some poor, and suggested a bargaining strategy.
Hopkins referred to parcels as “wood-lots”, clearly showing that they were being purchased for
fuel. The strategy must have been successful, as the third item was a receipt for the land.\textsuperscript{473}

This emphasis on fuel supplies did not diminish after the Revolutionary war. In a
February 11, 1787 letter from “Captain Hopkins” to the “Owners”, Hopkins expressed his
concern about keeping the wood workers busy:

(The snow has been deep, slowing the cutting; now only about 8 weeks remain)
“…to chop wood before the people will be taken up upon their farms and there that

\textsuperscript{472} January 29, 1781; Rufus Hopkins to Nicholas Brown and Company; JCB: B.179, F.3.
\textsuperscript{473} Hopkins would eventually purchase this parcel, as shown by a receipt for land, included in the folder with the
offer and Hopkins’ letter to Nicholas Brown; JCB: B.26, F.7.
proposed making coals are as much behind and in cutting their wood as the snow has been so deep…”

A few months later, (May, 1787), Hopkins was still concerned that the available fuel was inadequate. In the interest of keeping the furnace supplied with wood, he suggested paying cash up front. This was an uncommon practice, as commodity “goods” such as iron, flour, or molasses, were typically at least half of any payment made by the furnace to workers. Hopkins reasoned:

“If the money is paid immediately for chopping the wood as promised will be an inducement to chopping more which the choppers proposed doing but if not paid will put a stop to any moore being done…

(There) is about 300 cords moore choppers not yet measured, I think if this first sum is paid when called for should be able to have the quantity Choppers proposed otherwise I have hope where we are.”

The following December Hopkins is again on the prowl; ever vigilant about the fuel needs of the furnace, this letter hints at his planning years in advance for sources of wood. In this letter of December 7, 1787, he relates that he has been offered parcels within 3 miles of the furnace. The first he estimates will provide 400 cords of wood, “200 per season” and be delivered for 3 shillings per cord. He urged the owners to secure this wood supply. A second parcel is 40 acres at 6-dollars per acre cash and assorted goods: “If we intend providing another stack for next year I don’t see that can do better then to buy his wood, wish your opinion upon both offers…”

Modest Fuel Needs of the Engine

---

474 February 11, 1787; Rufus Hopkins to Owners Hope Furnace; JCB: B.179, F.6.
475 May 8, 1787; Rufus Hopkins to Owners Hope Furnace; JCB: B.179, F.6.
476 December 17, 1787; Rufus Hopkins to Owners Hope Furnace; JCB: B.179, F.6.
The fuel availability and cost for the steam engine should be viewed in the context of the overall fuel needs of the Hope Furnace complex. Providence Plantation did not have the wood resources of rural Pennsylvania. Even before they undertook the production of iron, the owners of Hope Furnace understood that the cost of wood to make their charcoal fuel would be a critical choke point. Over the 17 years they operated the furnace prior to the construction of the pumping engine, they successfully took control of their upstream wood fuel needs, and were able to provide 6,000 to 8,000 affordable cords of wood to the furnace each year.

The fuel requirements of the pumping engine at the ore pits fit into the broader energy matrix of the foundry it served. In comparison with the fuel demands of the furnace, those of the steam engine were quite modest. To operate for the six to eight months of the digging season at the ore beds, the engine would need only 400 to 500 cords of wood; this represents not more than 5% to 8% of the total energy needs of the furnace.

The fuel demands of a Newcomen engine are typically characterized using word such as “voracious”. However, within the context of the foundry that had control of its energy inputs, the fuel needs of the engine were easily supplied. The question for the operators was, how did its fuel costs compare with its benefits?

**At the Ore Pit**

“To procure a sufficient quantity of ore to be dug and carted for the use of the Furnace…”

The discovery of the iron ore deposits in Cranston set in motion the activity and investment that resulted in Hope Furnace. However, during the first few years following the establishment of the furnace, discussion of the Cranston ore pit in the correspondence is conspicuous by its absence. This is not surprising because, as Hedges details in *The Browns of*
Providence, the project’s initial years were marked by trial and error at the furnace in Scituate, and a low volume of production. During these years, once the agreement with Burlingame had been secured in 1765, the supply of ore appears to be a minor consideration for the owners of the furnace.

We can suppose that the initial digging followed the experiences of other 18th century bog iron ore “mining”. This took the form of surface recovery or shallow-pit digging of iron deposits.477 We know from references that the workers in Cranston “uncovered” or “cleared” the soil covering a bed of iron ore so that it could be dug out.478 Once dug out, the ore would be “uncored” by breaking out any soil or rock mixed in with the ore. The resulting, somewhat more concentrated ore, was then carted the 4 or 5 miles to the furnace.

Following the first blast in 1765, a summary of resolutions was prepared at the owners’ meeting of December 23, 1765. It is insightful that they made no special provisions for securing ore; they simply called for the “carting” of 200 tons of ore over the winter.479 This implies they did not anticipate any difficulties in getting the ore. In the day-to-day business correspondence, the ore pit only appears when paying for carting.

A rough estimate of the volume of soil dug during the first years of operation at the ore beds shows that it would have been quite modest. A ton of soil occupies a relatively small volume; a single cubic yard (3-feet tall, 3-feet wide, and 3-feet deep) will contain 1.25 tons of average soil; heavier iron ore would occupy even less volume. To put this in perspective, a round pit 8 yards (24 feet) in diameter has an area of just over 50 square yards; digging down just 3 to 4 yards would yield well over the 200 tons called for at the December 1765 meeting.

---

477 See Hartley.
478 November 20, 1767; Letter of William Burton (Cranston) to Nicholas Brown and Company; JCB: B.178, F.1, also discussed below.
479 December 23, 1765; Resolves of the Furnace Company; JCB: B.177, F.6.
The missing variable in estimating the volume of digging at the pit is the relative richness of the ore, but we can reasonably assume that the most productive veins were dug first. Given the relative the richness of the initial find, plus the slow pace at the furnace, securing ore would be a chore on the order of digging a basement for a moderate-sized building.

The Browns and their associates were not the only ones who contracted for ore from the Cranston deposits. Another member of the Burlingame family, John Burlingame, had title to part of the boggy land, and was willing to sell the ore rights. An agreement (August 17, 1765) between John and the pair of Thomas Potter and Job Manchester allowed Potter and Manchester to dig ore on land, north of a brook called Harrods Brook “…as is mentioned in said deed called Harrods Brook…” which John had received from his deceased father’s will of 1755. These competing claims would come into conflict when, after several years, the demand for ore intensified.

For the owners of Hope Furnace, the only difficulties concerning the ore in the first years of operation involved carting it the 4 to 5 miles from Cranston to the furnace. However, at least initially, even the task of carting did not present any problems. A July 11, 1766 letter from Caleb Potter to Moses Brown indicates that there were more people willing to haul the ore than needed. In the letter, Potter was angry, believing that the Browns were snubbing his offer to cart ore; note he is writing to Moses, not Nicholas:

“(you are being unreasonable) with my brother Thomas and I, for you say if we cart any (ore) we shall be the last that is paid. But if I had a thought that you were of that opinion perhaps I should not have (gone down) with my team a four hand (for the) good part of two days to work… as sundry other men may cart for you. But I discover there is some jealousy arises, (suggesting) that we are enemies to your affaires concerning your carting of ore. But this I have to say for myself: I always desired to meet at (Burlingame’s and do the hauling).”

---

480 August 17, 1765; Agreement between John Burlingame and Thomas Potter and Job Manchester; JCB: B.177, F.6
481 July 11, 1766; Caleb Potter to Moses Brown; JCB: B.177, F.6.
The Potters had offered to haul for 7 pounds per ton, but the Browns would pay only 6; Potter assured them that, despite what Brown may have heard, Potter would be willing to haul for 6 pounds, payable in goods. Like many good businessmen, the Browns were ever ready to drive down wages when offered a surplus of labor.

The absence of any difficult in securing sufficient ore is also implied in the formal agreement with Rufus Hopkins to manage the furnace operations. In the agreement, dated November 7, 1766, Hopkins’ responsibility to provide the furnace with wood and “cole” (the charcoal made from wood) was discussed at length, as were his other rights and responsibilities. Ore, however, remained a side-concern; it is only mentioned once and then only in the same context as sand and clay (from a list of duties Hopkins is to perform):

“To procure a sufficient quantity of ore to be dug and carted for the use of the Furnace, as also sand, clay, and every other necessary material…” 482

Note how this agreement foreshadowed what would be Hopkins’ overriding concern during his long tenure at the furnace, fuel supplies. As Hopkins’ correspondence will show, keeping an ample supply chain of fuel for the furnace would never be far from his mind.

By 1766, the ore was being washed prior to its use in the furnace. This seems to be an innovation at that time, as Joseph Brown had been testing the quality of iron made with washed ore. In an October 1766 letter to his brother Nicholas, Joseph discussed testing the quality of the iron pigs made with various preparations of ore:

“Mr. Attwood comes with a ton of washed-ore pigg. You’ll keep them separate so as to know what sort they are.” 483

---

482 November 7, 1766; Agreement between the Owners of Furnace Hope and Rufus Hopkins; JCB: B.177, F.10.
483 October 17, 1766; Letter from Joseph to Nicholas Brown; JCB: B.177, F.9.
By this time, the furnace was finding its market: it was acting as a provider of iron pigs to foundries that would render them into final products. For his part, Joseph Brown was working with the furnace to identify the properties of iron pigs produced by various mixtures of inputs and blast procedures. This example of technical problem solving is illustrative of the role Joseph Brown would play at the furnace and ore pit.

**Initial Methods of Digging Ore**

In addition to hiring their own workers to dig ore, the furnace owners also offered to pay by the ton for ore dug by others. Insight into how the ore was processed during the third year of the furnace’s operation is provided by a formal agreement struck with the Burlingame family in August of 1767:

> “Cranston, August 4, 1767

Tis agreed by the Owners of the Furnace Hope to pay or allow Mrs. Burlingame £ 4 Old Tenor per ton for every ton of ore she procures, dugg and carried out to a convenient place (for carting)… to be paid in rum molasses, sugar, or any other goods at the common price that the said Owners sell their goods at i.e. …Rum at 50/ by the (hogshead) and other goods in proportion…

Tis further agreed that the ore dugg on ground to be dugg by Mrs. Burlingame is to be in such places as may be agreed on or marked out by said Owners, and

Tis also expected that the dins taken off or uncorred from the ore is to be carried to the same place by those who may dig by the ton as the Owners carry the Dirt, dug by those who work by the day or Month…

Witness John Brown and Jabez Bowen.”

Note that prices are somewhat chaotic, as at least three monetary systems -“Old Tenor”, “New Tenor”, and “Lawful Money”- were in place in Rhode Island even before arrival of the

---

484 August 3, 1767, “Agreement…”; JCB: B.3, F.4 (note this had previously been filed in Box 2, Folder 17).
inflation-prone Continental with the Revolution. For comparison, these prices discussed here will be converted into “Lawful Money”, and expressed in “pence” (rather than pounds and pence).

Implied in the above agreement is the cost of the labor to raise one ton of good ore. Note that £4 Old Tenor is about 36 pence or a little under 2 shillings “Lawful Money”. Since, per the original agreement, the Burlingames would already be entitled to 6 pence lawful money for each ton dug by the furnace company, the offer is essentially 30 pence worth of goods for the digging of each ton of ore.

This agreement also indicates that the ore was being dug by the day by workers who separated (“uncorred”) the richer ore from the dirt, prior to carting it to the furnace. Since no mention is made of washing the ore, it is not clear whether that was being done at the ore pit or furnace. This initial separating out of the ore brings out the question: what exactly is a “ton of ore”. The furnace owners would encounter some “inconveniences” paying for a ton of ore, since the actual iron content could vary. A letter of August 1767 from Nicholas Brown and Company instructed “Cap’t Hopkins” that the workers at the ore pit would be paid by the day, rather than by the ton:

“We have considered of the digging + carting of our ore for present blast and are of opinion to have it Dugg by the Day or Month as so many inconveniences may arise by getting it done by the ton, the wages are proposed to give is four pounds...”

Having secured the ore at the pit, the next step was to deliver it to the furnace, approximately 4.5 miles distant. The route required crossing over a relatively large hill, rising from the pit to the peak, before descending to the riverside furnace. Carting was accomplished by two-wheeled carts, pulled by a team of two oxen; these carts would typically carry one ton of

---

485 August 3, 1767, Nicolas Brown to Cap’t Hopkins; JCB: B.178, F.1.
The carts were subjected to rough usage, as an early letter from Joseph Brown to his brother Nicholas relates: “You may depend (that) no pains will be spared (sic) to supply teams while I stay, but carts is more wanting than oxen as there is always more or less axletrees broke”

The company continued to take advantage of the surplus of willing carters. In 1766, the Potters (Caleb and Thomas) had offered to cart at 7 pounds per ton, but had to accept 6 pounds. A year later in 1767, the rate had dropped to 5 pounds, as reflected in the agreement of August 7, 1767 with Thomas Potter:

“… to cart ore from Cranston to the Furnace in Situate at five pounds O(ld) Tenor per ton to be paid in cash for carting sixty ton which is to be carted as soon as possible and the money will (be paid) at Christmas or sooner…”

On this same document, dated Christmas Day 1767, Potter made an “X”, in acknowledgment of the receipt of “300 pounds old tenor” for the sixty tons delivered.

The relative ease with which the ore was acquired, as opposed to transported, is revealed by a comparing Potter’s payment for cartage to the price offered to the Burlingames for the ore itself. Burlingame was offered 4 pounds for each ton dug, broken out of its dirt context, and piled ready for cartage. Potter was paid 5 pounds for transporting each ton to the furnace. However, the difference is even greater, as Burlingame was already entitled to a payment for each ton of ore, no matter who raised it. Converting the prices into pence “Lawful Money” for comparison, the Burlingames were paid a net of 30 pence (after subtracting their mineral rights payment of 6 pence) for lifting, while Potter received 45 pence for carting. It is reasonable to conclude that during these early years, the operators’ had little worry about raising a sufficient quantity of ore, at least less than transporting it to the furnace.

---

486 See for example a letter of December 1, 1785 from Joseph Shaw at Cranston to Nicholas Brown and Company, in which he lists 9 loads of pig iron totaling 10 tons; JCB: B.179, F.5.
487 August 7, 1767; agreement with Thomas Potter; JCB: B.178, F.1.
“…no first Days to furnaces;” the Industrial Nature of Work as the Ore Beds

To say that the ore was easy to get is not to say that the actual work at the ore pits was easy. There are indications throughout the correspondence that the work at the pit was physically difficult. This is seconded by evidence that the work was often accomplished using coerced, if not slave, labor. In using coerced labor at the Cranston ore pits and Furnace Hope, the operators were following a path established by the very first forges in the colonies. As noted earlier, the Swedes had used prisoners of war at Dannemora; in the colonies, indentured servants, slaves, and also prisoners were used.

The Cranston ore bed, as well as Hope Furnace, was worked by the Brown’s slaves, other slaves hired out by their owners, and indentured servants. In a letter of November 20th, 1767 William Burton of Cranston complained to Nicholas Brown and Company about the abuse of black slaves at the ore pit. These slaves were overseen by Burton’s slave named Sharper:

“These are to acquaint you that where as you have employed my Negro fellow Sharper as an overseer of the Blacks to dig ore at the mine + as I understand by them + others they have been illly used: (the Negroes) having cleared several beds of ore, the white men that were employed by your overseer broke into the place the Negroes have cleared; and lately, on the first day of the week past, the blacks having cleared a bed of ore I understand Jeremiah Burlingame’s son Pardon has hired hands + dug the ore (the Negroes had) uncovered; all of which is ill usage; and they ought to have a reasonable allowance for their trouble from somebody.”

In addition to documenting the use of slaves, this letter also provides insight into how beds of ore were excavated, circa 1767. As Burton relates, the dirt covering a deposit of ore is removed, prior to the ore itself being dug out. The letter then continues, providing insight into Burton’s view of both slaves’ religion, and the nature of furnace work. While the religious

---

488 November 20, 1767; Letter of William Burton (Cranston) to Nicholas Brown and Company; JCB: B.178, F.1.
aspect is outside the realm of this dissertation’s interest, Burton’s comment that there are no
days-off underscores the industrial nature of the work:

“Sir, the reason I allowed my Negro to work in the mine on the first day of the week was I thought it might be a means of keeping him + such as he employed out of Mischief as there is but few Negroes troubled with Religion and no first Days to furnaces;…” 489

A month later, in December of 1767, further labor difficulties were described in a letter from Scituate. Rufus Hopkins reported to Brown and Company that there has been trouble at the ore pit.

“PS. I have been and sent several times to Mr. Brandon for an (accounting) of the work done at the ore while he was there, that he might settle (with) …some of the people (who have) been here several times to settle. (I) believe that most of the laborers have taken near or quit…” 490

**Intensifying Extraction at the Ore Beds**

By the end of 1767, they had been digging at the ore beds for three seasons. The labor troubles suggests that securing the ore might was becoming a more difficult task. The company decided they needed better oversight of that branch of the project, and the following spring they determined on a change of management. Per the “Sundry Determinations made by the Owners of Furnace Hope April 16th, 1768”, it was decided:

“That Capt Hopkins call on James Randall and desire him to undertake to oversee the digging the ore, and call on the owners to agree that the owners all meet at the ore” (the ore pit in Cranston) “as soon as may be in order to settle on out with Jeremiah Burlingame and to order the digging the ores.” 491

---

489 Ibid.
490 December 20, 1767; Rufus Hopkins (Scituate) to Nicholas Brown and Company; JCB: B.178, F.2.
491 April 16, 1768; Sundry Determinations made by the Owners of Furnace Hope; JCB: B.178, F.3.
This “Determination” shows that the digging of the ore had become of sufficient concern that the owners needed to meet out in Cranston to set affairs in order. It is unclear what “settling on out” with Burlingame entailed. It may be his payment for ore, or some other purchase of land or rights.

By the close of 1768, the company had been digging bog iron in Cranston for almost four years. James Randall’s letter of May 2, 1769 indicates that the initial phase of their mining activity was coming to an end: the easy ore had already been recovered. The ore pits had entered the next phase in the life cycle of an extractive industry where getting the ore was becoming a somewhat more difficult task, and the quality of the easily available ore was declining.

(James Randall, manager of the ore pit at Cranston, to Nicholas Brown and Company):

“Cranston May 2, 1769

Gentlemen

The hand you sent up to work at the ore, I could not set him to work by the reason I could not gitt him boarded. We could have hands sufficient at this time, if we had board. I do not think it proper to employ any great number of hands at this time for the water is high in the brook and too cold to lower it. The ore that we have got out is very poor and the lower we gitt I think the ore grows rather poorer. I expect that we must search for a new place to dig in and am uncertain whether we find any that is good except that which is now covered with water. I should be glad if you would consult how we should (proceed?). Shall do for board for we have but six hands at this time and I do not expect that I can gitt all them boarded above one week.

From yours to serve,
James Randall”492

492 May 2, 1769; James Randall (Cranston) to Nicholas Brown + Co; JCB: B.178, F.4.
As with other mining operations, Nicholas Brown and Company’s first step was to counter declining ore-quality by intensifying their activities. The Company decided to take action to alter the course of the stream, and thus gain access to previously unavailable ore. Note that in Nicholas Brown and Company’s response to Randall, the “Waterman” referred to in the first line of the letter was one Andrew Waterman, who had rights to the land on the other side of the brook. Andrew Waterman operated a foundry in Smithfield, Rhode Island and secured iron ore from the pits in Cranston. As we will see, moving the brook obscured the property lines, leading to a lawsuit the following year (1770). The lawsuit would be settled in the spring of 1771.

(Nicholas Brown and Company to James Randall)

“Mr. Randall Sir, July 4, 1769

The barer, Dennis Ryan offers to Lore (lower?) the Brook at the ore, if Waterman will pay him half the expense, + he will do it according to our directions. We will pay him (Ryan) the other half at whatever rate you agree with him… 1/3 in cash and 2/3 in goods. Therefore we leave the whole matter to your direction not doubting but that you’ll do as though the interest was you own.” 493

Expanding their mining area

“…we don’t expect to be able to get more ore dugg this season than we shall want to work.”

Prior to 1770, the Cranston ore beds had been prolific enough to allow the Browns to sell excess ore to other furnaces. However, by the fall of 1770, the supply of ore was becoming a bottleneck for the furnace. Ryan’s work moving the stream appears to have allowed access to a sufficient amount of ore for the campaign of 1769. The following year, however, ore supplies were less than had been anticipated. Brown and company had been providing extra ore to a

493 July 4, 1769; Nicholas Brown and Company to James Randall; JCB: B.178, F.5.
furnace operated by Griffin Greene. However, in a letter of September 27, 1770, Nicholas Brown had to explain to Greene that they would not be able to supply him with the ore pledged earlier:

“…we limit you to the quantity… as we don’t expect to be able to get more ore dugg this season than we shall want to work.” (end of letter).

Brown followed up with a second letter a week later on October 4th, 1770:

“Since writing you a few days ago, have seen Cap’t Hopkins who sess we shall be put to difficulty to get our ore enough for the Furnace this year. Therefore wishing you to agree with Waterman” (Andrew Waterman) “for as much as you will work between this & April next, and we will supply you with the money to pay for it… we may depend on you agreeable to the proposition of our agreement.

You friend, N Brown”

The obvious question is: why is it that Brown’s company was not getting the ore they needed, while Waterman (on the other side of the stream) had a surplus? The answer is possibly found in a lawsuit laid out in a letter of December 12, 1770. Nicholas Brown and Company asked their lawyer Joseph Winson to pursue a lawsuit concerning the exact boundary

“… between the furnace Owners + Andrew Waterman, concerning the dividing line between them in the Brook which bounds both partys, where the iron ore is dug in Cranston.”

Apparently, the Browns had been coming up short on iron ore, and the lawsuit was their response to assert their claims. In a letter of December 24th, 1770, Brown and Company called upon Peter Burlingame (“Capt’n Burlingame”) to provide evidence as to where the middle of the

---

494 September 27, 1770; Nicholas Brown to Griffin Greene; JCB: B.178, F.6.
495 October 4, 1770; Nicholas Brown to Griffin Greene; JCB: B.178, F.6.
496 December 12, 1770; N. Brown and Company to Joseph Winson; JCB: B.178, F.6.
“Brook” originally was, as this was the dividing line between the property of the Brown’s and that of Andrew Waterman. Brown’s letter stated that the jury would be looking at the land tomorrow (Christmas day) and Burlingame was instructed to come by and give his testimony any time, as they will be in session all day

“in order to ascertain as near as possible the middle or center of the original Brook and to Platt and bound the same accordingly.”497

The lawsuit appears to have resulted the following spring in an agreement, dated March 14th, 1771, between the Browns and Andrew Waterman that gave the Browns control of the ore beds. In this contract between the two parties, the Browns agreed to provide Waterman annually with 100 tons of iron ore for use at his foundry in Smithfield, Rhode Island. Waterman could either pick up the ore at the Brook (“on dry land”) for 9-shillings per ton, or for only 6-shillings and 9-pence if Waterman dug it himself. In return, Waterman turned over control of his part of the ore-fields to the Browns.498

Note that Waterman is offered two prices, one for dug ore and a discount if he digs it himself; the difference between the two is the implied price for lifting a ton of ore. The difference between the offered prices is 2-shillings, 11-pence per ton; converted to pence for comparison, this is 51 pence per ton. This is a significant increase over the 30 pence per ton offered the Burlingames four years earlier. Other factors may be in play, but this price increase is suggestive that, as activity intensified, the iron ore was becoming more difficult to mine, and thus its lifting became more expensive.

By purchasing Andrew Waterman’s land, the Browns secured control of the iron ore for themselves. Never ones to miss an opportunity, they quickly determined which part of

497 December 24, 1770; N. Brown and Company to Peter Burlingame; JCB: B.178, F.6.
498 March 14th, 1771; Agreement between Nicholas Brown and Company and Andrew Waterman; JCB: B.178, F.6.
Waterman’s land they needed to mine, and sought to gain some benefit from the rest. An April of 1771 agreement between Brown and Company and one Richard Searle leased Searle “…the land thy purchased of Andrew Waterman and in Cranston all except the lott near the ore which is reserved for the use of laying ore carting & etc…also lease the house with the land for the term of one year.” Having leased the unneeded land, they then sought to gain some advantage for the furnace: “…(rent is) fifty dollars or the digging and carting of 50 tons of ore from the bed as it naturally lays to the furnace.” (Set our hand this seal etc…)\(^\text{499}\)

With these agreements, the Browns had a clear legal claim on the iron ore they needed. The next phase would be to deal with nature, in the form of water flooding the pits. They had begun in 1765 by digging the easiest ore; by 1769, they had taken to shifting the brook’s course to allow access to additional deposits. By 1772, the intensified digging at the ore pits necessitated working down below the water table. As many a miner before them, the Browns needed to turn to pumping if their extractive activities were to continue. While the initial procurement of ore had been accomplished by human muscle power (with the assistance of oxen), their mining in the 1770’s would require substantially more primary energy. The Browns were confronted with the task of finding additional primary power sources for pumping water.

\(^{499}\) April, 1771; Agreement between Nicholas Brown and Company and Richard Searle; JCB: B.178, F.6.
Chapter 12: Hope Furnace and the American Revolution

The advent of the America Revolution shifted activities at Furnace Hope into a new dimension, greatly increasing the demand for iron ore from the Cranston beds. During first ten years of production, the furnace had found success as a producer of simple pig iron, an intermediate commodity. After 1775 its focus turned to cannon, a finished product that, with the advent of the war, found itself suddenly fashionable.

Recasting pig iron into cannon created several needs. The production of cannon required greater expertise in casting and an additional mill for boring. Fuel was required to re-melt the iron, and then the roughcast cannon needed to be finished. At the furnace, the Browns met this need by extending their energy-use menu to include coal, that is, mineral coal. To bore-out the cannon, they harnessed additional waterpower to drive a turning mill.

The ore beds also needed additional primary energy beyond what could be provided by human labor or ingenuity in re-routing streams. They employed mechanical power to pump water out of their ore pits. Initially, the Browns first drew on waterpower for their pumping needs. This is not surprising, as they were thoroughly familiar with this technology from its various applications at the foundry. Eventually, in 1783, they would enhance their pumping capabilities through the installation of an atmospheric steam engine. The date is surprising, as it comes at the end of the Revolutionary war. Rather than a response to a need for pumping, the engine can be seen as a desire to master energy conversion, maximizing profit. The chain of events that led to the erection of the engine began with the building of an air furnace several years earlier.
Coal at the Air Furnace

The Americans in revolt needed cannon to defend themselves. It was not lost on the some that cannon could also be used to outfit privateers. The steady parade of ships that plied between Britain and the Americas was a source of wealth for the home country, but not particularly well defended. Capturing some of these would weaken the enemy, perhaps weaken the will of the trading classes in Britain to continue the war, and not incidentally enrich the venture capitalists that outfitted the vessels. It should not be surprising that the Browns were keen to enter the cannon-making business.

In 1776, led by John Brown, the owners determined to build an air furnace to compliment the blast furnace already at Scituate. An air furnace, technically called a reverberatory furnace, is used to re-melt pig iron so that it can be cast into molds for finished products. Unlike a blast furnace where the fuel and metal was mixed in the same combustion chimney, in an air furnace the two were physically separated. The heat was exchanged through the “air”, thus the common term for the furnace. This form of heat exchange was less efficient than a blast furnace, but necessary to avoid introducing impurities into the finished product.

While it is possible to cast simple shapes directly from a blast furnace, the air furnace allowed the molder greater control over the process. To cite just one factor, the qualities of the iron pigs put into the air furnace were known in advance; this allowed the founder to closely control the quality of the iron going into the casting, an essential requirement for complicated castings, such as a cannon.

As with other technical challenges for the furnace and ore beds, Joseph Brown was called upon to direct the building of the air furnace. The documentation shows Joseph gathering his materials and labor. In October of 1776, his cousin Nicholas Powers wrote him that he had

---

500 Hedges, p. 277.
secured from Peares Hall “...a boat load of good merchantable bricks…” suitable for the air furnace. 501

Figure 12-1. Typical Reverberatory (“Air”) Furnace for Re-Melting of Pig Iron.

- “Coal” (mineral coal) was placed into the furnace at left; “A” is the ash pit below the coal.
- “W” is the bridge wall to separate the fuel from the metal in the furnace.
- “B” is the furnace arch, which reflects heat down upon the furnace charge. The arch on the Brown’s air furnace would require extensive repair at various times.
- “Pig Iron” was placed in the hearth to be melted, after which it would be drawn off into molds.
- “C” is the chimney opening, controlled by a damper

Modified from: An Elementary Outline of Mechanical Processes by G. W. Danforth (1912).

Casting Cannon

It would be difficult to overstate how thoroughly the topic of cannon production would dominate the correspondence between Hopkins and the Company during the period 1776 to 1783. Domestic production of this armament was not only important for the war effort, but also profitable for the company. Before they could take advantage of this trade, they needed to secure experienced molders. The Browns had sought for founders in the New Jersey and Pennsylvania,

but without success.\textsuperscript{502} Governor Steven Hopkins (Rufus Hopkins’ father), while attending the Continental Congress in Philadelphia, inquired after cannon founders, but had to report to Nicholas Brown that “But one other man in America who understands Foundery of that kind”, somewhere in Maryland. He advised the Browns to seek elsewhere for cannon casting expertise.\textsuperscript{503}

Joseph recruited among the iron-founders of Massachusetts, and found his men among the Keith family of Bridgewater. The iron founders at Bridgewater had already successfully produced cannon. Bridgewater had an air furnace, and the local founders had learned the art of casting cannon from a French officer, Louis de Maresquelle. De Maresquelle had been appointed superintendent of furnaces by the Massachusetts colonial government in 1776.\textsuperscript{504} He introduced the technique of casting cannon solid and then boring them out. This is the same technique that would later be used at Hope Furnace, which suggests that the source of the casting expertise was the Frenchman, via the Keiths. This is a small point in the context of cannon production, but will prove important when tracing the pedigree of the Brown’s engine. Hedges suggested that Peter Curtenius of New York had been their source of founders familiar with cannon casting.\textsuperscript{505} Recall that Curtenius was the founder who cast the cylinder for the pumping engine in New York City in 1776. Following Hedges, Purcell specifically states that these founders would likely have helped with the casting of the cylinder of the New York engine in 1776, and thus provided the expertise for the Brown’s engine casting.\textsuperscript{506} However, given that the correspondence shows the early involvement of the Keith family with the air furnace, it seems

\textsuperscript{502} Hedges, p. 269. \\
\textsuperscript{503} Quoted in Hedges, p. 269. \\
\textsuperscript{505} Hedges, p. 270. \\
\textsuperscript{506} Purcell, p. 9.
more likely that they were the source of expertise. When they came to build an engine, the Browns were not copying New York, but relying on their own company’s expertise.

![Figure 12-2. A Cannon Boring Mill. Illustration from Biringuccio’s *Pirotechnia* showing how cannon castings may be bored. At Hope Furnace, the boring was powered by a waterwheel, and most likely the cannon was in an upright position. Note the cannon-mill would have been water powered, an additional demand for prime movers.](image)

The Keiths were called upon to help with the construction of the air furnace. In early 1776, apparently prior to the start of construction of the air furnace, Joseph Brown wrote to Ezekiel Keith, Scott Keith and Jonathan Keith, asking them to come to begin work on February 26th of 1776. He asked them to inform Jonathan Stearns that he also had a job, Joseph also sent a similar note to Lewis Sweeting. A formal agreement from a few years later (March, 1780) shows the typical terms for molders. In it, Seth and James Keith agree to do cannon molding for the year of June 1780 to June 1781. They will govern the work of five others, and are to be paid in bar-iron and Indian corn.

---

507 February 17, 1776; letter from Joseph Brown to Ezekiel, Scott, and Jonathan Keith; JCB: B.178, F.8.
508 February 18, 1776; letter from Joseph Brown to Lewis Sweeting; JCB: B. 178, F.8
509 March 26, 1780; agreement between Seth and James Keith on the one hand and the company on the other; JCB: B.178, F.10.
The history of cannon production at Hope Furnace was well discussed by both Hedges and later by Rappleye.\textsuperscript{510} The early production of cannon had some difficulty as a number of cannon burst during “proving”. Cannon were proved by loading them with powder, two cannon balls, and double wadding. If the cannon survived this double-shot, they were deemed adequate for military use.\textsuperscript{511} Early bursting problems, not unlike the early quality problems the company faced in 1766, appear to have been quickly overcome through practice.

Most of the cannon produced at Hope Furnace were small 3 to 6 “pounders”. By 1780, they were also producing quantities of 9-pound cannon.\textsuperscript{512} The furnace would on occasion cast larger 12-pound canon, but a February 1780 letter from Joseph Brown to his brother Nicolas suggests that this was unusual. In the letter, Joseph describes the materials needed to produce a pair of 12-pounders. The production of these larger cannon appears to be an innovation, and the list of materials provides a good overview of what went into casting ordinance:

“Extra experience in casting cannon at the air furnace  
Carting in every part  
All kinds of labor  
Black Smith works  
Repairs of the furnace  
Boarding of the men”

He estimates the cost of the 12-pounders at £ 3400. He summarized the materials needed concisely: “Lots of iron, Sea Cole, ChawCole + wood”\textsuperscript{513}

Without calling into question the Brown’s patriotism, or devotion to the Revolution, it should be noted that the cannon they produced were exceptionally profitable. This goes beyond just the obvious wartime demand for cannon: these small cannon were also employed profitably.

\textsuperscript{510} Hedges, Chapter 13; Rappleye, Chapter 9.  
\textsuperscript{511} See April 8, 1780 agreement between the company and John Brown; JCB: B.178, F.10.  
\textsuperscript{512} A cannon’s size refers to the weight of the shot it fired; for example, a “6-pound” cannon fired an iron ball weighing six pounds.  
\textsuperscript{513} February 28, 1780, letter from Joseph Brown to Nicholas Brown; JCB: B.28, F.4. “ChawCole” refers to charcoal from wood.
Many of Hope Furnace’s light cannon were destined for privateers, where they would be used against unarmed, lightly defended merchant ships sailing under the British flag. It should be noted however that even the frigates of the new “Continental Navy” were not much more heavily armed.\textsuperscript{514} John Brown and his brother Nicholas were eager to get into the lucrative privateer game, which they pursued from 1776 onward.\textsuperscript{515} Their first privateer, the \textit{Diamond}, although it carried only six 4-pound cannon, captured five British vessels during its one-month cruise off of Bermuda.\textsuperscript{516}

In its essence, a cannon is a tool for concentrating the chemical energy in gunpowder. This facilitates what Douglas North has called dryly referred to as “a comparative advantage in violence”.\textsuperscript{517} To produce these cannon, the Browns, led by Brother John, studiously managed their energy resources, a skill the family had demonstrated previously. John’s financing of the air furnace allowed for the exploitation of coal, certainly an early example of converting this stored energy. This studious attention to energy conversion paid well: By the end of the Revolution, John Brown was the wealthiest man in Rhode Island.\textsuperscript{518}

\textbf{Mineral Coal Use at Hope Furnace}

\textit{“Sea Cole Deliver’d at the Air Furnace…as much cole as they can get to 20 or 25 chaldren.”}

Even prior to the Revolutionary War, Hope Furnace was already an energy intensive operation. It demanded wood energy in the form of charcoal, waterpower to drive the bellows, harnessed chemical energy to reduce the iron, and consumed labor in both its human and animal forms. The air furnace added a new dimension to these energy demands, in the form of coal.

\textsuperscript{514} These vessels of the “Continental Navy” rarely carried a cannon larger than a 12-pounder. See William Fowler \textit{Rebels Under Sail} (New York: Charles Scribner and Sons, 1976).
\textsuperscript{515} Hedges, p. 279; see also Rappleye, pp. 201-204.
\textsuperscript{516} Rappleye, p. 203.
\textsuperscript{517} Douglas North, \textit{Structure and Change in Economic History}, p. 21.
\textsuperscript{518} Rappleye, p.211.
Mineral coal was not used in 18th century blast furnaces for the reason that it altered the chemical properties of the iron. However an air furnace, unlike a blast furnace, heats iron indirectly. For this reason, mineral coal could be used. It is significant that, once the air furnace was available, the Browns lost no time in expanding their menu of energy inputs by adding mineral coal. Coal is not typically thought of as a fuel in New England, certainly not in the 1700’s. However, the documentary evidence is clear that Hope Furnace was receiving regular shipments of mineral coal, which they usually referred to as “sea coal”, following the usage of the term in Britain.

The exact source of the coal used at Hope Furnace has not yet come to light, but it most likely came from Rhode Island itself. There are a number of local coal deposits in Rhode Island that were in use prior to the Revolution. While certainly small by the standards of Pennsylvania, three local areas - Portsmouth, Providence, and indeed Cranston itself - all had exploitable seams of coal that were worked in the 18th century. In Portsmouth Rhode Island, located only a dozen miles down the bay from Providence, mineral coal was actively mined into the early 19th century. As early as 1768, the Rhode Island General Assembly had granted a patent to parties who were to dig after “Pit-Coal” or “Sea-Coal” in “the Hill at the Back of the Town” of Providence.

The quantity of coal shipped to the air furnace was not a trivial amount. Preparing for the production of 36 9-pound cannon in the spring of 1780, Joseph Brown called for delivery of 20 to 25 cauldrons (“chaldren”) of sea coal.

“As to my self, I would agree to make and sell Mr. Clark Nightingale the 36 9# each sold at as much less than £4,500 per pair as they can get… Sea Cole Deliver’d at the

519 See discussion in Gordon’s *American Iron, 1607 – 1900.*
520 The furnace was completed c. 1776/77, and using abundant amounts of coal by 1778 at the latest.
Air Furnace for less than £425 per chaldren, for as much cole as they can get to 20 or 25 chaldren.”

A “caldron” of coal in the colonies is thought to have equaled 36 bushels and 2,880 lbs., implying a weight of 80 pounds per bushel. Thus Joseph is calling for the delivery of 28 to 36 tons of coal.

In an October 30th (1778) letter to John Brown, Rufus Hopkins described coal being delivered to the Air Furnace and charcoal to Hope Furnace:

“35 loads of coal d’ at the air furnace amounts to three thousand eight hundred + thirty three bushels at nineteen dollars per £ 218, 11.6”

The eleven loads d’ at Hope Furnace amounts to one thousand two hundred + five bushels at sixteen dollars per £ 51.17.0”

While the quantity of coal in 35 “loads” is vague, the 3,833 bushels provides a likely context. At 80 pounds per bushel, the quantity of coal delivered is just over 150 tons.

As with other projects, the correspondence provides greater detail when unexpected trouble strikes. At the air furnace, this occurred in September of 1780 when the arch of the furnace (part “B” in the air furnace diagram) broke down. In a series of letters, it was determined to reline the arch with white clay bricks, and then temporarily brace it. Over the following winter, the Browns had the air furnace rebuilt. In February of 1781, Nicholas Brown secured the services of Giles Leach to oversee the re-construction, beginning in March.

In anticipation of the furnace rebuild, the deliveries of coal resumed:

---

522 Note from Joseph Brown, appended to an agreement between Nightingale and John Brown, April 8, 1780; JCB: B.178, F.10.
524 September 5, 1780; letter from Rufus Hopkins to Nicholas Brown; JCB: B.28, F.5.
525 February 22, 1781; letter from Nicholas Brown to Giles Leach; JCB: B.179, F.2.
February 6, 1781  
Dexter Brown has Del’d one load Sea Coals, W16~1~14  
R. Hopkins”

Dexter Brown was paid for carting the coal. The weight is recorded on the receipt using a “tons-hundredweight - pounds” convention, meaning the total delivered was 32,114 pounds. While far too much for one load, billing for multiple cart-runs was common. Converting back to cauldrons, it would equal approximately 11 cauldrons; compare to the 20 to 25 caldrons Joseph Brown called for to cast 36 “9-pound” cannon. A series of receipts from May of 1781 underscores the brisk pace of mineral coal deliveries to Hope Furnace:

“May 10, 1781  
Joshua Partridge delivered Twenty three (tons) sea coals and rec’d 1pr six pounders for (Mr. Cabelly?) (signed) Rufus Hopkins.”

“May 24, 1781  
George Colvin has del’d one load Sea Coals wt 16, 1, 14”

“Scituate 29th May 1781  
Mr. Wm Henry has delivered at Hope Furnace Wt 37, 1- Sea Coal (signed) Stev. Hopkins Jr.”

“Scituate 31 May 1781  
“George Colvin has delivered at Hope Furnace Wt 15, 2- Sea Coal (signed) Stev. Hopkins Jr.”

These delivery figures follow the convention of “tons, hdwt, pounds”, meaning that in just the month of May (1781), the air furnace received 23+16+37+15 = 91 tons of coal. The extensive deliveries of coal, along with the other materials and the shipment of the finished cannon, strained the available cartage. A January 1781 letter of Nicholas Brown’s not only mentions “Sea Cole”, but it also speaks to the chronic shortage of transportation (oxen energy) at

---

526 February 6, 1781; receipt signed by R. Hopkins; JCB: B.932, F.1. By hauling 16 tons, Dexter Brown may have learned the answer to Tennessee Ernie Ford’s rhetorical question, but it is not recorded. Pity.

527 Receipts issued at Hope Furnace; JCB: B.932, F.2.
that late date of the Revolution. In a letter to John Knap, he discusses the shipping of cannon but notes:

“Sir: The nine pound cannon are now ready, and as there is loading up every cart or wagon must be high enough to hold sand or the fine part of Sea Cole as no team will be loaded down with cannon without taking up a load with suitable carriage---and if you cart them you must (do so at your own risk).”

The cannon would have been delivered from the Furnace down to Providence; Nicholas made it clear that the cannon would only be shipped in a wagon suitable for bringing back a load of sand (for casting) or “the fine part of Sea Coal”. If Mr. Knap wanted the cannon sooner, he would have to arrange his own transport.\textsuperscript{528}

The use of coal by the Browns foreshadows the pattern industry would follow in the 19\textsuperscript{th} century. They initially sought to provide for the energy needs of their manufacturing using organic energy sources. However, as production intensified, they sought out additional sources. Eventually they employed the concentrated power found in coal. A similar evolution took place with regards to their use of labor. Initially, they operated using a combination of human and animal labor. As production intensified, the energy demands outstripped these supplies. They would employ mechanical labor for these additional needs. Here again, their first choice would be the organic energy, such as watermills, with which they had long experience.

\textbf{Expanded Primary Energy Demand at the Ore Beds}

Prior to the Revolution, the recovery of ore had already become a duel with water. The early search for ore avoided flooded areas. However by the early 1770’s, avoiding water was already impractical. Under the direction of Joseph Brown, pumping began at the ore pits. The

\textsuperscript{528} January, 1781; letter from Nicholas Brown to John Knap; JCB: B.179, F.1.
early evidence is sketchy, but receipts suggest that pumps were being used at the ore beds at least as early as 1772. In that year, Joseph Brown (signing “for the company”) made an agreement with Hannah Smith for pump work:

“Agreed to give Hannah Smith six dollars per month for Pump work till the season be over or digging ore which will be seven or eight months—~ to pay one half money and half goods at cash price by retail.”

As with other technical problems Furnace Hope had faced in the past, Joseph Brown was on the scene devising a solution. The agreement does not provide details about what powered the first pumps. An interesting detail, it should be noted that the digging at the ore pit lasts “seven or eight months” until the “season” would be over.

With the advent of the Revolution, the expanding demand for labor and primary energy made itself felt at the ore pits. In March of 1776, the ore beds received a new overseer, Benjamin Handy. His contract called for pay of 60 pounds per year and he was allowed 7 shillings 6-pense per laborer per week for the board of up to 15 laborers. Handy was to board the laborers at local farms and the “Company will supply bed and blankets”. Two weeks later, the company ran this advertisement in the Providence Gazette:

\[\text{\textit{\footnotesize\textsuperscript{529}1772 (month not recorded) Agreement between Joseph Brown and Hannah Smith; JCB: B.178, F.7. \textsuperscript{530}March 13, 1776; Agreement with Benjamin Handy; JCB: B. 178, F.8. \textsuperscript{531}Providence Gazette, page [3], vol. XIII, iss. 639; publication date: March 30, 1776}}\]
Assuming that Handy found his workers, the pits employed as many as 16 people to provide ore when Independence was declared. By 1780, the management of the ore pits had passed from Benjamin Handy to Joseph Shaw. Shaw appears to have been successful, as he directed work at the ore pits until well into 1790’s. Shaw would be in charge of the ore pits during their most intensive periods of production.

As ore extraction intensified during the Revolution, water pumping would emerge as a task of critical importance. At some point, the company harnessed waterpower to drive pumps clearing the pits in Cranston. The date of the initial construction of a mill wheel to provide primary power to the pump out the ore pits is not yet known. While it is possibly as early as 1772, the earliest definite description of the waterwheel used to drive the pumps comes from a replacement of the pumps in 1780. How long the previous pumps had been in operation is not certain.

In a 1780 letter dated February 28th, Joseph Brown discussed activities at the air furnace, and then returned to a discussion about the construction of replacement pumps that Joseph was designing for use at Cranston:
“…the Potters are mistaken about pine pumps lasting as long as oak; they wont last half as long for our use but they may probably last long a nough so that if oak can’t be gott pine may do, but then they should be rather longer or they will split as the long bore means of necessity (that they) be placed near the bottom of the (longer) log of the 2 which are to be put together and the upper one must be bored threw and threw so as to be straight and all the way of a bigness…”

When Rufus Hopkins was first managing the furnace in the 1760’s, the supply of ore had been a rarely mentioned, trivial concern. By 1780, even with the new pumps, supply of ore was a growing worry for him. In a letter of October 30, 1780 his primary concern was the shortage of oxen for carting. Turning to the problem of ore supplies in P.S., he suggested to Nicholas Brown:

“PS: should you have time … think it advisable to give Shaw a visit and if possible have a hundred ton of ore more got by washing or other ways, as the Blast will be very short (of supplies without it).”

There seems to have been some problem with the ore, as indicated in a terse note six weeks later from Benjamin Alpin “for Rufus Hopkins” to Nicholas Brown: “The Ore is not carting as yet, and as Captain Hopkins is not yet returned, am not about to give you any further account of it.”

**Pumping water with a millwheel**

“…ready this week to set the wheel a going.”

Although the discussion is not recorded, the Company decided to take steps over the winter of 1780/81 to improve its ability to mine ore through a project that would give them control of additional primary energy. To clear the ore pits, they would harness waterpower itself,

---

533 Not incidentally, this is a shortage of animal-power, and indicative of the general stress on available sources of energy during the war.
534 October 30, 1780; letter from Rufus Hopkins to Nicholas Brown and Company; JCB: B. 28, F.5.
535 December 9, 1780; letter from Benjamin Alpin (Scituate) to Nicholas Brown and Company; JCB: B. 28, F.5.
using an improved mill wheel to power the pumps.\footnote{536} Unfortunately, as with the pumps themselves, the date that the wheel was first employed is a bit obscure. Fortunately, the rebuilding in early 1781 of a penstock to divert the water from the brook to the millwheel was discussed in detail in several letters from Joseph Shaw, the manager at Cranston, to Nicholas Brown and Company. Shaw’s discussion of problems with the “old penstock” indicates that they were rebuilding, or perhaps moving, an earlier mill wheel.\footnote{537}

In a letter dated February 5\textsuperscript{th}, 1781, Shaw notes that the weather had not been good otherwise he would have put many hands to “the task”. A February 26\textsuperscript{th}, 1781 note from Shaw in Cranston to the Browns acknowledged receipt of lumber for the project: “Have rec’d of John King, Esq. One Thousand feet of plank (for) which he is to have three hundred of sound iron per agree’t.”\footnote{538}

In a separate letter dated that same day, he elaborated on the progress with the construction:

“I cant be ready for a \textbf{corker} so soon as I expected by reason the dirt is so frozen on the plank on the \textbf{old penstock} but next Monday at surest I shall be ready. I shall want about 50 wt of okam …and half a bbl of tarr…”\footnote{539}

In a seacoast town it would not be hard to find a skilled ship’s corker. A corker would typically use the oakum (“okam”) and tar to waterproof the gaps between a ship’s planks. At Cranston, the task was to cork a trough, technically called a penstock, to keep the water in, rather than out. The penstock would carry diverted water to a mill wheel. Also note that Shaw refers

\footnotesize{\textsuperscript{536} For a discussion of using water power to pump mines, see Clavering “The Coal Mills of Northeast England: The Use of Waterwheels for Draining Coal Mines, 1600-1750” (1995).  
\textsuperscript{537} As noted elsewhere, it is problems and delays that tend to generate the correspondence that provides insight into the workings of the furnace and ore pit.  
\textsuperscript{538} February 5, 1781; letter from Joseph Shaw (Cranston) to Nicholas Brown and Company; JCB: B. 179, F.2.  
\textsuperscript{539} February 26, 1781; letter from Joseph Shaw (Cranston) to Nicholas Brown and Company; JCB: B. 179, F.2, emphasis added.}
to the “old penstock”, indicating that this new one is a repair or rebuild. More detail is provided in Shaw’s progress report, a letter dated March 4th, to Nicholas Brown:

“…half the penstock is ready to cork… (Shaw has one corker, needs a second) …had 14 hands yesterday, expect 6 more tomorrow…set all the hands that did not understand working on timber to digging out the Trench below the mill, which have nearly completed. I hope and expect to be ready this week to set the wheel a going.”

His letter shows that it is late winter and Shaw is overseeing twenty men who are building the penstock “to set the wheel a going”. The pumps themselves had been replaced the previous year (1780). The brook used and the type of wheel it drove is not identified, but either Meshentucket or Furnace brook could have been diverted to drive a wheel in the vicinity of the ore pits. Before steam power there was stream power: the mill wheel would drive the pumps to drain the pits.

**Intensification of Labor Needs**

“… Street Negroes and Indians will be gladly received.”

Shaw’s project to enhance the company’s ability to drain the ore pits appears to be part of an overall plan to mine greater quantities of iron ore. Already in February of 1781, Nicholas Brown was seeking additional workers. That month, he had written to George Keith of Bridgewater, offering a significant pay increase to any hands willing to go to Cranston and work in the ore pits. Note that in earlier years, Brown had tried to entice skilled workers from Bridgewater to come to Hope Furnace. A shortage of laborers is suggested in that, in 1781, he is seeking relatively unskilled diggers:

---

540 March 4, 1781; letter from Joseph Shaw (Cranston) to Nicholas Brown and Company; JCB: B. 179, F.2.
“…we shall want a number of hands to dig ore this spring. Will pay their wages in ore… 5 tons for each man working at the rate… this is the manner we agreed with Mr. Dean and others.” Brown noted to Keith that previously “We gave 2 tons of ore for a man the work of good hands.” ²⁴¹

Note that this higher wage is a real increase, based on a commodity (iron ore), and not a reaction to the devalued Continental currency. The wartime labor shortages and urgent demand for iron ore had induced the Browns to increase returns to labor.

By April 1781, the work on the penstock-waterwheel-pump complex was completed and the water-powered pumps were draining the ore pits. Shaw described the work in a letter; significantly, this letter was written directly to Joseph Brown, rather than Nicholas Brown and Company. Joseph Brown appears to have had special supervisory authority when it came to technical improvements at the ore bed.

“Sir, have the works under the best way… possible… with what I have to do with. I yet lack of hands: I have seventeen and I want thirty at least.” ²⁴²

“I have got the deep hole within about a foot of the ore, (although) much more dirt then I expected has been taken out (with the) ore… more or less. (Digging) every day since I was at Providence, in the whole about 150 ton.” ²⁴³

Shaw had been experiencing the same difficulty finding workers that Nicholas Brown had discussed with George Keith. Shaw concluded his letter to Joseph Brown with an appeal for additional workers:

“(send barrels of beef and pork)… Should be extreamly glad the owners would pick up a few hands along… Street Negroes and Indians will be gladly received.” ²⁴⁴

²⁴¹ February 14, 1781; Nichols Brown to George Keith; JCB: B.179, F.2.
²⁴² Note that this would be 30 laborers, twice the number Benjamin Handy was allowed to employ in 1776.
²⁴³ April 26, 1781; Joseph Shaw (Cranston) to Joseph Brown; JCB: B.179, F.2.
²⁴⁴ Ibid
This seems to be an example of how intensified labor demands lowering barriers to employment. Industrialization, it seems, provides wage opportunities to individuals who might otherwise be excluded.

In an earlier paragraph of his April 1781 letter, Shaw provided some key details about how the digging was conducted at the Cranston ore beds (emphasis added):

“Sir if we dig ore in three pits at once, I shall want about 40 fathom of main warp a part of which I stand in immediate want of to strap tubs. I likewise want some small rigging for safety lashing which I have not one fathom…”

Shaw is still addressing himself directly to Joseph Brown; he is asking for “main warp”, a type of heavy rope or cable such as used for ships’ anchor or mooring lines. These heavy lines were used to lift the tubs filled with ore from the bottom of the pits. Each tub would hold one-ton of ore and dirt. Significantly, the digging is planned for possibly three pits simultaneously. Given Joseph Brown’s role of technical trouble-shooter, his direct involvement in the setting up of the millwheel and the multi-pit system suggests that this may have been an innovation at this time, or at least was a technically tricky project that could not be left to the local manager.

Shaw’s letter states that the digging is planned for possibly three pits, and he needs “40 fathoms” of heavy lifting line. Note that a fathom is six feet, so 40 fathoms would be 240 feet of lifting lines, divided among the three pits, or 80 feet of lifting line per pit. The description of the three-pit system is consistent with that given by the Reverend Cutler during a visit six years later (1787). Cutler describes the ore pits as “wells”, which they no doubt resembled. From Reverend Cutler’s June 1787 description:

\[\text{Ibid.}\]
There are two large pumps in the well, which is 80 feet deep and 23 feet wide. The sides of wells are supported by the large timbers, laid horizontal, so as to make the form of the wells quintangular, and the ends of the timbers let into one another.”

“By the sides of the well from which the water is drawn are two other wells of the same form, 70 feet deep. These are sunk down in the bed of ore; and in these are the workmen, about ten or twelve in number, digging ore. The ore is raised in large buckets, which hold about one ton weight, let down and drawn up by large chains, carried from the well to a large capstan, which is constantly turned by an ox. As one bucket rises, another goes down. These wells are kept dry by the water continually drawing off into the well where the pumps are fixed, and the pumps keep water below the height where the men work.”

Cutler was describing the pits as they appeared six years later when the steam engine was in operation. While the pits drained by the millwheel were probably not as deep, they were likely drained using the same system, with digging conducted in several pits at the same time. The water was drained off from the pits where ore was being recovered into a deeper pit, which functioned as a sump. This sump-pit was then drained using the pumps. The prime mover for the pumps in 1781 was the water-powered mill wheel.

The lifting system in 1781 was probably the similar to Culter’s description. Shaw’s 1781 letter requested heavy lines (“main warp”) to strap and lift the tubs of ore; these are the tubs Cutler described as holding about one ton of ore, each. Note that these tubs were relatively compact; a round tub (or barrel) three feet across and four feet high could easily accommodate a ton of dirt.

We can assume that the work went well during the summer of 1781, as the following October Shaw was able to report to the owners of Hope Furnace that:


547 Compare the similar tubs depicted in the landscape painting of Dannemora.
“I go on in digging ore as well as may be expected; have our shaft within 16 feet of
the Gangway above the height of dirt carried out from the other pit… have got out
upwards of a hundred ton of ore and can nearly supply the Furnace dayly with three
hands vz can take out about six ton per day…”

Firsthand Examples of Temporal Limits of Waterpower

“…before the water is gone.”

The power provided by a small stream or brook was not always reliable. In addition,
although the bulk of the power needed to drive the pumps was provided by the water-powered
wheel, the penstock and mill system required a certain amount of labor. In the following spring
of 1782, labor shortages had again made procurement of sufficient ore supplies difficult. In
April, Shaw reported to Nicholas Brown and Company:

“I have not yet a number of hands sufficient to set the Wheel a Going so as to dig in
the Deep Hole and Keep the underground Work going on.

-- Am sir you ready ser’t Joseph Shaw”

At that same time, five miles away at Hope Furnace in Scituate, Rufus Hopkins was
preparing for another campaign of pig iron production. He had written a number of letters about
cannon that were either in production or waiting to be proven. By the 18th of May, he reported to
the Owners in Providence that the furnace was ready to blow. However, in a letter dated May
28th, 1782, Hopkins expressed his concern for the ore supplies; he wanted the company to push
Shaw’s mining efforts. At the root of this concern was his perceptive assessment of the limited
nature of waterpower:

“(would be less worried if) …had we (a larger) quantity ore dug first… which I think
Shaw had better have ordered to do. …I doubt he the least proficient of… providing

548 October 22, 1781; Joseph Shaw to Owners of Hope Furnace; JCB: B179, F.3.
549 April 5, 1782; Joseph Shaw to Nicholas Brown; JCB: B.179, F.4.
us with ore by digging. This is a matter which the Company would think of and give directions immediately, before the water is gone.”

Hopkins’ concern was that a lack of waterpower could make it impossible to get a sufficient quantity of ore, and without ore the whole blast would be brought to a halt. Hopkins’ concern was based in the spatial and temporal inflexibility of organic power sources, discussed in Chapter 3. An eloquent earlier example is found in a letter of Abraham Bush to the company. Bush had been sent some pig iron that he was to draw into merchant bars, for use by a blacksmith. However, in late May (1773, emphasis added), he regretted that he…

“May inform you that I have got the iron made for you to pay for the pigs I had of you but cannot draw it for want of water yet, but as soon as we can draw it will send it to you. It has been a very lean times for water with us this winter and even spring…”

Summer was not the only time when waterpower might fail. Frozen water in the winter, or a heavy snow that would fill in a millwheel’s penstock, was a peril for operators. To cite another example, January of 1780 was a crucial time for the Revolution, and so Hope Furnace was pushing ahead with the boring of cannon at its “cannon mill”, a water-powered rig for boring out the roughcast cannon. Unfortunately, Hopkins had to report that the cannon mill was idled due to snow and ice filling its trench and that the delivery of the cannon would be delayed.

Hopkins provided a graphic first-hand description from a later 1786 episode at Hope Furnace. Related in a letter to the Owners, Hopkins described how an early December storm

---

550 May 28, 1782; Rufus Hopkins to Nicholas Brown; JCB: B28, F.6
551 May 20, 1773; Abraham Bush (Taunton, Mass) to Nicholas Brown and Company; JCB: B.5, F.3, emphasis added.
552 January 12, 1780; Rufus Hopkins (Scituate) to Nicholas Brown and Company; JCB: B.28, F.4.
slowly choked the power to the bellows that provided the blast, leading to an “unhappy affair for the Company”:

“We began to blow the Furnace Sunday morning 26 November: the very cold weather that set in reduced the water very much, and when the snow storm set in Monday evening the 4th” (of December, 8 days after starting the blast) “just had barely sufficient to keep the wheel going so as to keep the furnace in order, and before twelve at night the snow had blocked so into the river…”

Hopkins explains that the crew spent what must have been a long, cold night trying to keep the blast in order as they “…turned wheel by hand over night to keep going, but eventually had to shut down.” The losses were considerable. They had produced only 16 tons of iron; the furnace was 2/3rds full of un-smelted material; and Hopkins confessed himself at a loss how to clear it without damaging the hearth. The unreliable nature of waterpower had produced what Hopkins concluded was “…this unhappy affair for the Company and to myself in particular…”

---

553 December 6, 1786; Rufus Hopkins (Scituate) to Owners; JCB: B.179, F.6.
Chapter 13: The Brown Steam Engine at Cranston

Much like the water-powered mill wheel it replaced, we lack the details about the deliberations that led up to the decision to build an atmospheric steam engine. However, we do know the circumstances surrounding the engine’s inception, and much about its construction can be pieced together from correspondence and accounting receipts. The research for this dissertation has revealed an important shift in context of the decision to build an engine; the engine was not built in 1780, during the Revolution, but in 1783. Hedges, in his excellent history of the Browns, was not able to date with precision the year of the engine’s construction. He reasonably concluded “…it must have been contemporaneous with the replacement of the pumps in 1780.” This date made sense, assuming the engine was intended to provide steam power where waterpower was faltering.

The supposed 1780 construction date supported the suggestion that the building of the engine was forced by the contingencies of the War: labor was in short supply, and cannon were extremely profitable. This interpretation provides both a reasonable explanation for the engine’s construction, and as to why its fuel demands would be tolerated. However, given that the true construction date was three years later, this can not have been the motivation.

Since it was actually erected in 1783, only a few months before the formal end of the War, we are presented with a puzzling question: Why was the engine built just as demand for cannon was falling? The answer may be found by considering the actual relation of the engine to cannon production: the engine was not built to facilitate cannon production; rather the Browns had an opportunity to erect the engine because the demand for cannon was evaporating.

---

554 Hedges, p. 279. All other authors that have come to light have followed this incorrect date.
555 In addition to Hedges, see Rappleye or J. Walter Wilson “Joseph Brown, Scientist and Architect” in Rhode Island History, quarterly journal published by the Rhode Island Historical Society; vol. iv, no. 3, pp. 67-79.
It seems more than coincidental that the engine was constructed the year the Revolution ended. Its first operation may have even been in September, the month that the Treaty of Paris was signed, formally ending the war. Production of cannon, which had so taxed the abilities of the furnace, would trail off. This slowdown in production would also take pressure off of wood supplies. Rather than meeting the frantic production demands of 1780, the Browns were confronted with a different business problem: how could they profitably employ these idled energy sources? The timing of the engines construction suggests that it was part of their answer. The engine’s fuel needs may have not even represented an incremental increase in wood demand, but possibly a way of using excess wood supplies.

First, we can dismiss any notion that their declining need for iron ore was a surprise to the furnace operators. In February of the previous year, 1782, they had placed an advertisement in the *Providence Gazette* newspaper:

“The Owners of the Cranston IRON MINE inform their old Customers, and others, that there is ORE to be sold at the Ore Bed. Good Bar Iron or Cash will be received in Pay.”

This was only twelve months after the rebuilding of the penstock, which indicates that the millwheel-driven pumps were allowing the company to dig more ore than they needed for their own use. They now have plenty of ore for their “old Customers”. Since the company had excess ore to sell, it means that the millwheel was more than keeping up with the pumping needs of the ore pits. This undermines any suggestion that the steam engine was meant to replace insufficient waterpower.

---

Over the winter of 1782/83, the Browns no doubt found themselves discussing what to do with a surfeit of ore, fuel, and casting expertise that would result from the peace. They needed to figure out a way to employ these resources. As they had in the past, they showed themselves masters at anticipating and manipulating energy flows. With Joseph Brown taking the lead, they determined to erect a steam engine to operate the pumps at the ore pits. This would allow them to convert wood energy into useful work, while freeing up the water-powered millwheel at the site for other tasks. As we will see, they did not neglect the waterpower at the ore pits, but put it to good use powering a blacksmith’s shop.
Building the Engine, 1783

“...six tons (of pig iron) are reserved for Engine, which quantity I think Mr. (Joseph) Brown told me would be wanted."

In an interesting example of how experience tends to feedback on innovation, the Browns were enabled in their attempt to erect a steam engine by the very thing that had earlier created the need for additional pumping. Their extensive casting of cannon had greatly increased the demand for iron ore; one result of the intensified digging was an increased need for water pumping. They had initially met this demand with the familiar technology of waterwheel, which they had already employed successfully for the blast furnace, air furnace, cannon mill, etc. As the work progressed, the experience gained from casting a thousand or more cannon emboldened them to take on the technical challenge of casting an engine cylinder two feet in diameter and perhaps eight to ten feet long.

Their casting experience was essential. There is a distinct learning curve to casting of cylinders that will withstand various pressures. An alarming number of the first cannon cast at Hope Furnace burst during testing at the foundry. As late as November of 1778, Rufus Hopkins had to report problems proving cannon, where he had to prove seven to secure four, as three of them had burst. By the spring of 1783, the problems of bursting cannon, which is to say weak castings, had been relegated to the air furnace’s early history. The company could call upon the extensive casting skill of the brothers Keith of Bridgewater. The steam engine cylinder would be a bigger project for them, but not conceptually different from casting cannon.

---

557 The figure used here of 1,000 cannon is likely too low; Hedges concluded from his examination of the records that John Brown’s claim to have produced 3,000 cannon was boastful, but that the actual number was no doubt quite large; see p. 275-7. Using one-third of John Brown’s figure seems a safe minimum, and more than enough for the molders to have developed extensive casting expertise.

558 November 5, 1778; Rufus Hopkins to Nicholas Brown and Company; JCB: B.178, F.9.
It is not known if any of the Browns had seen first-hand either of the two earlier
Newcomen-type engines built in the colonies. The engine erected in New York City in 1776 had
been cast by Peter Curtenius, their some-times business partner. Early in the furnace’s history,
Curtenius had on several occasions provided the Browns with technical advice regarding iron
production. On the strength of these connections, Purcell in his Early Stationary Steam
Engines in America conjectured a connection between Curtenius and the “unknown” skilled
casters hired by the Brown’s in 1776. The research for this dissertation has shown that the
casting was actually done by members of the Keith family of Bridgewater Massachusetts. As
note earlier, the “moulders” at Bridgewater appear to have learned the art of casting cannon from
a French officer, Louis de Maresquelle. In any case, it is not at all likely that the Browns
would have traveled to New York during the time it was occupied by the British, September
1776 to November 1783. All this suggests that any connection between the Brown engine and
that in New York was tenuous, at best.

As for the design of the atmospheric engine itself, it may be possible to set aside any
outside guidance, as Joseph Brown had already demonstrated technological precociousness on a
number of occasions. For example, he had solved the early problems of poor quality pig iron
through a series of controlled experiments using different ratios of inputs. In 1776/77, he
oversaw the building of the air furnace, and he directed Shaw in the rebuilding of the mill and
penstock in 1781. Hedges noted that Joseph had designed new pumps for the ore pits in 1780.
All this suggests a person who could readily grasp the principles of an atmospheric engine.

559 See Hedges, p. 152; he dates the first contract with Curtenius to July 3, 1767. For Curtenius’ casting of the
cylinder of the New York engine, Chapter 10.
560 Purcell, p. 9.
Elsewhere, it has been noted that Joseph’s scientific interests had led him to participate in an observation of the transit of Venus across the sun in 1769.\textsuperscript{562} Among his other technical achievements, he had overseen the building of a fire-fighting pump in Providence 1772, and over the years had planned five architecturally important buildings in Providence. These five include the “College Edifice” at Rhode Island College, which became University Hall on Brown University’s campus.\textsuperscript{563} Given these technical inclinations, especially his experience with pumps and other air-pressure machines, it is not a stretch to believe that he would have made himself familiar with the principles of an atmospheric engine using steam as a medium to produce a partial vacuum. A 1774 inventory of goods belonging to the Brown Brothers includes among its books at least two “Dictionary of Arts”, which would have likely contained descriptions of various industrial machinery, including fire-powered engines.\textsuperscript{564}

It is interesting that at no time in this correspondence does anyone refer to the proposed machine as a “fire” engine. The term fire engine, used since the early 1700’s, accurately describes an atmospheric engine, which derives its motive power from fire. The term fire engine had been used to describe the machine built in New York eight years earlier; this suggests the Browns learned about engines from some other source.\textsuperscript{565}

By February 1783 the project of casting the cylinder was already underway. In his letter of February 13, Rufus Hopkins asked for confirmation of how many tons of pig iron Joseph Brown wanted set aside for the engine:

\textsuperscript{562} Wilson noted Joseph’s work with Benjamin West, citing the latter’s \textit{An Account of the Observation of Venus Upon the Sun, the third day of June, 1769, at Providence, in New England} (Providence, 1769).

\textsuperscript{563} A discussion of these achievements is found in Wilson.

\textsuperscript{564} JCB: B.5, F.13.

\textsuperscript{565} For its part, the Oxford English Dictionary claims that the expression steam engine appears to be no older than 1751 in Britain.
“(have made some cannon) …and have eighteen ton pigg iron left which suppose may make up the 14 sixes and ten three pounders …Provided six tons are reserved for Engine which quantity I think Mr. Brown told me would be wanted. But I should be glad to know from him the just quantity… for fear I must remember what he told me at once… (letter continues, discussing casting and cannon).”

In the same letter, Hopkins wants to clarify how the molders will be paid. When casting cannon and other products, the molders were paid by the piece. However, for the casting of the engine, they want to be paid by the day. It is a testament to the casting skill of Seth Keith (again of the Bridgewater Keiths) that his presence was thought essential to a successful casting of the engine cylinder. Further, Keith was able to specify that he would be paid in cash, at a time when most workers were paid some if not all of their wages in goods. Hopkins wrote that he could not keep Keith waiting at the furnace, but that:

“Seth Keith has (gone home)… …and don’t propose doing anything towards the steam Engine at this time but go home for a short time and return when Mr. Brown may be ready.”

A few days later, February 16th, 1783, Hopkins confirmed that he had received Nicholas Brown’s reply, and would reserve the six tons of pig iron for the casting of the engine. Hopkins informed Nicholas that the steam engine molds were being worked on, and were “…mostly partly ready”. Always with an eye to his fuel supply, Hopkins in the same communication noted that he had 350 cords of wood on hand.

The setting up of the steam engine at the ore pit was not widely discussed in the documentation that survives. While frustrating from a research point of view, this is typical of

---

566 February 13, 1783; Rufus Hopkins to Nicholas Brown and Company; JCB: B.26, F.6. Note how cannon still dominate Hopkins’ concerns, even at the late date of 1783.
567 Ibid
568 February 16, 1783; Rufus Hopkins to Nicholas Brown and Company; JCB: B.26, F.7.
the Brown’s business correspondence: their letters generally discuss problems (and their solutions), or the receipt of goods; there is little discussion of projects that are working smoothly. This lack of discussion has been noted for their other innovations such as the watermill-powered pumps and the air furnace. In the case of the air furnace for example, it was little discussed during its construction in 1776-1777, except for the occasional mention of the receipt of bricks for its construction. Its operation was scarcely mentioned, save for receipts for coal and output of cannon. However, when the arch of the air furnace broke in 1780, and it required extensive repair, it was the subject of numerous letters back and forth. This pattern suggests that, since any of these expensive innovations would have required agreement among the owners, they were discussed during face-to-face meetings and the resources for the projects agreed upon. By contrasts, any surviving on-the-spot correspondence would have dealt with unexpected problems or receipts for goods and payments.

While the accounting documentation does not specifically speak to the engine’s casting, from Hopkins’ earlier letter we can surmise that Seth Keith was the key employee for the casting of the engine. An accounting receipt dated July 5th, 1783 asked for the rather high payment of $60 cash to be made to Keith:

“Scituate 5th July 1783
Sir if you have any money on hand belonging to the Company, please to pay Seth Keith (illegible) moulders Sixty Dollars + charge the same to Hope Furnace the same being charged to the moulders here. Rufus Hopkins”.

Another worker known to have been involved in the erecting of the steam engine was Calib Ormsbee. Rufus Hopkins sent the Company a bill for Ormsbee’s services two days later,

---

569 July 5, 1783; Rufus Hopkins to Nicholas Brown; JCB: B.932, F.6.
on July 7, 1783.\textsuperscript{570} Calib, along with his brothers John and Elijah, would perform a number of skilled tasks at the Cranston ore pits during the 1780’s and ‘90’s. Their skill as mechanics led Calib and John to be founding members of the Providence Society of Mechanics and Manufacturers.

The documentation is suggestive, but little more, about the setting up of the engine at the ore bed. Its construction is hinted at in a mid-July (1783) receipt for bundles of shingles (along with a barrel of beef) that was sent out to the ore pits.\textsuperscript{571} Early the following month (August), John Ormsbee, who described himself as a house carpenter, was paid $60.\textsuperscript{572} Since we know from a later description that the engine was enclosed in an engine house, it is possible to suppose that he was involved in construction of the engine’s structure and housing.

An unusual request in September of 1783 may have been related to the truing-up of the engine cylinder. Joseph Brown sent Rufus Hopkins on a special mission; Hopkins wrote directly to John Brown asking for “bars of English steel of the best quality”:

> “Mr. Joseph Brown desires that (Stodd?) and myself pick it out as the best Quality is wanted, and charge the same to Mr. Joseph Brown.”\textsuperscript{573}

It should be noted that on a number of occasions Hopkins had requested bars of “German” steel for preparing the roughcast cannons.\textsuperscript{574} It is tantalizing to suggest that the “best Quality” of English steel is for a more precise project such as truing up the various valves and parts for the parts for the engine, but this is only conjecture.

\textsuperscript{570} July 7, 1783; Rufus Hopkins to Nicholas Brown; JCB: B.932, F.6.
\textsuperscript{571} July 15, 1783; receipt for cartage to the ore pits; JCB: B.932, F.6.
\textsuperscript{572} August 9, 1783; Rufus Hopkins to Nicholas Brown; JCB: B.932, F.6.
\textsuperscript{573} September 11, 1783; Rufus Hopkins to John Brown; JCB: B.79, F.4.
\textsuperscript{574} See for example letter of January 30\textsuperscript{th}, 1783 from Hopkins to Nicholas Brown and Company; JCB: B.79, F.4. Note that “English” or “German” were not imports, but locally produced; the proper names indicate certain types of steel.
The following month, October 1783, Calib Ormsbee acknowledged payment for his work done at the ore bed:

"Rec’d of Nicholas Brown three pounds and sixteen shillings, six pence (lawful money) toward work done at the Ore for the Furnace company P/month £ 3.,16.,8 (signed) Calib Ormsbee" 575

The receipt does not specify the work Calib did in 1783, but it was specifically “at the ore” beds in Cranston, not the furnace. Later documents that do specify Calib’s tasks at the ore pit show that he was paid for work on the engine, such as in 1786 when he was paid for operating the steam engine.

**Timeline**

Putting these pieces of evidence together, the following timeline of the engine’s construction emerges. Over the winter of 1782 to 1783, the company decided to build an atmospheric engine to provide the primary power for the pumps at the ore pits. While building a steam engine would be a significant capital investment, Hope Furnace was well positioned to provide the materials and expertise in-house. With the winding down of cannon production, they would have surplus materials and time for the castings. They already had the six tons of pig iron, plus a highly experienced and skilled casting staff on hand. Joseph Brown himself could have provided the design work, drawing on his experience successfully designing pumps and other pressure-dependent mechanical devices.

In February of 1783, the work preparing the molds to Joseph’s design was begun. Seth Keith was in charge of the casting, which was completed some time before July. The central cylinder, not counting piston and other subassemblies, is estimated to have weight between 1,800

---

575 October 7, 1783; Calib Ormsbee to Nicholas Brown at Providence; JCB: B.932, F.6.
and 2,600 pounds. Its transportation the 5 miles from Hope Furnace to the Cranston ore beds would have been a significant task, but within the hauling abilities of ox carts that typically carry one ton of cargo. At the ore bed, the engine and its boiler were erected in a house specially designed for them. From later descriptions, the building was two and a half or three stories high. The various pipes and plumbing were set up, and trued-up, circa September 1783. Calib and John Ormsbee were likely the key personnel in the mechanical setting up of the engine and probably the building the engine house as well. While the first date of operation is not noted, Calib Ormsbee was retained to operate the engine, a task he would continue into at least 1786.

**First-hand Descriptions of the Engine**

“The engine raises 7 hogsheads of water in a minute, and the flue consumes 2 cords of wood in twenty-four hours.”

Even if we knew nothing else about the engine built at Cranston, we could assume, since it was built during the war, that it was a Newcomen engine. This is because Watt’s first version of an engine with a separate condenser was not completed until after the start of the Revolution. Fortunately there are first-hand descriptions that confirm the engine was of that type. David Wilkinson of Pawtucket visited the ore pits in 1792, when he was 21 years old. Among his “reminiscences”, Wilkinson included a brief description of the engine. Note that he describes the water as being raised 72 feet (highlighting added).

“On my way home from the Hope furnace I called at the ore bed in Cranston, and found Mr. Ormsbee (I think Elijah) of Providence repairing the large steam engine, which raised the water **seventy-two feet** from the bottom of the ore pits. The engine was made with the main cylinder open at the top, and the **piston raised with a large balance lever**, as the news of the cap on the cylinder by Bolton & Watt had not yet come to this country when that engine was built. Mr. Ormsbee told me he had been reading of a boat being put in operation by steam at the city of Philadelphia, and if I would go home with him and build the engine, he would build a steamboat. I went
home and made my patterns, cast and bored the cylinder, and made the wrought iron
work, and Ormsbee hired a large boat of John Brown, belonging to one of this large
India ships—should think about twelve tons.”

Wilkinson would become a leading mechanic in his own right in the early 19th century,
working with Samuel Slater and would later erect his own “Wilkinson Mill” in 1811. He
certainly would have understood the difference between a Newcomen-style engine and a Watt
engine with its covered cylinder and separate condenser.

Wilkinson shows his grasp of the engine’s technical detail when he describes the piston
as being raised by the beam lever. He is not being casual in this description: The beam,
connected by chains to the pumps in the pit at one end and the piston on the other, is weighted so
when at rest it pulls the piston back to the top of the cylinder. Steam pressure is not used to raise
the piston; the balance lever raises it, as Wilkinson accurately observed.

Elijah Ormsbee is perhaps best known for this experimenting with a steam-powered boat
in the mid-1790’s. He had been working at the ore beds since at least 1785. In this, he was
carrying on the family business, as his older brothers were involved in the setting up of the
engine at Cranston in 1783. By 1792, when he experimented with propelling a boat using a
steam engine, Elijah could have had as much as seven years’ experience overseeing the operation
of the Brown engine.

The most complete description that has come to light is from the Reverend Manasseh
Cutler. The Reverend Cutler, who kept a detailed diary of his travels, was an acquaintance of

Pawtucket, North Providence, of the One Hundredth Anniversary of the Incorporation of the Town, June 24th, 1865.
(Pawtucket, Rhode Island: Robert Sherman, Printer, 1865).
http://books.google.com/books/about/North_Providence_centennial.html?id=IUMuAAAAAYAAJ (accessed March
17, 2012).
577 Gary Kulik and Patrick M. Malone The Wilkinson Mill, 1811 Pawtucket, Rhode Island (published by The
American Society of Mechanical Engineers, October 12, 1977).

578 See receipt for his board, dated March 18, 1785 and countersigned by Joseph Brown; JCB: B.932, F.7.
Jabez Bowen, one of the partners in Hope Furnace. While traveling through Rhode Island, Cutler made a side trip of eight miles to Cranston specifically to view the engine. His diary description of the engine is from 1787, or four years after the engine had been constructed. His description is quoted in its entirety, and then analyzed below.

“Wednesday, June 27, (1787)

This morning I received a polite invitation from Governor Bowen,” (Jabez Bowen) “in the name of a large company, to join them in a Turtle frolic, six miles out of town. Mr. Hitchcock and the other clergymen of the town were of the party, but, much against my inclination, I was obliged to excuse myself. Spending my time in Turtle frolics would very illly comport with the long journey and public business I had undertaken. As I went out of town, Mr. Hitchcock and I waited on Governor Bowen. 579 I informed him that it was my wish to visit the famous steam engine at Cranston, of which he is one of the proprietors. He proposed excusing himself from going with the Turtle party, and riding out with me to the engine, eight miles from Providence; but it must have deprived him and the company of so much pleasure as they had then in prospect, I insisted on his not thinking of it, and went on myself to Cranston. To go to the furnace and engine was eight miles, nearly, out of my way, and a road I had never traveled; but my curiosity was so much excited by the description of so singular a machine, and the only one in America, that I could not deny myself the pleasure of viewing it.

I arrived at the ore-beds at 12 o’clock. The engine was at work, raising water from a well 80 feet deep. The iron flue is 2 ½ feet wide and 6 feet long, with a square hearth at the mouth, secured from fire by large, thick, iron plates. On the back part of the flue is a winding funnel, which passes into a chimney on the back part of the building. A wooden boiler of 6 feet diameter is placed above the flue, which is constantly kept full of water when the engine is in motion. The boiler rises above the first story of the building, much in the form of the large cisterns in distilleries, where it receives at the top the condensing cylinder, 2 ½ feet in diameter, and made of plated iron. From this cylinder a large worm passes with many windings down the boiler. The valve” (the engine’s piston) “that passes into this cylinder is more than 2 feet in diameter, and rises and descends by means of an iron rod made fast to one end of the large beam. Around the top of the boiler are numerous leaden pipes, some connected with the condenser and some not, furnished with stopcocks for admitting or excluding air or water, as necessary in working the machine; but they are too numerous and complicated to admit of any description from a mere view of the machine.

579 Jabez Bowen had been Deputy Governor of Rhode Island 1778-9.
A large reservoir of water is placed in the third loft of the house, constantly affording water to the works below, and as constantly supplied (with a pump for the purpose), by the working of the machine. The large beam is a massive piece of timber, nearly 4 feet in diameter and 20 feet long, being two very large oak timbers nicely forged together. It moves on a large iron bolt in the center, like the beams of scales, and has two arching timbers at each end, forming the segments of a circle, along which two chains of a prodigious size play as the beam moves. One of these leads to the piston or valve of the condenser, and the other, at the opposite end, to the pumps in the well. There are four cold water pipes, one feeding pipe, and one venting pipe. By the same motion of the beam which raises the water out of the well, all these pipes open or close, by the means of stop-cocks and valves, as the design of them requires.

There are two large pumps in the well, which is 80 feet deep and 23 feet wide. The sides of wells are supported by the large timbers, laid horizontal, so as to make the form of the wells quintangular, and the ends of the timbers let into one another. The engine raises 7 hogsheads of water in a minute, and the flue consumes 2 cords of wood in twenty-four hours. The immense weight of the beam, the cast-iron wheels, large chains, and other weighty parts of the works, occasion a most tremendous noise and trembling of the large building in which it is erected, when the machine is in motion.

By the sides of the well from which the water is drawn are two other wells of the same form, 70 feet deep. These are sunk down in the bed of ore; and in these are the workmen, about ten or twelve in number, digging ore. The ore is raised in large buckets, which hold about one ton weight, let down and drawn up by large chains, carried from the well to a large capstan, which is constantly turned by an ox. As one Bucket rises, another goes down. These wells are kept dry by the water continually drawing off into the well where the pumps are fixed, and the pumps keep water below the height where the men work.

This curious machine was made under the direction of Joseph Brown, of Providence, and is a standing proof of the abilities of that able philosopher. The invention was not new, but he has made many valuable improvements, in simplifying and making the working of it more convenient, above what has yet been done in Europe. It cost upward of one thousand pounds sterling.\(^{580}\)

The completed engine must have been a tremendous sight. By itself, the oak rocking-beam linking the piston to the chains that operated the pumps, at four feet in diameter and twenty long, would have weighed over 11,000 pounds. In an interesting detail, Cutler describes the beam as 4 feet in “diameter”, suggesting that that the main beam was made of two rounded

---

\(^{580}\) Cutler, pp. 205-208.
pieces of oak. In another interesting detail, Cutler confirms that the machine had self-activating gear that opened and closed the valves “By the same motion of the beam…”.

The Reverend Cutler was not an engineer, and, at face value, we do not know how accurate his description may be. However, upon examination, his description contains insights about the engine’s horsepower and fuel efficiency that are consistent with later analysis of Newcomen engines. Cutler stated that the pumps operated by the engine “raises 7 hogsheads of water in a minute”. The volume of water in a “hogs head” varies, but about 60 gallons was a common colonial measure. 7 hogsheads per minute would be $60 \times 7 = 420$ gallons each minute. Since water weights 8.3 pounds per gallon, the machine was clearing 3,500 pounds of water from the bottom of the sump pit each minute.

If the well really were 80 feet deep, this means 3,500 pound of water was lifted 80 feet, or the work done was about 280,000 “foot-pounds” each minute (3,500 pounds times 80 feet). Since one-horsepower is 33,000 foot-pounds per minute, dividing 280-thousand by 33-thousand equals the power of the engine, about 8.5 horsepower. 8 ½ horse, while a bit on the high side, is reasonable for a Newcomen engine with a cylinder 24 inches in diameter. Since it is extremely unlikely that Cutler would have been familiar with the operating characteristics of the average Newcomen engine of the 18th century, we can attribute the reasonable nature of his estimates to close observation on his part.

Alternatively, Wilkinson described the engine as raising the water 72 feet. The two figures are close; perhaps 80 feet was the depth to the bottom of the well, while the engineer Wilkinson was more accurately noting the 72 feet is the depth to the water level (the “lift”). If

---

581 Contrast this availability of high-quality wood resources in Rhode Island of the 1780’s with Dannemora Sweden fifty years earlier, where the beam was a composite of pine and oak.

so, then the 80 foot-deep well described by Cutler had 8 feet of water in it, which the pumps worked. Lifting the water only 72 feet would be 10% less, for an engine rating of 7.6 horsepower. Again, a rating quite in line with a typical Newcomen engine of that size.

Cutler stated that the engine used two cords of wood per day. It is possible to crosscheck the accuracy of his observations using the concept of thermal efficiency. Using his figure for fuel inputs, and the work done by the engine as estimated in the previous paragraph, it is possible to calculate the engines efficiency. Consider first the inputs: in round numbers, two cords of a good hard wood, such as oak, has 51 million BTUs of energy. In return for this input, the output of an 8 ½ horsepower engine run for 24-hours would be the energy equivalent of 0.5 million BTUs. This would be an efficiency of 1%, or one useful bit of work out for every 100 bits of fuel used. Note that 1% would match the level of efficiency of the well-run Newcomen engines in Europe. Alternatively, assuming the lift of 72 feet reported by Wilkinson would indicate an efficiency of 0.9%, still an excellent, but quite realistic, efficiency for an atmospheric engine without Watt’s separate condenser.

These realistic estimates of thermal efficiencies suggest that the operators were forthcoming to Cutler, and that he was accurate in his recording of the details. Compared with other engines and their known operating characteristics, we can conclude that the fuel-use figure of 2 cords per 24 hour day is a reasonable figure for an engine that pumped 7 hogs-heads (420 gallons) per minute, as it implies estimates of thermal efficiency and horsepower output consistent with a well-built and operated Newcomen engine. With this information, we can now gauge the cost of fuel for the Brown engine.

---

583 These concepts would have been unknown to Cutler and the engine’s operators, as the science of thermodynamics was not developed until the 19th century.
584 One horsepower produces 61,113 BTUs in 24 hours; 8.5 HP would produce eight-and-a-half times as much or 518,323 BTUs, or about half a million in round figures.
585 Chapter 7 discussed the efficiency of these engines in greater detail.
An Inefficient Engine that fit into an Efficient Energy Using System

Newcomen engines were notoriously inefficient. The 1% efficiency rate calculated for the Brown engine, typical for these types of engines, rendered them prohibitively expensive for most applications. Yet, the Brown engine was used well into the 1790’s, to about the year 1800. This is in contrast to Britain, where these engines were tried in a number of different applications, but succeeded mostly in coalmines. At the mine, the engine’s fuel was right to hand, and some of its extravagant fuel needs could be met using “wasters”, which were bits of coal uneconomical to ship. The steam engine’s use in mills and foundries had to await Watt’s separate condenser, with which an atmospheric engine to would require only one-fourth or one-fifth as much fuel for the same output of work.

Given these consumption characteristics, how is it possible that the Brown engine could be run economically? The cost of fuel was a limiting factor in the application of engines during this time period. By contrast, the documentation for Hope Furnace contains surprisingly few references to the fuel for the engine. A possible answer comes to light by considering the furnace/ore bed complex as an energy using system. When tallying the overall energy use at Scituate and Cranston, several factors emerge for why the engine would have been economical for the Browns. These factors are listed below, and then discussed in detail:

1. The engines fuel needs, which appear so voracious in other contexts, were relatively small compared with the truly staggering wood consumption at the iron furnace.

2. The wood fuel for the furnace needed to undergo the charcoaling process, which required certain species of wood, of a certain size. On the numerous wood lots owned by the Browns, there was likely a quantity of wood not acceptable for the colliers’ use that would be suitable fuel for the engine.

---

586 The weight of a cord of wood varies with the type, but is 3,000 pounds more or less; the engines two cords would be 6,000 pounds, or 3-tons of wood per day.

587 See Hill, Chapter 4 “The economy of power”.
3. The engine, constructed at the end of the war, was erected using what had become surplus materials and casting skill. In this surplus environment, the engine would have allowed the Browns to more fully utilize any excess wood energy available. Switching to a wood-fired engine also freed-up the water-powered millwheel for other uses.

1. Fuel Needs

The company had displayed great skill and planning in providing a steady stream of wood for the furnace. Recall that by start of the 1783 campaign, they had been meeting extensive fuel demands for over 17 seasons. The fuel consumption of the furnace was on the order of 6,000 to 8,000 cords of wood per year. Supplying these fuel needs was one of the manager’s primary concerns. Other than cannon production during the Revolution, nothing dominated the correspondence of Rufus Hopkins more than supplies of wood. His ability to provide, in a timely fashion, all the charcoal the furnace required was testament to his success in controlling fuel supplies.

By contrast, during the six to eight months of the digging season, the engine’s wood fuel requirement of 2 cords-per-day would have totaled not more than 360 to 500 cords.\(^{588}\) To put this in the broader context of the furnace as an energy using system, the engine’s needs were no more than 5% to 8% of the furnace’s consumption of wood. Note that this is the percentage of wood used by the furnace complex, exclusive of mineral coal. While making special provisions to provide fuel for the engine may have burdened some other industries, it would have been a small incremental increase in demand at Hope Furnace. With the end of cannon production, the engine may even have taken up some of the slack in demand for wood fuel.

2. “Waste” Wood from Charcoaling

---

\(^{588}\) No use of coal to fire the engine has been found in the documentation.
A blast furnace does not use cut wood directly; the wood needed first to undergo the charcoaling process. While the collier had flexibility in the type of wood he could use, not just any wood lot of trees would do; certain types of hardwood were preferred. To transform cut wood into charcoal, the collier would construct conical stacks of wood 30 to 50 feet in diameter. The collier’s goal was to uniformly burn off the volatile constituents, leaving charcoal which, although only one-third the volume of the original wood, would burn much hotter. To accomplish this, among other things, the logs needed a certain amount of uniformity. They were generally about 6-inches diameter and 4 feet in length. Furnace operators also preferred certain species of wood, particularly oak and chestnut.589

Given the needs of the collier for uniformity, and the preference of the furnace operators for certain woods, it seems likely that a portion of the trees on any given wood lot owned by the Browns would be not be usable by the furnace. The wood, “wastage” from the point of view of the furnace, may have provided a quantity of usable wood for the flue of the steam engine. This is possibly analogous to the situation that existed in the coalmines of Britain. Lumps of coal below a certain size were not economical to ship. These “wasters” were available to fuel a pumping engine at the mine.

3. Engine as an Outlet for Surplus

The end of the war would have brought a period of transition for the furnace, as demand for cannon, and thus its inputs charcoal and ore, fell off. In February 1782, a year before the engine was constructed, the Browns were already advertising to sell excess iron ore. The engine would be a way of putting some of the surpluses of the furnace to profitable use. They had the

589 Gordon, p. 34.
pig iron, casting skill, and design talent of Joseph Brown. Given their access to wood fuel lots in the area, they probably also had excess wood.

With the engine taking up it pumping duties, the mill wheel at the ore pits was freed up for other uses. Subsequent receipts suggest that it was used to power a blacksmith shop. It is unfortunate that the details of the discussion to build the engine have not come to light in correspondence. It seems likely that Joseph Brown was an advocate for the engine. He was absolutely indispensable to the construction of the engine, and part of his pay may have been use of the mill rights at the ore bed. Later receipts show that the blacksmith shop expenses were charged to his account, which implies that it was his enterprise.

The Blacksmith Shop at the Ore Bed

With the engine in place by late 1783, the millwheel and penstock would have been available for other uses. From subsequent receipts, it appears that Joseph Brown wasted no time putting the millwheel at the ore bed to alternate use by setting up a blacksmith’s shop at the ore bed. It is extremely unlikely that the new blacksmith shop was an afterthought: it no doubt was part of the deliberations leading to the decision to build the engine. In December of 1783, a receipt was issued to Nehemiah Burlingame for hauling blacksmith tools from “furnace Hill” to the ore bed in Cranston:

“December 2, 1783

Rec’d of N Brown three shillings lawful for carting of furnace” (the word “Hill” was inserted at this point) “Black smithy tools from here to Cranston Ore Bed

Nehemiah Burlingame”

590 Note from Joseph Shaw at Cranston to Owners of Furnace Hope, Providence; JCB: B.932, F.7.
On the back of the receipt, it is noted that payment was for “…Carting of Hill Tools, December 2”. Receipts show that after this date a blacksmith was at work at Cranston. The smith, Edmund Burton, was an employee of Joseph Brown’s at the ore bed. It appears that his stay at the blacksmith shop was an extended employment, as receipts for his board continue to appear through 1786. An example from October of 1785 shows that this long-term employee was working for Joseph Brown:

July 1785  Joseph Shaw Cranston to Owners of Furnace Hope in Providence:

“Due to Edmund Burton Blacksmiths board the value of a bb’l of flower which he wants very much and apply (to the acct) Joseph Brown for which he ingaged to him.

Am gent your noble serv’t Joseph Shaw”.

The fact that Edmund Burton’s board was Joseph’s expense suggests that the blacksmith shop was part of Joseph’s separate company, Brown, Rogers and Brown. Joseph had set up this company to bring his son Obadiah into the business. Note that Burton was still boarded at the ore bed in the summer of 1786, when a bill was submitted to “pay for boarding Edmund Burton, Blacksmith”. However, Joseph Brown himself had suffered a stroke in November of 1784 and had died in December of 1785. This indicates that Burton was an employee of the Brown, Rogers and Brown, which had survived Joseph’s passing.

In the history of the ore pit’s operation, the setting up of a blacksmith’s shop on the site may seem an insignificant detail. It importance is in what it reveals about the Browns’ genius for manipulating energy sources. Within the context of shifting to an engine for pumping, it suggests that the Browns were liberating the water power formerly used for pumping so that it could be used to drive a bellows, or perhaps a forge hammer, at the newly established blacksmith shop. Thus, the engine set up by Joseph Brown not only provided direct pumping services for
the ore pit, it indirectly freed up mill-power that also accrued to Joseph’s profit. A neat bit of energy manipulation, so characteristic of the Browns.

**Fuel for the Steam Engine**

“…one hundred cord of wood for the Engine upon advantageous terms”

The first documented payment for fuel for the engine was in the summer of 1785. It was mentioned in a September 1786 receipt submitted to “Brown and Benson”. Brown and Benson was the successor company to Nicholas Brown and Company, and were owners of the foundry and ore pits from 1783 to 1792. The receipt, authorized by Rufus Hopkins, instructed Brown and Benson to pay 3-pounds, 12-shillings in goods to John Burton for wood provided to the engine in 1785. This would have been a relatively small quantity of wood, perhaps a little under 50 cords. At 2 cords per day, this would fuel a less than one month’s operation.

In January of 1786, Joseph Shaw wrote from Cranston to Brown and Benson informing them that he had secured fuel for the engine:

“I have agreed with Sean Arnold esq for one hundred cord of wood for the Engine upon advantageous terms (request Arnold be paid six pounds cash)…”

Shaw requested that Arnold be paid six pounds cash, but the following day Arnold was paid eight-pounds, ten-shillings worth of goods. From this we can surmise that the engine was in operation in 1786, burning wood as its fuel. Using the Reverend Cutler’s quote of 2 cords of

---

591 Following Nicholas Brown’s death in 1791, ownership of the complex was again reorganized in 1792. The new company, “Brown, Benson and Ives”, would be in control from 1792 to 1796, to be succeeded by “Brown and Ives” after 1796.
592 September 7, 1786 receipt from Rufus Hopkins to Brown and Benson; JCB: B.933, F.1.
593 Based on a payment of 8-pounds for 100 cords (see January 1786).
594 January 16, 1786; Joseph Shaw to Brown and Benson; JCB: B.177, F.5.
595 January 17, 1786; receipt; JCB: B.932, F.7.
wood per day, this would support the engine for 50 days worth of pumping. This would be not quite one-third of a six-month digging season.

The wood was cut and piled by workers at the ore bed. It appears from the receipts that the fire wood for the engine was charged to the account of Joseph Brown. Again, since Joseph had died the previous December, the account was likely carried on for operations of his son’s company, Brown, Rogers and Brown.\textsuperscript{596}

“April 4, 1786
Please to pay the Barer Mr. Seth Crossman twenty four shilling in such sort of goods as he may want being due him for his work at the ore bed carting and piling wood…
Joseph Shaw” \textsuperscript{597}

The Engine at Work

“We shall want 300 curb sticks early in the spring and 600 more in August…”
---Joseph Brown

Fortunately, although the documentation lacks detail about fuel use, it is possible to follow the progress of digging by examining the purchase of materials used at the ore beds. Cutler’s recorded description of the operating details at the ore pits can be cross-referenced with various letters and receipts to flesh-out the implied volume of digging made possible by the operation of the pumping engine.

Cutler’s 1787 description stated that “The sides of wells are supported by the large timbers, laid horizontal, so as to make the form of the wells quintangular, and the ends of the timbers let into one another.” These timbers, referred to by the company as “curb sticks”, were discussed in several letters from Rufus Hopkins to the Browns. In a 1783 letter, Hopkins reports

\textsuperscript{596} See an April 6, 1786 note from Joseph Shaw to Brown and Benson; JCB: B.932, F9-10.
\textsuperscript{597} April 4, 1786; receipt; JCB: B.932, F9-10
he has been offered timber, apparently for the sinking of the sump-pit the steam engine will be
draining.

“February 3\textsuperscript{rd}, 1783

I have not as yet been able to procure the timber for the steam engine at 5/per hth. W. Collins… offered to git the timber and make boards at 5/6 per c. He would engage provided can agree to provide the timber for the pitts at the ore which believes may be had cheaper in gining timber than heretofore in round sticks.

Should be glad to know from Mr. Jos Brown what quantity he supposes may be wanted for that acts next season, the length and how big squares; suppose this timbor may cost some mooor than rough timber, all being… of one length, by which some waste in timber.”  (letter continues with discussion of cannons)\textsuperscript{598}

On the back of the letter, Nicholas Brown noted that his Joseph Brown jotted the
following instructions to Hopkins:

“We shall want 300 curb sticks” (Nicholas also called them “curb sticks) “early in
the spring and 600 more in August next - all to be 13 feet long and 6 inches square
of chestnut or oak.”\textsuperscript{599}

These are the curb sticks used to line the wells or mining pits for the ore, as well as the
drain pit at Cranston. Each is a standard 13 feet long, and 6 inches on the square; each “stick”
would weigh between 150 and 160 pounds, with the full 900 totaling 70 tons of material
delivered to the ore bed.\textsuperscript{600}

From the quantity of sticks Joseph is requesting, it is possible to judge the volume of
digging he was contemplating between spring and August. The 300 sticks would exactly line a
6-sided well 25 feet deep. The additional 600 curb sticks Joseph Brown is calling for in August

\textsuperscript{598} February 3\textsuperscript{rd}, 1783; Rufus Hopkins to Nicholas Brown and Company; JCB: B.179, F.3.  Note that the cannon business was still brisk in the spring of 1783.

\textsuperscript{599} Instructions to R. Hopkins, written on letter reverse side of letter dated February 3\textsuperscript{rd}, 1783 from Hopkins to Nicholas Brown and Company; JCB: B.179, F.3.

\textsuperscript{600} The carting of this material would require 70 trips at one-ton each.
would line another 50 feet, bringing the total depth to 75 feet. This digging was most likely accomplished, as the quantity and description of the curb sticks planned in 1783 is close to Cutler’s description 4 years later of a sump 75 to 80 feet deep, lifting water something over 70 feet, and keeping adjacent wells up to 70 feet deep dry enough to work.

**Operational Details: Mechanic’s Pay and Curb Sticks for Lining the Pits**

Additional details of the engine’s operation can be gleaned from the accounting records. A bill from the firm of Brown, Rogers, and Brown (Joseph’s company) sent to Brown and Benson (the successors to Nicholas Brown and Company) indicated that the engine was in operation during the summer of 1784:

“There appears due Calib Ormsbee… his % against the owner of Hope Furnace for work he did at the engine last summer, a balance of two pounds one shilling.”

The “%” owed by the Furnace owners arises from their partial ownership of the ore beds. Partners were responsible for their percentage share of the expenses, as they were entitled to their percentage of the profits.

We can be confident that the engine was operating efficiently enough during the summer of 1785. The activity of the engine is shown not only in payments to the mechanics that kept it in operation, but also by the demand for additional “curb sticks” at the ore bed. By examining the quantity of curb sticks purchased, it is possible to calculate the implied volume of additional digging at the ore bed.

In August of 1785, Joseph Shaw in charge of the ore pits reported to Brown and Benson, (the “Owners of Hope Furnace”) that “Angell Fisk” (referring to a Mr. Angell and Mr. Fisk of Scituate) “delivered 16,000 board feet of curbing timber for the use of digging ore @ 4 2/6 per

---

601 April 16, 1785; Brown, Rogers and Brown to Brown and Benson; JCB: B.177, F.5.
thousand, per agreement .”\textsuperscript{602} The total of 16,000 feet of “curbing timber” may appear to be an excessive amount of lumber, but at 13 feet long it would be 1,231 curb sticks. This compares to the 900 sticks Joseph Brown required two years earlier in 1783. Since each foot of excavation of a 23 foot-wide pit required 12 curb sticks, this purchase would provide enough large, horizontally laid, timbers to conduct just over 100 feet of digging. This volume of digging, perhaps spread over at least two pits, would remove on the order of 2,000 tons of mixed soil and ore. No doubt Shaw would prefer more ore than dirt.

The digging must have gone well, as only six months later the ore pits purchased additional curb sticks. As they had six months earlier, Mr. Angell and Mr. Fisk supplied the curb sticks in February of 1786. In a bill of sale forwarded to Brown and Benson, Shaw acknowledged that:

Feb 13, 1786; Joseph Shaw in Cranston to “Owners of Furnace Hope, Providence” (Brown and Benson):

“Mr’s Angell (and) Fisk has delivered Eight Thousand feet of timber Board measuring @ 4/3 per hundred to be paid in Uropean Goods at wholesale price.”\textsuperscript{603}

The 8,000 board feet would equate to a little over 600 13-foot curb sticks, which would provide for 50 feet of excavation. These sticks would allow for the excavation of just under 1,000 tons of dirt. Depending on the percentage of iron in the ore, 1,000 tons might be half to two-thirds the annual needs of the furnace.\textsuperscript{604}

Note that this purchase of curb sticks for the 1786 season is only half the quantity purchased six months earlier. It is unknown whether this reduced purchase of sticks is due to a

\textsuperscript{602} August 11, 1785; Joseph Shaw to Brown and Benson; JCB: B.177, F.5.
\textsuperscript{603} February 13, 1786; Joseph Shaw to Brown and Benson; JCB: B.179, F.6.
\textsuperscript{604} As always, the amount of useable ore in the 1,000 tons depends on the ratio of ore to soil; typically, the content of ore was 30\% to 40\%. 
slowing of demand for the ore, or perhaps a sufficient quantity of sticks was still available. It is also possible that the curb sticks were reused from pit to pit. Added together, the curb sticks purchased in August of 1785 and February of 1786 would line 150 feet worth of pits, or two pits 75 feet deep and 23 feet across. These may be the two pits described by Reverend Cutler the following June 1787. The other pit, the engine’s sump-pit, had presumably been dug first, as its ore was recovered. Once dug, it would have been left in place to function as the sump drain for further mining pits, the arrangement Cutler observed in 1787.

The volume of curb sticks purchased and used at Cranston indicates busy years of mining. This implies that the engine was up to the task of draining the pits. Note that the activity described in 1787 is only an expanded version of the multi-pit mining operations run by the ore bed manager Joseph Shaw in 1781. The “deep hole” Shaw described at that time drew-off the water from the shallower pits containing the ore. The engine had fit neatly into the system already in place.

**Was the Engine Merely Joseph’s Pet Project?**

“Examined the within and find it exactly right—(signed by) Joseph Brown”

One goal of this research is to identify the factors that prompted proto-industrial activities to adapt mechanical power. Its focus is on the relationship between fuel availability, price, and its influence on the success or failure of early installations of steam engines. One question that should be addressed is the issue of Joseph Brown’s motivation in building the engine. As noted, Joseph had a keen interest in technical projects. He was also a wealthy man. What if the engine was merely his vanity-project? If the engine was nothing more than his hobby, it would not truly be a “commercial” success, and so provide little insight into other productive activities. The question that needs to be addressed is: Was the engine actually economically viable, or was its
operation subsidized by Joseph as part of his interest in scientific novelties? Joseph was, after all, an amateur scientist, and had taught science classes at the college that would later be named Brown University.

Upon review of the correspondence, I believe any suggestion that the engine was not a sound investment, but only Joseph’s pet project, to be unfounded. Joseph suffered a stroke in November of 1784, and died in December of 1785. His activity was greatly reduced for most of his last year. In a March 1785 letter, President Manning of the college described him thus: “Mr. Joseph Brown’s indisposition is indeed a very heavy stroke to us… There is little possibility of his ever being restored to his former usefulness, though he again goes a little abroad.” Joseph died the following December 3rd at age 52.605

Thus, Joseph was incapacitated after the engine had been working for little more than one season. Yet the bulk of the digging accomplished using the engine, as evidenced by the curb sticks, came after that time. It seems unlikely that the successor company would have followed up the initial investments with these additional purchases if the operating costs of the engine had been higher than alternative methods. If it had been more economical, say, to go back to using the mill wheel to drain the pits, it seems certain that method would have preferred by the successor companies.

Further, any depiction of Joseph as a dilettante uninterested in making money would be a gross mischaracterization. If Joseph seemed less of a businessman, it is only in comparison with his extraordinarily brothers. He was far from a disinterested participant in the furnace. He believed that profit was the proper due for a manufacturer’s efforts. Any doubts that he saw maximum profit as the objective of manufacturing can be dispelled by considering a 1777 letter he wrote to Nicholas on the subject of how much the company should charge for cannon, relative

605 Quoted in Wilson, p. 70.
to its cost of production. In it, he strongly favors price gouging (yes, in time of war) when offering cannon for sale:

“You know it is only when there is a dull sail for an article that the low price it can be made for is computed but when it comes in grate demand then is the Manufacturers or Vendor’s Time & he always gitts as much as he can in order to make him some satisfaction for his past labour when he rubed hard to hold his own etc. And what disintrusted Person if he knew every circumstance attending the building stocking & cariaing on the Furnace the Vast deal of Business Labour trouble & time about it and the small profits on the whole which we have made by it… Would think we have ever bin paid what so much exertion & Trouble in any Business deserves...”

Not only does he see maximum profit as the company’s due, he reveals a grasp of economics worthy of a graduate student in the subject. As he noted in the first two lines, cost of production is only a determinant of selling price when there is a “dull” sale for an article, i.e., when the item is a commodity without special characteristics. Joseph would no doubt have immediately grasped the idea of “branding” in 21st century marketing. It seems unlikely that he would mix business and personal vanity. As noted above, when the atmospheric engine took up the pumping tasks formerly performed by the water-powered millwheel, a blacksmiths shop was set up to take advantage of the now available water-power. It appears that Joseph’s company of Brown, Rogers and Brown operated this shop. This profitable use of primary energy would have accrued to Joseph’s benefit.

It is interesting that one of the last items signed by Joseph Brown, in a shaky hand, was a March 1785 confirmation of a request for payment for the room and board expenses of Elijah and Calib Ormsbee (“Armsbee”):

“Gent.m Cranston 18 March, 1785

---

606 Quoted in Hedges, p. 277, emphasis added.
“Mr Calib Burlingame Boarded Calib & Elijah Armsbee (sic) six days last summer packing 4 meals 32 meals @(?)/ (per) week.

Gen.m your able serv’t Joseph Shaw”

On the reverse side, Joseph Brown approved the request:

“Providence 18 March 1785 Examine the within and find it exactly right—
(signed by) Joseph Brown” (in a weak and shaky hand). 607

This note is the first mention of young Elijah Ormsbee, who would have been about 23 or 24 years old at the time. Elijah would operate the engine well into the 1790’s, and is the same Elijah Ormsbee who joined with David Wilkenson to experiment with a steam-powered launch in 1792 608.

At the time of Joseph’s death in 1785, the engine had been working for only two years. If he had been the machine’s only advocate, one would expect its operation to have been quietly curtailed, if not shut down. Instead, activity was expanded. We are certain that the engine continued work at the ore beds until at least 1794, and it is most likely it continued in service until the furnace was shut down around the year 1800. 609 This is a testament to its profitable operation as the pumping of the flooded iron ore pits could have been accomplished by other means. Joseph Brown’s decision to construct a steam engine may have been aided by his scientific proclivity, but it was also consistent with an entrepreneur seeking to extract maximum energy rent.

The Steam Engine and Hamilton's Report on Manufactures

Nicholas Brown Sr. died in May of 1791. With the passing of Nicholas, his brother Moses emerged from the shadow of his older brother in his role as a businessman. He was, of

607 March 18, 1785; note from Joseph Shaw, countersigned by Joseph Brown; JCB: B.935, F.7.
608 See Wilkerson’s 1792 description above.
609 See discussion below on last years of the engine’s operation.
course, the same Moses Brown who in the 1790’s would play such an essential role in the setting up of Samuel Slater’s mill in Pawtucket, Rhode Island. In his work with Slater, Moses would demonstrate the same keen interest in controlling primary energy sources that marked other Brown-family business ventures.

In the early 1790’s, the manufacturing-oriented Secretary of the Treasury, Alexander Hamilton, undertook to inventory the state of industry in the young republic. In July of 1791, Moses was contacted by the John Dexter, Treasury agent at Newport, and asked to respond to Hamilton’s circular letter. Moses responded in a long letter in November of 1791. As part of his report, he noted the engine at the ore beds:

"We have in this county one furnace for making pig iron in Scituate, the ore bed in Cranston. The water from the pit is discharged by a steam engine, also made here and at the furnace. We have 12 or 13 forges which make bar iron out of pig ore, scrap iron and black sand."

Moses would have had ample opportunity to observe the engine at Cranston and its costs of operation. In other correspondence, he reveals that he had been impressed by the potential of mechanical power, and was eager to apply it to the manufacture of textiles. In 1787, when setting up textile frames on his property at Prospect Hill in Providence, he planned to use waterpower, which was available eight months out of the year, and steam power the remainder. Thompson notes that this was years before steam power was applied to textiles, even in England. Although he located a suitable engine and negotiated for its purchase, Moses was unable to secure the engine due to copyright difficulties. Although he was unsuccessful in securing an

---

611 Edward Field; *State of Rhode Island and Providence Plantations at the end of the century* (Boston: Mason Publishing and Printing Company, 1902) pp. 332-333. [http://archive.org/details/staterhodeislan01fielgoog](http://archive.org/details/staterhodeislan01fielgoog) (accessed September 26, 2009). In the same letter, Moses notes that mill yarn is “…spun by water, upon Arkwright principles…” a reference to the mill he and Samuel Slater were establishing in Pawtucket.
engine in the 1780’s, and would eventually use waterpower at Pawtucket, we can be fairly certain about the source of Moses’ positive view of the prospects for steam. It seems likely that he had been favorably impressed by the operating characteristics of the engine at Cranston.612

**Spurious “Contemporary” references**

A number of references to the engine, its builder, and its years of operation turn out, upon examination, to be apocryphal, or at least wildly inaccurate. Confusion about the engine’s last years of operation has been introduced by references that appear contemporary, but were actually compilations based on earlier sources. For example, a reference implying that “In 1808 the engine was in operation…” was cited by no less an authority than Purcell, but is most likely erroneous.613 Purcell quotes Thomas Green Fessenden’s *The Register of Arts* description of the furnace and steam engine:

> “The Iron works on the Pawtuxet River, twelve miles from Providence are supplied with ore from a bed four miles and a half distant. The ore pits are cleared of water by a steam engine, constructed and made at the furnace under the direction of the late John Brown Esq. of Providence, which continues a very useful monument of his mechanical genius.”614

At face value, this implies the engine was in operation after John Brown’s death in 1803, and has been cited as such. However, further research shows that Fessenden’s reference was culled from a 1795 description by William Winterbotham. Winterbotham compiled *An historical, geographical, commercial, and philosophical view of the American United States, and of the European settlements in America and the West-Indies* (printed in London in 4 volumes). This

---

612 Thompson, pp. 216-217.
613 Purcell erroneously cites this as evidence the engine was working as late as 1808; see p. 7.
http://archive.org/details/registerofartsor00fess (accessed December 9, 2010).
gazetteer included in its description of Rhode Island a mention of the engine at Cranston (phrasing Fessenden would later use is highlighted):

“The bowels of the earth in this State offer a large recompense to the industrious adventurer. Iron ore is found in great plenty in several parts of the State. The Iron works on the Pawtuxet River, twelve miles from Providence, are supplied with ore from a bed four miles and a half distant, which lies in a valley, through which runs a brook; the brook is turned to a new channel, and the ore pits are cleared of water by a steam engine, constructed and made at the furnace, by and under the direction of the late Joseph Brown, Esq. of Providence, which continues a very useful monument of his mechanical genius: at this ore bed are a variety of ores, curious stones, ochres, &c.”

Fessenden’s 1808 reference appears to have been based on Winterbotham’s 1795 work. The phraseology is identical, with “John” being swapped “Joseph”. As such, this 1808 reference can not be taken as evidence as to the engine was in use into the 19th century.

Examining Winterbotham’s 1795 work suggests that at least part of his description was based on Reverend Cutler’s (1787). Winterbotham, in his preface to Volume 1, listed the authors upon whom he relied. Along with authors including Jefferson and Adams is one “Cutler”, who is doubtless the Reverend Cutler. Winterbotham’s description incorporates some of Cutler’s phraseology, such as the engine as monument to mechanical abilities of its deceased builder. Winterbotham however adds details not found in Cutler, such as distance from Providence to the furnace, and then furnace to the ore pits. He also locates the ore pits in a valley, and accurately notes that a brook that runs through the valley had been turned from its original bed, a detail lacking in Cutler. While these additional details suggest he was referencing other sources for the

---

engine, the 1795-publication date would at best extend the time the engine was working to the mid-1790’s.

**Operation of the engine in the mid-1790’s**

“...to encourage men to go into the mine at the risque of their lives.”

After Nicholas Brown Sr. died in 1791, his son Nicholas Jr. formed “Brown, Benson and Ives” in 1792. This company would control the furnace and ore pits until 1796, when it was succeeded by “Brown and Ives”. The younger Nicholas’ correspondence shows that the pits were actively worked during the mid-1790’s. His concern about keeping ore diggers at work expressed itself as caring for the worker’s families. Work at the ore pit could be dangerous, as a fatality documented in a 1794 letter from Nicholas to Rufus Hopkins shows. The letter refers to a worker named Tyler who apparently had been killed in the iron ore “mine” at Cranston. This most likely refers to William Tyler, who had worked at the ore bed since at least 1785.  

Nicholas had been visited by Tyler’s father-in-law, who asked the company for help on behalf of his daughter, Tyler’s widow.

> “Gent W. Roberts is now here and informs me that his Daughter, the wife of Tyler is sick or confined with the Rhumetisim.” (Rheumatism).

> “I have ever been of the opinion that the Owners of Furnace Hope ought to make some provision for the family of Tyler – as he was killed in their service – his widow and children should receive some aid from them, which will have a tending to encourage men to go into the mine at the risque of their lives.”

In response, Rufus Hopkins noted that he would be sending her $10 worth of clothes, and the other owners had agreed make provisions for the widow. The Owners’ concern that workers

---

616 Tyler had signed various receipts over the years, making his mark with an “X”. See for example the June 1, 1785 letter of Joseph Shaw to the Owners; JCB: B.179, F.5.

617 February 1, 1794; Nicholas Brown (Jr.) to Rufus Hopkins and Sons; JCB: B.177, F.7.
should be encouraged to work digging ore strongly suggests that the flow of ore was as essential as ever. Note that young Nicholas Brown refers to the ore pits as a “mine”. This suggests how the complexion of the digging in Cranston had changed. From the casual open-pit recovery methods of the 1760’s, the digging had evolved to an intensive mining operation with lined shafts (the “wells” of Cutler’s description) reaching into the earth. While this 1794 reference does not specifically mention the engine, the description of the ore pits as a “mine” implies deep digging. Water pumping would have been necessary, and the services of their pumping engine, of which Moses was so proud, would have been an essential part of the furnace’s production system.

**Last Years of the Engine’s Operation**

While activity no doubt slowed after the end of the Revolution, Hope Furnace continued to produce both pig iron and finished goods. Typical finished goods were specified in an agreement signed by Seth and Daniel Keith in late 1784 to produce “sugar boylers” and pot ash kettles. They would have needed the ore from Cranston to carry on this production.

Cannon had been by far the most profitable item that had ever been produced at the furnace. The Browns, especially John, remained alert for any opportunity to return to that lucrative business. In the 1790’s, as a result of the seizure of American ships by the French and other hostile powers, they got their opportunity. During Washington’s second administration the Federal government passed the “Naval Act of 1794”, authorizing the building, or acquisition, of six frigates. This led to the construction of what would become the famous “original six” large frigates of the new navy: the *United States, Constellation, Constitution, Chesapeake, Congress*,

---

618 Agreement dated October 27th, 1784; JCB: B.179, F.5.
and President. One result was that in late August of 1794 Hope Furnace received its largest single order for cannon ever, 128 pieces of ordinance.⁶¹⁹

While neither the ore pit nor the engine was discussed, circumstantial evidence suggests the engine that it would have been active. The brisk pace of activity is shown in an October 1794 bill from Benjamin Williams to Jabez Bowen for 32 tons of clay.⁶²⁰ The clay would have been used for the casting of the cannon. The work apparently progressed well, as the Providence Gazette of February 14, 1795, was able to report that 76 cannon had been produced:

"The workmen at the Hope furnace have already cast seventy-six cannon for the frigates and fortifications of the United States. They are ornamented with the American eagle, and are allowed by good judges to be equal to any guns from the foundries of Europe. They are cast solid and bored by water."⁶²¹

Note that the furnace was using the method mastered by it molders during the revolution: a solid cast which was then bored-out.

Unfortunately, this flurry of activity aside, references to the engine’s operation, and indeed the whole furnace’s output, becomes sketchy after 1795. The Quasi-War with France in 1798 appears to have produced additional demand for cannon, and there is some suggestion that John Brown was able to secure additional contracts for the furnace at that time, but it is not conclusive.⁶²²

We can suppose that in the second half of the 1790’s, the output of the furnace was winding down. The furnace had always been located in a relatively developed area, forcing it to compete for resources. Activity in the broader economy was also working to undermine the

---

⁶¹⁹ Quoted in Discover Hope Village, p.7.
⁶²⁰ The bill signed by Jabez Bowen was for 11 pounds, 4 shillings; October 1794; JCB: B.179, F.8.
⁶²¹ Providence Gazette, February 14, 1795; quoted in Field, p. 371.
⁶²² Rappleye, p. 314.
demand for Hope Furnace’s pig iron. At this time, lower cost iron production coming on line in Pennsylvania was resulting in an overall decline in coastal-Atlantic iron-producing sites.623

From Iron to Textiles

“…well calculated for erecting one or more COTTON MILLS…”

In Rhode Island, as the 18th century drew to a close, manufacturing activity was going the way of textiles. The Browns had not been slow to take part in this trend. Old Moses Brown had led the way, and secured the services of Samuel Slater to establish a mill to produce yarn “…spun by water, upon Arkwright principles…”624 When setting up this mill, Moses applied the by now well-honed family ability to arrange for primary energy sources.

When securing the waterpower rights for Slater’s mill in Pawtucket, Moses spared no pains in securing as much primary power as possible. Area farmers sued to stop the dam, as it would interfere with spawning fish. The abundant fish during the spring were an important part of the farmer’s livelihood. In an echo of the establishment of the dam for Hope Furnace in 1765, Moses used his political influence in Rhode Island’s General Assembly to exempt the Slater’s Mill Dam from the Fish Act.625 The objections of downstream mill owners were similarly swept aside.

One result of the development of the textile industry in Rhode Island was that the mill-site that had provided power for Hope Furnace since 1765 (40 years!) was becoming more valuable for its access to waterpower than for its furnace investments. The essential resource was the primary power; the conversion of iron ore was only the form used during those years. The generation of Browns rising in the early 19th century would transform the tasks for that

623 See Gordon, American Iron, Chapter 11 for a discussion of Maryland blast furnaces.
624 Field, p. 333.
primary energy from iron to textiles. Note that this is a shift in form, but not the underlying principle of converting energy.

Although it was likely earlier, we can set 1802 as an absolute terminal date for the engine’s operation. By this time, the furnace had become beset with debts. The minutes of an owners’ meeting in March of 1803 discussed the selling off of parcels of land, amounting of some hundreds of acres, to pay off these debts. The minutes contain a page and a half detailing what they will be selling to retire the Furnace’s debts. Jabez Bowen was empowered to do the selling of the parcels. The owners further agreed:

“‘That the houses and land containing 50 and 38 acres at the Oar (sic) Bed be leased out to some good tenant for the sum of one hundred and fifty dollars – or as much as can be obtained… tenant to pay the town and state taxes that may be ordered during the term…”626

It was only a few years later in 1806 that all of the company’s holdings at the furnace and ore bed were put up for sale. An advertisement carried in the Providence Phoenix suggested the mill privileges would be well suited for textile milling:627

626 Minutes of a meeting of Owners of Furnace Hope Company, March 18, 1803; JCB: B.179, F.8.
627 Providence Phoenix, page [1], vol. IV, iss. 205, Publication Date: April 19, 1806. Published as: The Providence Phoenix; Location: Providence, Rhode Island
In July, “Governor” (Jabez) Bowen was authorized to sell the property holdings of the furnace. The furnace and mill privileges at Situate were sold for $7,000 and the “Potter Farm” was sold for $2,000. At that time, the ore beds were offered for sale, but were not purchased as part of the 07/12/06 sale.\(^{628}\)

The furnace site at Scituate was sold to Sylvanus Hopkins, son of Rufus Hopkins, and a group of Providence investors that included the Bowen and Eddy Company. The mill constructed in 1806 was described as “a 44-foot by 27-foot building with a gable roof and full-

\(^{628}\) July 12, 1806, JCB: B.179, F.9.
width clerestory monitor” (a row of upper-story windows providing light), “and belfry --smaller in scale but similar to the 1794 Slater Mill in Pawtucket.”

(Sale) “…of a Cylender for a steam Engine belonging to the late Furnace Hope…”

A month after the sale of the furnace, ownership of the ore beds also changed hands. According to the transfer document, on August 18th, 1806 “Forty-nine Sixty-fourth parts” of the ore bed was sold to Joseph Brown’s son Obadiah for the sum of $4,400. The sellers were:

“Jabez Bowen, James Brown, Nicholas Brown, Thomas P. Ives and Hope Ives, & Nicholas Powers all of Providence in the County of Providence + Rufus Hopkins & Silvanus Hopkins both of Scituate in the County aforesaid Gentlemen, Tenants in common of forty nine sixty fourth parts (of the property)”.

The remainder of the ore bed property was presumable already under Obadiah’s control, suggesting that his father Joseph had owned 15/64ths of the ore beds. The document specifies that Obadiah was acting on behalf of his father’s heirs:

“(sold to) …the said Obadiah Brown… In Trust for the benefit and behalf of the Heirs of the late Joseph Brown Esq. of said Providence …a certain tract of parcel of land lying & being in the Town of Cranston & County of Providence containing fifty nine acres… and is the land from which the Ore has been taken to supply the Furnace Hope.”

Actual ore mining appears also to have come to an end before this time. Although the Obadiah apparently did not engage in the digging of ore, the land’s value continued to be linked to potential mining. When Obadiah sold the sold ore pits in 1823, the mineral rights were specifically mentioned, which suggests that they were considered of value. However, despite a

---

629 Discover Hope Village, pp. 19-20.
630 Copy of Deed Book 7, p. 171, Cranston; Rhode Island Historical Society, Manuscripts Division; Paul Campbell Research Notes, circa 1976-1985; Catalog number: MSS 369, Box 8; Processed by: Robin Flynn, April 1997.
number of plans and schemes that would attract some level of investor interest up until the 1870’s, there is no evidence that any further mining was conducted after 1806.\textsuperscript{631} The end of the Brown engine itself appears to be recorded in an April 1808 bill of sale. At that time, Jabez Bowen acknowledged the sale “…of all the cannon + of a Cylinder for a steam Engine belonging to the late Furnace Hope Company….”\textsuperscript{632} It is not known what the new owner intended for the “cylinder” or the iron cannon, but the most likely fate would be for them to be broken up, melted, and then recast into new iron artifacts. Assuming the company began to wind-down operations circa 1800, the furnace and ore bed had been in operation for 35 or more years. The engine, erected in 1783, certainly was at work for at least a dozen years, and probably more.

\textbf{Summary and Conclusion}

What would proto-industrialization look like? What are the features of a productive facility that would make it most likely to experiment with steam-powered mechanical energy? The case study of the Brown engine echoes the British experience that steam engines are likely to be put to work where 24-hour per day pumping is required. However, this echo bounced back with a nuance as regards fuel. While the iron ore pits at Cranston were not a coalmine, they did exist in a system marked by intensive use of energy. This suggests that it is not a coalmine \textit{per se}, but an energy intensive environment where the use of an engine would be likely to germinate.

\textsuperscript{631} In May, 1976, Paul R. Campbell and Glenn LaFantasie were hired by the Rhode Island Attorney General’s Office to research ownership claims by the Narragansett Indian tribe, who were seeking to regain lands in southern Rhode Island which they claimed had been illegally taken from them in 1880. As part of this work, they traced the ownership history of the Cranston ore pits; their research found that, although the mineral rights were resold a number of times, no commercial mining occurred after the sale in 1806. Rhode Island Historical Society, Manuscripts Division; Paul Campbell Research Notes, circa 1976-1985; Catalog number: MSS 369, Box 8; processed by: Robin Flynn, April, 1997.

\textsuperscript{632} Bill of Sale dated April 14, 1808; JCB: B.179, F.9.
In the 18th century, the British colonies of North America had numerous small blast furnaces producing pig iron. Access to a sufficient source of raw iron ore was only the beginning of their needs. The smelting of iron using the “cold blast” technology of the time was extremely energy intensive; the successful production of pig iron also required the power of a reliable river (a stream was rarely sufficient) and thousands of acres of wood. The resulting iron can be thought of as energy rendered into a solid form.

The Atlantic Coast of North America provided ample resources for iron production, so much so that on the eve of the Revolution the colonies were the world’s third largest exporter of pig iron. The entrepreneurs who would succeed in this industry were those who had a skill in the managing of energy inputs. It was into this industry that the Browns of Providence were drawn in 1765.

The generation of the Browns that directed the family’s businesses during the last third of the 1700’s centered around four brothers: Nicholas, Joseph, Moses and John. Excellent histories of the Browns of Providence and the Revolutionary war have been written. This case study has considered in detail one of their business investments: It has followed the Browns’ in the iron business to illuminate their proclivity for securing and exploiting energy sources. The Browns and their partners were not a casually energy-oriented group of businessmen. This single generation of Browns would, in turn, control and profit from wind energy (merchant sailing ships), slaves (as merchandise and for their labor), waterpower, wood-energy, coal, and eventually the concentrated mechanical power of an atmospheric engine.

Iron smelting and casting was energy-to-money opportunity. It is significant that coal was used at first opportunity the Browns found to work it into the enterprise’s mix of energy
inputs. By 1778, they were using coal in their “air” furnace. This foundry, technically called a reverberatory furnace, was used to melt the iron ore pigs for re-casting into cannon.633

While skillful manipulation of energy was necessary to succeed, the business began with digging iron ore. The Brown’s experience followed the path of the generic mining model experienced by other mineral-extraction enterprises. At first, securing the ore was a relatively simple task, but over time intensification led to increasing problems with water. Their initial response was to shift operations to avoid the water (1768); then the stream was shifted to divert the water (1770); eventually pumping was employed to clear the pits. Facing the water problem head-on by pumping required a significant amount of primary energy. The steam engine was not their first choice for a prime mover. A water mill wheel was employed, probably by the mid-1770’s; we know for certain that the mill wheel was in place in 1780 or before, as its penstock was rebuilt in the spring of 1781.

Beginning in 1776, an extensive number of cannon were cast at Hope Furnace. Through this experience, the molders at the air furnace would have developed the skills needed for the casting of an engine cylinder. Theirs was an interesting example of the feedback among experience, problems, and solutions. The demand for cannon both put a strain on the ore pits ability supply the furnace, and provided experience in the skills needed to cast an engine cylinder.

The decision to build the engine needs to be considered in its proper context. Previous authors had viewed it as a contribution to the war effort. In this view, the demand for iron ore to make cannon had necessitated more pumping than could easily be done by other methods; the

633 Following energy use downstream, many of the cannon were used by privateers to concentrate the chemical energy in gunpowder against lightly armed British merchant vessels. It should not be surprising to find that the Browns, particularly John and Nicholas, were keen to get into the privateering game. They succeeded handsomely by 1776. See Rappleye, pp. 200-203.
belief was that in 1780 the Browns resorted to building a pumping engine. By this explanation, the engine was a contribution to the war effort, which would make fuel consumption less of a concern.

In actuality, the casting of the engine was not undertaken until 1783, and its first operation was likely at the end of the war. In its true context, the engine was the Browns’ solution to a situation where they had a surplus of ore, pig iron - and probably casting skill and wood fuel into the bargain. This requires an alternative explanation of their motivation. Their engine was a way to usefully sop up those resources idled by the war’s end, and put them to profitable work. In this, the Browns again showed yet again that their mastery of the energy flows in their environment was an essential ingredient in their success.
Chapter 14: Energy and the Industrial Revolution

It would be overly simplistic to advance “one cause” for something as complex and transformative as the Industrial Revolution. Energy was only one of the many things that contributed to, and was then transformed by, the Industrial Revolution. However, while only one factor, energy may be the most restrictive. This dissertation has been an investigation into this perhaps most structuring of restraints.

This concluding chapter will briefly recap the case studies that were presented, followed by a comparison among them, and what they reveal about energy in the Industrial Revolution. The role of slavery, gender, and resource availability will also be noted. Finally, the elements of these case studies that have broader application will be drawn out. For example, was coal necessary for industrialization, or is it merely the historically-specific form experienced in Britain? By abstracting the elemental nature (for example, “prime mover”) from its historical forms (for example, “steam engine”), may possibly be used to examine examples of proto-industrialization elsewhere in the world.

A truly transformational aspect of Industrial Revolution was the radical change in the way energy was used. This change was abetted by the adoption of mechanical power, which in its ability to convert energy proved successful beyond anyone’s dreams. When grappling with the changes referred to as the Industrial Revolution, it may be analytically useful to group them into two events. The first, a commercial revolution, transformed certain parts of the economy and, significantly, some of the things produced locally became commodities. Five hundred years ago, the phenomenon of a developing commercial economy was widespread around the world and every continent had “core” areas of development, Antarctica excepted. The world’s core
areas interacted by exchanging ideas, goods, and pathogens. These commercializing areas were developing what has been termed advanced agricultural economies.

From among this milieu of areas, Britain was the first to burst into the second phase of the revolution with something called industrialization. As Parthasarathi noted, this was wholly unexpected.\textsuperscript{634} The unanticipated nature of industrialization cannot be overemphasized, as it is a needed antidote to the historiography of the 19\textsuperscript{th} century. 19\textsuperscript{th} and early 20\textsuperscript{th} century European writers anachronistically projected back into the 18\textsuperscript{th} century the idea that the material expansion of the Industrial Revolution was inevitable. Histories need to reach back past the 19\textsuperscript{th} century if they are to put the roots of the mechanization of industry into its proper context.

Pomeranz contributed to the breaking down of the 19\textsuperscript{th} century’s version of “inevitable progress” by approaching the changes in Britain during the Industrial Revolution as an aberration.\textsuperscript{635} He termed the course followed by Britain a great divergence. He identified the two sources of this divergence: the inheritance of the resources of the Americas, and the presence of readily available coal resources. These two factors are important, but coal was plentiful elsewhere, and other countries had had access to wealthier parts of the Americans for centuries. He had identified the sources of the change, but we are still left with the questions about the mechanism: why Britain, and why then?

This dissertation has investigated the role of energy needs in the genesis of the second phase of the Industrial Revolution, that is, the question of “why Britain, and why then”. It has taken its cue from the work of Georgescu-Roeg\textsuperscript{\textdagger}an, Wrigley, Alam, and others who have advocated viewing the economy as an energy using system. Among these scholars, Wrigley described how the dynamics of an economy using organic power differ from one using mineral-

\textsuperscript{634} Parthasarathi, 2011.
\textsuperscript{635} Pomeranz, 2000. This “divergence” should be thought of as a movement away from equilibrium.
based energy. As an aid to illustrating the historical evolution of energy types, the useful concept of an energy rent was developed. Simply stated, subtracting the energy put into an activity from the energy that results is the energy rent. If the return is negative, the endeavor will be dropped as a functional activity.

Energy rents in a pre-commercial economy are a true “energy-in, energy out” calculation. If an activity requires more energy than it provides, it will not be pursued unless it has some other significance. In a commercializing economy, this calculation is transformed into a financial question. The actual energy expended is not the deciding factor, but its cost. The cost of the energy is now the yardstick against which the value of the output is measured. Energy is of course just one cost among many, but for certain activities in an organic economy (those where the ultimate amount of energy available is limited), it can quickly become the decisive cost. Mining is one of those activities.

With these analytical tools, which describe a society as an energy using system, we returned to the question of “why Britain”, and “why then”. This dissertation sought to contribute to answering these questions via case studies of the mining sub-sector in a commercializing economy. Mining is interesting for several reasons. First, as an extractive industry, it tends to be relatively capital and energy intensive as it expands. One may hear of the self-sufficient “family farm” where the labor, skills, capital, and resources are all found within a family, but one rarely hears of a “family mine”. As in the case of milling grain or grinding sugar cane, mining has some skilled aspects, but also required a great deal of bulk labor.

Second, the nature of mining changes rapidly with the advent of commercialization. Prior to the development of a commercial market, mining was undertaken to secure minerals for their use value. However, given a commercial economy that has potential markets, the output of

---

636 For an algebraic example, see Alam (2006), pp. 12-13.
a mine is likely to become a commodity. The volume of production comes to depend on financial decisions. This can lead to a rapid intensification of production from a mining area.

Finally, mining is an activity that lacks spatial flexibility. Because of this, any energy inputs it might need must provide the flexibility in which the mine is deficient. These energy needs are modest, until the mine encounters flooding. Unfortunately, as mining intensifies, it will tend to have increasing troubles with flooding. As the need to remove the water increases, the need for energy inputs tends to accelerate. Thus, mining brings into focus the historical process of the increasing demand for energy in a commercializing industry. The fact that pumping water was a deadweight loss to the mine operators served to sharpen the impact of this increase.

The timing of the flooding problems, the “when” of the question above, is linked to the original resource endowment of an area. As long as additional untapped resources are available, pumping activity it generally avoided. However, once all known resources are being exploited, the only remaining choice is to intensify digging at existing mines. This is perhaps the difference between the mines of China in the 17th century and those of Britain. To focus on the example of coal, all of the “easy” coal had been recovered in Britain. China’s much greater endowment allowed mine operators there to avoid digging below the water table; their mines were not so much “dry”, as they did not need to be “wet”.637

The timing then is related not to “ample” supplies of coal in Britain, but the lack of additional untapped resources, relative to their need. This lack had driven their mines under the water table; this set in motion a mechanization process, as the mines attempted to remove the water. This dissertation took up the case studies of several mines that had reached this juncture.

637 Pomeranz characterized the mines of Britain as wet and China as dry.
The response at these mines in dealing with the flooding provided repeated examples of the limitations of organic power.

Case Studies

Figure 14-1. Map of Atmospheric Engines Under Discussion. Note that, with the exception of Louisiana, all the engines were of the Newcomen type.

Case Study: Newcomen’s First Engines

Thomas Newcomen erected the first commercially successful machine powered by fire and air pressure at a colliery in 1712 (see Chapter 6). The site was most likely “Dudley Castle”, or more formally colliery at Coneygree, Tipton. His key innovation was to rapidly
condense the steam by injecting a spray of cold water directly into cylinder. It seems likely that, 
during the years up to 1710 he spent in development of his machine, the question of its rate of 
fuel consumption did not trouble Newcomen. For his experiments, he probably used a 10-inch 
brass piston pump, the sort used as a pump in the mines of Cornwall. The fuel necessary to 
produce steam for these experiments would have been minimal. However, when a full-size 
machine with twice the diameter was built, the volume of fuel required for his prime mover 
would have become critical to its success or failure.

A review of the evidence indicates that his first attempt to build an engine was at a tin 
mine in Cornwall, about 1710. The reasons why this engine was abandoned are not known. It 
has been suggested that this engine failed for some uncertain technical reason, or perhaps the 
mine failed.\textsuperscript{638} The mystery evaporates, however, when fuel costs are considered. Even in 
Cornwall, which lacked any coalmines, coal was still the low-cost fuel of choice in Britain. 
While wood would have been much more expensive, coal would not have been cheap: In 
Cornwall, the mine-mouth price of commodity coal would have been increased by the 1) 
shipping cost to a Cornwall port; 2) haulage overland, and 3) the 5s, 5d tax per cauldron on coal 
(“seacoal”). A cauldron of coal (not quite 1.5 tons), which cost 10s at the colliery’s pithead, 
would cost perhaps 3 times as much when it arrived at the tin mine in Cornwall.\textsuperscript{639} As a result, 
the cost of pumping using the Newcomen engine may have been more than alternative means, or 
perhaps more than the profit from the mine’s output. By itself, noting the high fuel costs and 
then suggesting that those costs were the cause for the engine’s failure is only a conjecture, but 
subsequent history in Cornwall supports this interpretation. During the 30 years between 1710 
and 1740, over 100 Newcomen engines were built and significant improvements in operation

\textsuperscript{638} Rolt and Allen, p. 45. 
\textsuperscript{639} Nef cites various cost of coal per cauldron. In 1701, coal at collieries in the Forest of Dean was 10s per cauldron. 
For that same year, coal delivered to Kings College was 30s. Nef, Appendix E pages 393 and 405.
were achieved. However in all of Cornwall, as of 1740, there were still only 3 engines in operation. Finally, in the 1741, an exemption from the tax for coal used in fire engines was pushed through Parliament, largely at the behest of the mine operators from Cornwall. As a result, less than 20 years later in 1760, there were an estimated 60 steam engines operating in Cornwall. It is not a heroic assumption that the lowering of the cost of coal (5s 5d) per cauldron was enough to turn its negative energy rent positive.

_Fuel and the 1712 Machine_

After failure in Cornwall, Newcomen shifted his area of work to the Midlands, north of Birmingham. What prompted this geographic shift? It has been suggested that his Baptist connections drew him there, or perhaps some London businessmen had reached out to him. It is curious how these 20th century suggestions echo Triewald’s original historiography in the early 18th century, which credited Newcomen’s success to luck if not divine intervention. Either of these interpretations implies that Newcomen had a passive role in his own success. If we instead attribute an active role to Mr. Newcomen, a simpler scenario suggests itself. From his experience up to the year 1710 in Cornwall, Newcomen probably realized he had a successful technology for his engine. What he needed was a less expensive way of making steam. If fuel costs were the reason for the failure of his Cornwall engine, then he knew he did not have a technical problem: He had a fuel-cost problem. He would address this problem by pitching his engine to mine operators in the coal country of the Midlands.

Several points support this “Cornwall-then-Midlands” interpretation. First, the location: Cornwall, just down the coast from Newcomen’s home of Dartmouth, would have been easily reached by ship. Newcomen had visited these mines many times, providing metal implements for them. By contrast, the coalmine at Dudley was over 200 miles away. Newcomen would
have needed a good reason to range so far from his established business area. In addition to proximity, Cornwall was producing tin, a much higher-value commodity than coal, and so clearing a flooded mine there would have been that much more profitable.

Second, the short interval of only one or two years between the 1710 failure in Cornwall and the 1712 success in Dudley casts doubt on the “technical problems” interpretation. Allowing for time to construct the 1712 engine, less than a year would have elapsed between the two. The short time period suggests that the engine’s technology would have been much the same.

Finally, we need to answer a practical business question: How did Newcomen, probably in 1711, convince a mine owner in the Midlands that they would be successful, when an engine built just the previous year was not? It seems unlikely that a gentleman capitalist would venture the significant sum required for an engine without some solid reason to believe that it would not merely work, but more importantly turn a profit. However, if Newcomen could reference an example where the technology was proven, but it was only the cost of coal that was a problem, he would likely be able to find a colliery owner willing to take a chance. This is what probably led to the successful engine built in 1712.

Feedback of Improvements

Once established commercially, the operation of the Newcomen engine accumulated the “learn-by-doing” improvements that tend to accrue to a new technology. Perhaps more importantly, the engine benefited from the curious physics of atmospheric power: Since the power stroke was provided by the atmosphere, the steam used was not pressurized in any way. The power of the engine came from condensing the steam, reducing the air inside the cylinder to less than one atmosphere of pressure. This means that no increase in pressure was required for increase in power. To make a more powerful engine, all that was required was to increase the
diameter of its piston. A larger piston would give the unchanged ambient air pressure a greater surface area to work upon. Also, since area of the piston increases with the square of the radius, a piston twice the size of Newcomen’s original machine would have four-times the power. By the 1770’s, Newcomen engines with pistons over 70 inches in diameter would be built.

Newcomen machines also benefited from falling capital costs. The greatest savings came from learning to cast cylinders out of inexpensive iron, to replace the earlier brass cylinders. Also, as the engines gained acceptance among the decision makers within Britain, there were benefits from political feedback. An important example of this was the removal of the coal tax on seacoal used in engines in Cornwall (1741).

Yet, for all these improvements, fuel cost were still the make-or-break factor for the commercial application of engines. It seems that an energy-rich environment, as provided by the coalmines, was a necessary incubator for these fire engines: of the 93 commercial engines built up to 1733 whose purposes were know, 85% were used in coalmines. Only after decades of accumulation of improvements, lower capital costs, and removal of the tax, were these machines able to even begin to move into a wider set of venues. Even with these improvements, during the next 46 years, from 1734 to 1780, 66% of working engines were still built in coalmines. This should not obscure the fact that the feedback of improvements had allowed nearly 200 engines to move out of their incubator at the collieries and find work elsewhere. With Watt’s improvement of the separate condenser (1770’s), the fuel limitation fell away, and so the prime mover was no longer dependent on an energy rich environment. The mechanization of the Industrial Revolution would begin in earnest.
Case Study: Dannemora

One of the earliest engines erected outside of Britain was in 1727 at the Dannemora iron mine in Sweden (see Chapters 8 and 9). This engine was built by Marten Triewald who, at that time, was one of the most experienced engineers in the world. He used the best materials, and the mine operators were well financed. Yet, this engine ran sporadically for two years and then was abandoned. The case study of this iron mine’s decision to build an engine provides an example of how commercialized mining sharpens energy demand; the engine’s failure shows the importance of an energy-rich environment to successful adoption of mechanical power.

The Limits of Organic Energy

Commercialization of the iron industry on Sweden’s Uppsala peninsular began in earnest in the early 1600’s. At that time, Dutch businessmen moving into the area brought their “Walloon” blast furnace technology for producing iron, and market contacts for selling the commodity pig iron. Once the commercialization of the iron mining got underway, water troubles were not long in following. By the mid-1600’s part of the mine was left unexcavated, to hold back the waters. Horses were initially used to lift the water; they were supplemented in 1680 by a substantial waterwheel 10-meters in diameter, costing 10,000 copperdaler. Since the power for the wheel was at some distance from the mine, the motion of the wheel needed to be transmitted the 1.5 kilometers to the mine mechanically. This was done using a stangenkunst, which is a series of poles with connected swinging arms. These arms transferred the motion from the wheel to the pithead, no doubt with considerable losses of energy along the way.

Twelve years later, in 1692, a windmill costing 9,000 copperdaler was erected to assist in the pumping, but even then the available power was insufficient for the pumping needs. Just 5

---

640 Lindqvist, p. 215.
641 For these interesting devices, see Reynolds Stronger Than a Hundred Men, pp. 118-19
years later, in 1697, the operators took the expensive step (30,000 copperdaler) of erecting a
dam. This altered the landscape, reducing the volume of water that could seep into the shafts.
This “solved” their problem, and did indeed allow further mining, but only a dozen years later in
1709 their deepest shaft, the “Nora Silverberg”, was flooded and shut down. What went wrong?

*Feedback, restoring the system to equilibrium*

Dannemora’s difficulties with flooding illustrate the structure of an energy system based
on organic sources. The limited nature of organic power tends to push activities that rely on it
back into equilibrium. The intensification of mining that accompanied commercialization can be
seen as a move away from equilibrium. To borrow Pomeranz’s phrase, this might be thought of
as the beginning of a divergence. Unfortunately, subsequent flooding limits the expansion of the
mining. The flooding is met doggedly with all the ingenuity a succession of water removal
methods can provide. Each “solution” of the problem permits a greater volume of digging,
which produces further flooding, eventually bringing digging to a halt. Superficially, it appears
that the flooding problem is the factor that limits the volume of mining. However, flooding is
only the *form* that the limit takes in the specific case of mining. The true limiting factor is the
organically-based energy sources available for the expansion of commercial activity. The cost of
the human labor, animal power, waterpower, etc, - which is to say, energy costs - eventually
limits any energy-using activity.

In the Dannemora example, successively more intense methods of dealing with the water
were used. This allowed further digging. The feedback within the system resulted in each
successful innovation that removed more water eventually brought more flooding.
Commercialization had set in motion a divergence, but within the existing organic energy
environment, the additional digging led the system back to equilibrium. The equilibrium was
reached in their deepest shaft, the “Nora Silverberg” when it was flooded beyond hope in 1709. This was not a piece of bad luck for the Swedish mine owners, but the natural result of the structure of an organic-energy system.

*Marten Triewald’s Engine*

Triewald came from a family of German immigrants to Sweden. As with the Dutch businessmen in the early 17th century, opportunity for profit had drawn them across “national” boundaries. Triewald had traveled to England in 1716, eventually working with Newcomen and Calley. He was an educated engineer and a scientist, and participated in the building of 4 engines. Triewald was ambitious; with his knowledge of engines, he returned to Sweden seeking a worthy task that would bring him fame.

Triewald proposed to build an engine to drain the Nora Silverberg shaft at Dannemora. His bold idea was accepted, and construction began in 1727; due to difficulties, the engine was not first run until July 4, 1728. Trouble with the pumps, not the engine, idled the machine for most of the remainder of 1728; further problems resulted in it running only intermittently in 1729. A falling out between Triewald and the mine operators over the winter of 1729/30 left the engine idle during the protracted lawsuit that followed. Except for a brief run for some tests in 1734, the engine was never run again. The engine was disassembled, stored away, and in 1736 the operators employed horse-powered whims to drain the pit, a process that took over 6 months.

What went wrong? Writing in the 1920’s, Rhys Jenkins suggested that a lack of engineering expertise in Sweden made it difficult to find men who understood and could repair the engine. Lindqvist, writing in the 1980’s showed that suggestion lacked any merit, and that 18th century Swedish technical expertise was at least the equal of Britain’s. In his excellent history of this machine, Lindqvist concluded that the engine’s demise was an example of a failed
attempt to transfer a technology transfer. He suggested that cultural and climate factors conspired against its success.

Fuel as a factor

The factors cited by Lindqvist certainly created difficulties for the engine, but none of them were insurmountable. None that is, with the exception of the fuel demands of the machine. An examination of the engine’s fuel use, and the mine operators’ reaction, shows it was a key factor in its failure. Shortly after it was first run, the mine directors specifically cited the volume of wood consumed by the engine as a problem.

Lindqvist cataloged the hostility of the mine operators, particularly one mine Bailiff named Kroger, towards Triewald, and his assistant Olaf Hultburg. He attributed this to the relative social position of the operators, which was being challenged by Triewald. However, by constructing a time line of the operator’s reports about the engine, it is possible to identify an alternate source of this hostility: it was the engines fuel use. This timeline revealed a dramatic shift in tone after the engine was first run. Prior to its first operation the project’s course had been less than ideal: it suffered cost overruns and was nine months behind schedule. Even so, a report filed by Bailiff Kroger one month prior to the engine’s first operation in July of 1728 was upbeat about engines prospects.

Afterwards, by contrast, the reports became negative, and the expense of fuel was a recurring theme. Specifically, in August of 1728, only one month after the first test, Kroger stated that the machine used 10 stafrum of wood per day, and that “…it has already wasted 57 stafrum of wood.” He complained that the cost of the wood used by the engine was “no little loss for the company”. 642

---

642 Lindqvist, p. 258.
What had changed to so sour Kroger’s expectations for the project? Triewald had certainly underestimated most of the construction costs, having spent twice his original estimate. However, these overruns do not appear to have greatly troubled the operators. Where Triewald had gone wildly astray was in his estimate of fuel needs. In his proposal, he had estimated the engine would use 300 stafrum of wood per year; this would be about 1 stafrum (1.5 cords) of wood per day. As Kroger reported, the machine used over 10 times that amount. This must have come as quite a shock to the operators.

**A Financial Decision**

It would have been immediately clear to the operators that the engine would not be affordable at anything close to its demonstrated fuel usage. Wood fuel cost them approximately 3 copperdaler per stafrum. At Triewald’s original fuel estimate, the cost would have been only 900 copperdaler per year. To put this sum in perspective, it cost 9,000 copperdaler to operate all the other existing lifts: the horse whims, the windmill, and the waterwheel. Perhaps they even expected, in light of Triewald’s other overly optimistic estimates, that the fuel costs would be double the original proposal. Even at that, 1,800 copperdaler would be a significant savings over the costs of other pumping methods, and the operators could be expected to recoup their 50,000 copperdaler investment over several years. However, if the engine really needed 10 times the original estimate, it would cost 9,000 copperdaler for fuel alone. It would be more expensive than organic methods of pumping, and the investment would never be recouped. The mine operators had little patience on that point.

In 1734, the engine was run in a test where its fuel usage averaged 8.9 stafrum per 24 hours of operation. Triewald, at about that time, claimed that he could run the engine on 6

---

643 One stafrum equals just over one and a half cords of wood.
stafrum per day. The 6 stafrum may be the quantity depicted in the illustration of his engine, included in his 1734 book. However, even if he could reduce fuel to this level, it was probably still not affordable. 6 per day, at 3 copperdaler each, would cost 6,570 copperdaler per year. Allowing modest amounts for maintenance and overseeing, the operating costs of the engine would be 9,000 copperdaler per year, 2/3rds of that on fuel.

The Uppsala peninsula in the 18th century was an energy-constricted zone. True, a great volume of wood fuel was available, however this source was already being employed to supply the 17 iron smelting furnaces that surrounded the Dannemora mine. For its fuel requirements, Triewald’s engine needed to enter into competition with these established iron furnaces. No special allowances had been in place for the fuel needs of the engine. As a result of this competition, fuel was relatively expensive. Once repairs, operation, and maintenance was added into the equation, the mine operators concluded that the engine would not provide any price advantage over their current “best-practices”. They chose horse-powered whims to drain the Nora Silverberg shaft.

**Case Study: Brown Engine at Cranston, Rhode Island**

Only a handful of Newcomen engines were built in the Americas. The first documented example was at the Schuyler copper mine in New Barbadoes Neck, an area that became North Arlington New Jersey, not far from New York City. The mine began production sometime around 1715, and experienced the typical pattern for mines. The first phase worked the copper veins using drift (surface) mining. Within 20 years (1735) the ore that could be recovered by this method was exhausted, and shaft mining began. In another dozen years the shaft, which would later be named the “Victoria” shaft, was reportedly 100 feet deep; it was also idled by flooding
The owners sought a “fire engine” from Britain, which was set up, after many delays, in 1755. This engine was professionally manufactured in Britain, and erected by Josiah Hornblower.

Despite the advantages of a professionally built engine, maintained by an experienced engineer, this machine had a checkered career. It ran off and on until from 1755 to 1768, after which it was idled by a fire and sat unused for 25 years. The circumstances are unclear. Josiah Hornblower rebuilt the engine in 1793, but its operation appears again to have been less than satisfactory.

The first engine believed to have been manufactured in the colonies was erected in the 1770’s to provide water for the city of New York. This engine actually functioned, but only briefly before the occupation of the city by the British in 1776. Details are lacking for this engine, although it is known that it did use wood for fuel.

In 1783, another domestically built engine was erected by a company belonging to the Brown brothers of Providence, Rhode Island. The Browns had operated an iron furnace, “Hope Furnace”, and iron ore pits to supply it, since 1765. The ore mine was in Cranston, while Hope Furnace was 4 or 5 miles away in Scituate. The Brown engine was built to drain the iron ore pits that supplied the furnace. On-site supervisors, who frequently wrote to the Brown brother in Providence, oversaw these operations. This business correspondence provides a rich, detailed account of the operation of the mine, the furnace, the production of cannon for the Revolutionary War, and eventually the building of the steam engine. Note that at this time, the 1780’s, it was always referred to in correspondence as the “steam engine”, whereas previous engines in the colonies had been referred to as “fire-engines”.
The case study of the operation of the Cranston iron ore pits provides a detailed example of the relationship between commercialization and industrialization. It supports the sequence of 1) the development of commercial markets, 2) commodification of inputs, which creates profitable opportunities for entrepreneurs who can control energy sources, and 3) the tendency towards mechanization of production, in order to increase profitability.

The Cranston pits were opened in 1765 to provide iron ore for Hope Furnace. In their actual operation, the ore pits followed the by now familiar pattern seen at the Dannemora, Schuyler’s copper mine, and countless other mines. In the Rhode Island case, the correspondence enabled a detailed study of the course of the iron mine from its very beginning. Initial recovery of ores was easily achieved, but increased extraction led to difficulties with water. Initially, the water was avoided by moving operations, then by altering the landscape (in this case, re-routing the stream). When shifting locations was no longer an option, the operators were forced to deal with the water directly. As at Dannemora, flooding was initially met by using a waterwheel to operate pumps. These pumps lifted water from a sump-pit, which drained adjacent, shallower pits where the ore was being recovered. As the Revolution drew to a close, the demand for iron in general, and cannon in particular, idled some of the furnace’s resources. The Browns decided to put these excess resources to profitable use. Under the direction of Joseph Brown, the company decided to use some of the available pig iron to cast a cylinder for an engine. This was accomplished in early 1783, and the engine house and engine were erected later that year.

The engine ran successfully well into the mid-1790’s, servicing the pumping needs at the pits. Eventually, declining demand for the products of the furnace idled the ore pits. The iron industry, which had first established itself in the tidewater areas from New England to Virginia,
was moving inland. By 1800, iron production in Rhode Island and other coastal furnaces was loosing out to the lower-cost production in Pennsylvania, and by circa 1800 the furnace at Scituate, and thus the engine at Cranston, was idled. A longer view reveals that this was simply a case of the primary energy source, the waterpower of the Pautuxet River, being transformed from one commercial task to another more profitable one. The site of the furnace became a textile mill, which was operating by 1807.

A Tale of Two Iron Mines

Why was it that the engine at the Dannemora iron mine failed while the one in Cranston succeeded? We can dismiss differences in technological skill, as they perhaps favor the Dannemora engine. True, 50 years had elapsed between the two, and it is possible that the accumulation of improvements favored the Brown engine. However, Triewald was a trained engineer with experience building successful “eld- och luft” machines. Further, the cylinder for his engine was cast in brass, a more efficient metal for the heat transfer process used by the engine. These technical advantages for the failed engine at Dannemora stand in stark contrast to the successful engine at Cranston. It is not certain if Joseph Brown had ever even seen an engine. Further, the materials were all cast locally by novices in engine building.

What the Browns did know was energy. They were thoroughgoing capitalists, and while they would not have phrased it this way, they experts at extracting an energy rent. In Sweden, Dannemora existed in a complicated communal environment that had evolved out of earlier social arrangements among owners, directors, bailiffs, customers (furnaces), and labor. By contrast, the Browns in 1765 were working with a blank slate. The iron-producing business they set up was designed from its inception as an energy converting system. Their goal was to
profitably transform energy and raw materials into a profitable commodity. The fact that the commodity took the form of merchantable pig iron was incidental to them: when the time came, they were more then ready to change this commodity form, in this case into textiles. When planning their furnace, they took great pains to secure sufficient energy for all its needs (principally wood for making charcoal, and waterpower for the furnace) prior to the beginnings of the enterprise. In contrast to this, the Triewald’s engine tried to establish itself in an energy-constrained environment: all the available sources already had claimants.

Earlier histories of Hope Furnace (Hedges) lacked details about the building of the engine. It was supposed, quite reasonably, that the needs of the Revolution had prompted the building of the engine, and so it may have been built in 1780 (3 years earlier than its actual construction). The narrative was: the Revolution had increased demand for cannon, which intensified extraction at the iron mine. This had resulted in increased water problems; to access the iron ore necessary to produce cannon for the Revolution, the Browns built the engine in 1780.

The research of this dissertation has shown, however, that the engine was not actually built until 1783, nearly 2 years after Yorktown and not long before the signing of the Treaty of Paris. The expansion of the pumping system in 1780, as identified by Hedges, was no doubt to produce more iron and cannon for the war. What the research of this dissertation has documented is that these pumps were actually powered by a waterwheel. This wheel was a rebuild, presumably an enhancement, of an earlier wheel used for pumping.

What are we to make of this surprising timing as regards the building of the engine? Why build a pumping engine at the end of the war? Again, by following the energy-use pattern, an interpretation suggests itself. First, we might suspect that the waterwheel was not supplying
sufficient power to clear the pits, however evidence suggests this was not the case. In 1782, the year prior to building the engine, the Browns had advertised iron ore for sale. Clearly they had more than they needed. Further, we know that the wheel was relatively powerful because it was used in the same three-pit method of excavation, where one pit served as a sump draining the two active pits, which would later be pumped by the engine.

The answer may be found in viewing the iron mine and furnace complex in the same way as the Brown’s: They would have considered it as a single, energy-converting system. With the end of the war, and the slowing of demand for iron, the furnace would no doubt find itself with a surplus of iron and wood to make charcoal. The question for the Browns, as always, was how to turn this surplus to a profit. They answered this by using the excess iron to build the engine, and the excess available wood as fuel to operate it. This provided them with several benefits. Not only did they now have a reliable all-seasons pumping method at the mines, the waterwheel was also freed up for other work. Shortly after the engine began operation in 1783, they set up a blacksmith shop at the ore pits; this shop almost certainly would have used the power of the waterwheel for its work. Using an engine rather than the wheel would also have increased the spatial flexibility of their mining. Seen in this light, the decision to build the engine in Cranston was an energy-savvy strategy.

Perhaps unknown “technical problems” really did cause the failures in Cornwall (1710/11) or at Dannemora (1730), but given that the Brown’s engine was colonial-built by workmen who were beginners at that trade, their technical challenges seems at least as difficult. It seems more plausible that the success enjoyed by the Brown engine at Cranston was rooted in the same factors that brought success to Newcomen’s efforts in the collieries of the Midlands 70
years earlier. Both of these were not just energy intensive environments: they had energy to spare. An ample supply of low cost fuel was a key factor in their success.

**Gender and Capitalism**

One of the striking differences between the mine in Dannemora, Sweden (circa 1730), and the one in Cranston, Rhode Island (established 1765), is the distinct shift in gender roles. At Dannemora, single women, married women and widows were all represented among its workforce. Lindqvist related an incident where the mine operators increased the workload of miners working windlasses at the Dannemora mine. Of the 22 workers disciplined for refusing to do the heavier labor, 8 of them were women. When we turn to iron ore mine in Cranston, there is no evidence that any of the people who ever worked there were women. While these are only two examples, they reveal a radical redefinition of gender roles. How do we explain this change in perception of gender?

This change in what constitutes suitable “woman’s work” may have been an example of the redefining of gender that occurred with the establishment of capitalism. At the risk of oversimplifying the shifting rights of women as feudalism gave way to capitalism, it has been noted that in pre-capitalist societies, there is less of a distinction between the household and the productive unit. Women were an integral part of production, and their rights and authority within the household reflected this. The establishment of capitalist forms separated the household from production. “Work” would eventually come to be defined as something that occurred outside of the home. This had the tendency to reduce the status of women. It is possible the difference is rooted in the establishment of the fully capitalist form of production in

---

644 Lindqvist, p. 124.
Rhode Island, as compared to Dannemora. The Swedish mines were, after all, owned by the feudal nobility, while Cranston was owned by businessmen.

It may be argued that on the Uppsala Peninsular in Sweden labor was scarce, and so women were incorporated into the workforce. However their labor needs were probably no more acute than the shortage in the Americas, especially during the time of the Revolution. Even so, when short of labor in 1781, the director of the Cranston ore pits sought out socially marginalized “Street Negroes and Indians”, but no suggestion was ever made of hiring women. While hardly conclusive, this difference in the composition of the laborers suggests that in the New England colonies a view of gender had been constructed that was significantly different from that in Europe.

**Slave Sugar Plantations**

The focus on energy also helps to explain the otherwise curious link between mechanical power and slave plantations producing sugar. Slavery as an institution has been regarded as slowing technological growth, but the example of sugar plantations suggests that this was not universally the case. Several aspects of sugar production, particularly the crushing of the cut sugar cane, required the energy intensity that is the signature of an extractive industry. As with pumping water from a mine, human labor will only suffice for a relatively small operation. Larger enterprises needed the greater primary power available from animal labor, typically oxen. The greater power of a waterwheel was used, where possible.

While its needs are great, the nature of sugar production created restrictions on the spatial and temporal flexibilities of the energy it could use. Sugar plantations were often located in lowlands, such as in southern Louisiana, where waterpower was not an option. Temporally, the

---

646 April 26, 1781; Joseph Shaw (Cranston) to Joseph Brown; JCB, B.179, F2
nature of sugar production put a premium on time: the grinding had to be done relatively soon after cutting. This made power sources with poor temporal flexibility, such as windmills, a risky choice. It should not be surprising that sugar plantations owners showed an early and persistent interest in adopting steam power to their needs. Unfortunately, the expense of fuel limited successful application. Even so, a Newcomen-type engine was likely in operation by 1768 on the island of Jamaica. As proposed, this engine had planned to use the steam from the sugar boilers to also provide steam for its cycle. That this proposal reflected a lack of understanding of the thermodynamics involved was not uncommon for the 18th century. The production of the additional steam would have required more fuel, limiting any savings from the proposed cogeneration. In the 1800’s, the issue of fuel would be at least partially addressed through the use of dried cane residue, the bagasse.647

Rather than laggards in application of steam power, the slave owners operating sugar plantations were in the forefront of those applying this technology. The survey of steam engines conducted on behalf of the U.S. Treasury in 1838 revealed that Louisiana was second only to Pennsylvania in the number of steam engines then at work in the state. This was largely due to the use of engines on sugar plantations. The survey listed a number of low-pressure Boulton and Watt-style engines still in operation in 1838 that had been erected in 1821 or earlier. Plantation owners, who were masters at extracting an energy rent from human labor, were not slow to see the advantages of mechanical power.

**Looking for Proto-Industrialization**

Energy is an insufficiently developed notion in the social sciences. Even the field of economics has been slow to incorporate this dimension. This lack of an overview has left the

---

647 Follett, p. 35-36.
humanities in a quandary when dealing with historical changes that have a significant energy element. While much can be explained without regard to prime movers and their fuels, the intensity of the transformation that accompanied the Industrial Revolution requires grappling with the energy dimension. This final section provides an overview of the elements from the case studies that might have broader application for world history.

Given that mechanization was such a crucial step, what were its particulars? Where should we look for this mechanical power to be applied? What kind of operations, productive activities, and skills should we expect to accompany mechanization? By developing a mid-level laundry list of what would prompt someone to try mechanical power, it should be possible to examine various situations where engines emerged, or did not. What enterprises in China and India should be examined for proto-steam engine activities? From the literature review and the case studies, several elements suggest themselves.

- Some segments of the economy need to be market-oriented;
- Commoditization of outputs, and perhaps inputs;
- 24-hour per day use, need to concentrate energy;
- Inadequate available supply of primary energy from waterpower;
- Energy intensive environment.

The first two elements, a market and production of commodities, were widespread throughout the world of 500 years ago, and the production of some commodities was already energy intensive. For these, human and animal labor were the first choices when additional power was required. It was only after this these became in adequate that further mechanical power was sought, with waterpower a typical next choice. We can expect that the mechanical industrialization of production will be powered organically if the energy-using facility has
geographic flexibility. Textile production, for example, used flowing water as its power source before turning to steam.

A textile facility could of course be brought to the power source. The corollary of this is that enterprises that cannot be moved will need to seek other power sources. Thus, when looking for proto-mechanization in other areas, we should focus on activities that lack locational (spatial) flexibility. Coalmines were the event-specific sites in Britain, but the power needs and geographic restriction of raw sugar production also prompted these sites to be early adaptors of mechanical power.

The case study of the Brown engine echoes the British experience that steam engines are likely to arise where 24-hour per day pumping is required. However, this echo bounced back with a nuance as regards fuel. While the iron ore works at Cranston were not a coalmine, they did exist in a system marked by intensive use of energy. This suggests that it is not a coalmine per se, but an energy intensive environment where the use of an engine would be likely to germinate.

**Commercialization, the Need for Power, and Fuel Availability**

The alien technology employed by an atmospheric engine has obscured the history of its invention. It is as if in the year 2203 the Wright Brothers’ flyer would be widely referred to as “the first jet”, because the internal combustion engine was simply too primitive to contemplate. Today the Newcomen engine is called a “steam” engine, but this is not how contemporaries described it. The earliest depictions termed it an engine for raising water with a power made by fire. This was not a quaint early 18th century expressions, but a description of the principles at work, and is considerably more accurate than calling it a “steam engine”.

This confusion regarding the forces that powered the first engines was compounded by
the historiography of the 18th and 19th centuries. These histories were recasting the 18th century
to construct the narrative of Britain as a uniquely technological and progressive society. To do
this, they enlarged upon the scientists of those days, and were generally unkind to Mr.
Newcomen the ironmonger. The storyline that gained acceptance was that Newcomen was an
unlettered blacksmith, and only by accident, or as some would have it direct divine intervention,
was he able to build a crude machine that he himself did not understand. This rude machine was
seen as being “corrected” by later scientists and “perfected” by James Watt.

The 19th century historiography of the steam engine coalesced around elite scientists and
their breakthroughs. This history typically begins with a Greek compiler of inventions named
Heron of Alexandria. Popular 19th century English-speaking writers invariably translated his
name as “Hero”, thus rendering the steam engine, quite literally, as a Heroic invention. This
heroic mantle was then modestly bestowed upon Watt, Trevithick, Brunel, and other noble
British scientists.

If we are to understand how mechanization proceeded, and what proto-industrialization
might have looked like elsewhere in the world, it is important to maintain at least a passing
acquaintance with the technology that was in fact used. The line of development that led to the
first commercial engine came via the discovery of air pressure. Since it was powered by
atmospheric pressure, the Newcomen engine, and Watt’s that followed, both dealt with pressures
of less than one atmosphere. This greatly reduced the strain on the materials, not an insignificant
factor in the first decade of the 1700’s.
Generic Mining Model

Mining may not be the only place where an engine could be developed, but it does bring together a number of factors that suggest a closer scrutiny of mining elsewhere in the pre-industrial world might reveal the type of activity that would promote mechanization. To examine the energy needs of mines in an organic economy, a generic model, as suggested by these case studies, may be useful.

In a pre-commercial economy, mining for base metals would generally be conducted only on an as-needed basis. Typically, an ample selection of untapped outcroppings was available, and so a mine with flooding problems could be abandoned for new, dryer, opportunities. An exception to this would be in the case of precious metals. When the goal was the mining of silver, water lifting devices were employed relatively early, and were used in both Roman Spain and medieval Central Europe. In the 1400’s, a sophisticated system of horse-whims lifting bags of water was already employed at the silver mines of Kutna Hora, which is in the present-day Czech Republic (Chapter 3).

With the advent of commercialization, the mining for commodities would be intensified. Production was now for a market, and the amount of mining pursued depended on potential profits: Whether or not to dig became a financial decision. The model posits that at some point, this more aggressive extraction of mineral resources will have had brought all previously untapped resources (those easily extracted), into production. The only recourse is then deeper mining, which eventually brings the shafts into contact with the water table. Since removing the water is an additional cost, without any benefit, mine operators are presented with a financial problem: what is the cheapest way to remove the water? Note that the initial endowment of
resources influences the *timing* of this intensification. Areas with greater initial resources would have the luxury of delaying pumping activity.

The methods used historically in 16th and 17th century Europe to remove water from mines provide a review of the energy sources available in an organic economy. Human labor was the first choice, physically bailing out water in mining pits. This was followed by animal labor, as had been earlier used at mines recovering precious metals. Eventually waterpower and wind would be employed, if possible.

The generic model outlines a negative feedback loop that eventually renders all these efforts to lift water, using organically-based energy, self-defeating. The problem for the miners was that any success in removing the water led to further digging. However, the lower the shaft, generally the more flooding it encountered, and the greater the distance it had to be lifted. This double whammy - more water lifted a greater distance - accelerated the amount of required pumping. As even more intensive methods of pumping were used, the negative feedback asserted itself in the form of ever more flooding. Ultimately, the additional cost of lifting the water exceeded any remaining profits from digging, and the mine was shut down. Again, this was a financial decision. The factor that closed the mine was not the flooding as such, but the negative energy rents from the organic prime movers available to remove the water.

This example from the mines illustrates a broader truism about organic energy: the dynamics of a commercializing economy will eventually be brought to equilibrium (no growth), by the limits of organically-based energy. A divergence from this equilibrium would require a different energy basis.
Taxonomy of Energy

It has been said that because mines cannot be moved, it was particularly difficult to serve their energy needs. This diagnosis, from the point of view of the mine operators, privileges their activity but reveals little about the energy types. Turning the question around, what is it about any particular energy source, what inflexibility, renders them difficult to use it at a mine? One could say waterpower is “unavailable”, or that wind power is “too sporadic”, or that lifting water more than a certain distance is “beyond” the abilities of human labor, but all these statements imply that there are characteristics unique to each energy type. In a broader view, these individual characteristics are really qualities shared among energy types. A list of flexibilities might include spatial flexibility, temporal flexibility, and intensification flexibility.\(^{648}\)

Upon reflection, these flexibilities can be seen to relate not to a prime mover itself, but to its fuel. To say that waterwheels were “unavailable”, that they cannot necessarily be built where they are needed, is to say they lack spatial flexibility. More specifically, the “fuel” that powers the wheel, flowing water, is found only in limited places. Temporal flexibility is a qualitative judgment about how much control a user has over when the prime mover would be available. The power from a windmill is “unreliable” because it cannot be switched on during the times when needed. Finally, to say that human labor is too easily “exhausted” means it is difficult to concentrate for heavy tasks. There are no returns to scale when coordinating the work of large numbers of people for a simple task.

Chapter 4 provided a suggested classification of energy types (Table 4-1), according to their relative flexibilities. To identify situations where proto-industrialization existed, we might do well to concentrate on identifying situations were flexibility was lacking in the activity’s location, and in the fuels it used for it power source.

---

\(^{648}\) See Chapter 4 for a more detailed comparison of these flexibilities.
Epilogue

This dissertation has been about energy, addressing this topic via several case studies of early stationary atmospheric engines. These engines were first used to pump water from mines in England, and later for the same task elsewhere in Europe and the colonies in America. It is hoped that these case studies can be vehicles to illustrate how a society comes to demand, control, and processes energy. The engines are, after all, only a particular historical realization of the larger process of socially controlling energy.

In themselves, these engines are of great interest as they were the first machines to convert thermal energy to mechanical energy: Through the power of fire, they drove pumps to lift water. Viewed more broadly, they illustrate how the constant pressure to expand a society’s energy envelope can create a transformational change. This demand for greater power was rooted in the commercial revolution, which had created a social process that allowed for the conversion of greater quantities of energy. During the course of commercialization a surprising, and wholly unanticipated, turn of events occurred: Mechanization took commercialization in a radically diverging direction. The fact that it continues to do so makes this process of more than passing interest to the 21st century.

But what of “fire and air” machines themselves, and their use of atmospheric pressure differentials to produce useful mechanical energy? They belong to a forgotten, Pre-Cambrian age. Their technology flourished for a century and then vanished. Vanished! These stationary atmospheric engines were so different from what the “steam engine” became in the 19th century that it is difficult even to simply grasp their operating principals. This difficulty has tended to obscure the historical process of the adoption of mechanical engines that occurred during the crucial first 60 years of what would become the machine age. By extension, looking for high-
powered steam engines makes it difficult to recognize any proto-mechanization that may have existed elsewhere in the world. This dissertation has been a modest attempt to review examples of this low-pressure technology, and their relation to the energy demands that brought them into being. It is hoped that this will contribute to the broader question of the history and future of the Industrial Revolution.
**Bibliography**

**ARCHIVAL SOURCES**

John Carter Brown Library (JCB): Brown University, Providence, Rhode Island

*Nicholas Brown and Company Records (1762-1783)*

*Brown and Benson Records* (1783-1792)

*Brown, Benson and Ives Records (1792-1796)*

*Brown and Ives Records (1796-1914)*

Rhode Island Historical Society (RIHS): Providence, Rhode Island

*The Records of Nicholas Brown and Company*

*Manuscripts Division; Paul Campbell Research Notes*
TEXTS PUBLISHED PRIOR TO 1900


Forestall, E.F. “Sugar of Louisiana” (1846), reprinted in J.D.B. De Bow *Industrial Resources. Etc., of the Southern and Western States* vol. III. New Orleans: Published at the Office


Woodbury, Levi, Secretary of the Treasury. *Steam Engines: Letter from the Secretary of the Treasury, Transmitting, in Obedience to a Resolution fo the House of the 28th of June Last, Information in Relation to Steam Engines, & C*. U.S. Treasury Department, December 13, 1838.


Discover Hope Village: A National Register Historic District In Scituate, Rhode Island.
Providence: Rhode Island Historical Preservation & Heritage Commission, 1996.


Field, Edward. State of Rhode Island and Providence Plantations at the end of the century.


Frost, Robert I. The Northern Wars: War, State and Society in Northeastern Europe 1558-1721.

Finley, M.I. Economy and Society in Ancient Greece, ed. Brent D. Shaw and Richard P. Saller.


Appendix A: Organic vs. Mineral Energy

Annual Production of Organic Energy

Energy (human labor, animal labor, or thermal energy) in an organic economy is produced from the land. Since land is limited, the amount of energy that can be derived from it is limited. Organic energy is based on the flow (or rate) of conversion. This rate can be variously expressed as bushels of wheat or cords of firewood per acre per year. Depending on the quantity of land available, and the amount of labor put into it, a certain amount of food (or other organic material such as cotton) can be produced annually. 649

Figure A-1. Labor, using Land, annually.

Beyond just labor, the rate of food production depends on a number of other factors (putting aside the variability of weather). Animal labor can be used; organization can improve growing techniques (irrigation, for example); tools (“capital”) can be used or improved (the heavy plow in medieval Europe). These are shown in Figure A-2; however, at best they improve the RATE of production for a given quantity of land. The limited nature of land was noted by Malthus, among others.

649 Refer to last page for a note on the diagramming conventions used here.
The elements of the simple model above can be used to illustrate how land, labor, capital, organization and energy inputs drive the dynamic behaviors of an organic economy.\textsuperscript{650}

\textit{Growth ("positive") loops: More food allows for more people, perhaps working more land.}

An organic economy can grow through scale of production. More food produced will support a larger population. This larger population can work more land, or more intensively the land currently in production. Larger scale production will likely enjoy some economies of scale. Per Adam Smith, larger economic units often benefit from specialization within sectors of the economy.

\textsuperscript{650} Beaudreau argued in no uncertain terms that productive inputs needed to be expanded beyond land, labor, and capital to adequately describe the evolution of an economy.
The positive dynamics in an organic economy are illustrated above. An increase in the rate of food production will increase food available per person; this tends to increase population; a greater population (labor force) will in turn increase the rate of output. This is a growth loop that can rapidly expand an agricultural society.\footnote{Note that “Labor” had been replaced by “Population”; the distinction between the two is not necessary for this illustration, and so the diagram has been simplified in the hopes of improving clarity.}

*Balancing (“negative”) loops: diminishing returns and the dreary Reverend Malthus*

There are also strong negative feedback loops at work in an organic economy. Perhaps the strongest check to growth comes from the population feedback, as famously articulated by Thomas Malthus.\footnote{Malthus, an *Essay on Population*.} In response to an increase in food, such as diagramed above, population will increase. Population is capable of increasing at a geometric rate (it can double over a period of time: 2, 4, 8, 16, 32). To feed this population, improvements in the rate of food production...
proceed at best linearly (2, 4, 6, 8, 10). Eventually, no matter how successful the food increase, population will outstrip it. The result is that “Food per Person” returns to its subsistence level, if not less. Famine will bring population and the food available back into balance. The best that can be hoped for is that real incomes stagnate at the level of poverty (economics has earned it appellation as the “dismal science”). This balancing (“negative”) loop is shown below.

![Diagram](image)

Figure A-4. Lacking additional Available Land, falling Food per Person restrains Population growth.

Note that nothing has changed in the positive growth loop previously identified; increased Population still increases the RATE of food production. The difference is that all Available Land is already in use. Lacking additional land, the increase in Population has to work with a fixed quantity of Land, which tends to result in slower growth in annual food production. Relatively less food has the impact of decreasing the “Food per Person” ratio: all other things
being equal, more people means less food per person. This restrains the runaway growth of the system, and is indicated by the “-” sign.

Starting at “Population”, an increase in Population decreases the “Food per Person” ratio (these two move inversely). However, as previously noted, any change in “Food per Person” is positively correlated with “Population Growth”; just as an increase in the first causes an increase in the second, a decrease in the first causes a decrease in Population Growth. Population will fall until at least until the ratio reaches minimum subsistence level. At that point, the growth and balancing loops are at a stable equilibrium (minimum subsistence food levels).  

*Other constraints on growth*

Land and animal inputs may be increased to deal with the falling ratio of food available per person, but these have there own constraints. Land is a limited commodity: the more that is used, the less remains to be brought into cultivation. In addition, since the best land is used first, only land of decreasing quality will be available for future expansion. On this poorer land, more inputs are required for each succeeding unit of output. Economists express this as the “law of diminishing returns”.

A similar constraint reduces the usefulness of animal labor. It is a characteristic of organic economies that all resources are already employed; any future option typically displaces some current use. The familiar story of how the horse collar and the heavy plow revolutionized food production in Northern Europe is an illustration of this. While they improved output, feeding these additional draft animals meant diverting some labor and displacing a quantity of agricultural land.

---

653 Note that finding new Available Land, for example an empty continent or two, would stimulate population growth.
Figure A-4. Lacking additional Available Land, falling Food per Person restrains Population

Possible Gains

Many gains to the level of production can be achieved using organic energy, such as flows of wind or water. Sails and sailing are a form of harnessing wind power; thus wind power can facilitate trade, which plays into the “specialization” benefits noted by Adam Smith. Wind and waterpower can also be used directly, typically in the form of mills. Grain mills and saw mills are a feature of what are referred to as Advanced Organic economies.

Unlike simple hand tool, things such as trading ventures, ships, or mills represent significant investment. Capital emerges as an essential factor in these more expensive endeavors. Things that facilitate capital accumulation and investment will increase a society’s access to these energy enhancers.
Mineral Economies

Organic economies have the virtue of being renewable: they can continue to produce useful energy indefinitely. The price of this virtue is that they are limited to a rate of production; the rate can be increased, but only within limits. The society also tends towards equilibrium (stagnation) at the subsistence level. This is not the case with a mineral energy source.

A mineral energy source is a LEVEL of energy, sitting untapped in the ground. Where organic energy can be produced at a rate such as bushels per acre per year, mineral energy can be produced directly. Its constraints are not physical (per acre), but only per unit of time (per year). As to what ultimate unit of time the whole of the stock of mineral energy will be used, the choice is up to the people using it. People now have a source of energy they may now use at the time of their choosing.

The difference between the two types of energy can be illustrated by considering a wheat field that has a vein of coal underneath it. As a wheat field, it can produce a certain number of bushels of wheat per acre per year. It can do this indefinitely, but any increase of the rate will be limited. Alternatively, consider the land could be developed as a coal mine. The coal available can be used a little bit each year over a long period of time, or the entire stock can be mined in one year. The total energy available is the same; the intensity of the energy use is at the discretion of the developer.

Inorganic energy, such as coal, had been known for a long time, but little used. As with the earlier development of agriculture, “discovering” something, and then being able to find a

---

655 The renewal of resources is actually much more complex, and it is certainly possible to use one beyond its ability to replenish itself. The collapse of fishing stocks or deforestation is two well-known examples.

656 All this ripping up the earth for energy production struck some people as a bit grotesque, spurring the “Romantic” movement of the early 19th century, and their not unreasonable revulsion at the sight of dark satanic mills.
socially controllable use for it, were two different things. A socially controllable system for transforming the energy is necessary. In advanced agricultural societies, commercialization began to alter how decisions were made about energy use. Perhaps the single most important factor in the adoption of mineral energy was the profit margin, as provided by commercialization. The first significant use of coal was as a substitute for wood, wood in some cases having become relatively more expensive. As we shall see, the development of the steam engine was also due to the profit margin.

The atmospheric steam engine developed by Thomas Newcomen (c. 1712) was able to provide mechanical pumping labor that would pay for itself. These early applications were followed by incremental improvements in engine design and operation. It was not until 60 long years later James Watt “invented” the steam engine. Watt’s engine, with its separate condenser, used only $\frac{1}{5}$ the coal of a Newcomen engine for a given level of useful work. This crossed an efficiency threshold where, for many applications, the operating cost of a steam engine was now cheaper than horse’s power even outside a coalmine. The advent of mechanical labor was at hand.

The development of mechanical labor began a process that would destabilize the dynamics of the organic economy. This was not obvious at the time. As keen an observer as Adam Smith, who spent his life studying the economy, did not see (1776) the potential of a stock of energy combined with a converter that could transform it into mechanical labor. From his vantage point 60 years later, Marx saw continuous accumulation by capitalists as not only possible, but inevitable. He believed the capitalists’ inability to distribute the benefits would lead to revolution; as things worked out, the distribution problem has been repeatedly addressed,
at least after a fashion, and the revolution has not materialized. However, the problem of scarcity of supply had been turned on its head: Rather than an inability to provide subsistence level, the economy would henceforth be plagued by repeated crisis periods of under-consumption. The malaise of the modern economy was not floods or drought, but a scarcity of ability to pay.

Mineral energy does not depend on a rate of production; the level of mineral energy available annually depends on the amount of labor (human, animal, and now mechanical) put to work to produce the energy. A mineral substitute for energy would remove the land constraint.

---

657 See Tylecote for a summary.
658 Compare the first organic (“Land”) diagram above; note that production from land requires the intermediate step of a RATE between the resource and its production.
Two feedback loops come into play in this dynamic; let’s begin by dismissing the less important balancing loop first. It is true that the ultimate amount of coal available depends on the stock of coal in the ground, and this can act as a limiting factor. However if the annual usage is a tiny fraction of the available stock, this does not restrain production at all. As a finite resource, once it used, it was gone.\textsuperscript{659} However, if the ratio of desired annual output of mineral energy to the total under the ground is small, then it is available in effectively unlimited quantities.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Available Mineral Resources could hold back growth, but initially the ratio of use is so small that it had no restraining effect.}
\end{figure}

In the above diagram, “Available Mineral Resources” is depicted somewhat larger than currently used “Mineral Resources”. In reality the resources available were many thousands of times larger than the use in the 19\textsuperscript{th} century. To this should be added that early phases of mineral exploitation often lead to additional finds and falling costs of production (learning by doing, and

\textsuperscript{659} Another point on which Malthus was an early contributor, circa 1810.
economies of scale). As it happened, this negative feedback loop would not come into play until the late 20th century.

A second feedback loop, between Mineral Energy and Mechanical Labor, it turns out, was truly revolutionary. Mechanical labor, such as the Newcomen engine, could be used to help produce mineral energy, such as coal. The revolutionary step was when mineral fuels began to be used to produce additional mechanical labor. This occurred during the last quarter of the 18th century in Britain, such as when atmospheric engines were used at iron forges. In its structure, this loop is analogous to the growth of population (labor) in an organic society, but with a crucial difference: the fuel for mechanical labor, unlike food (the fuel for human labor), is effectively unlimited. *Mechanical labor can be expanded without limit.*

---

660 It may be noted that unlimited energy availability is implicit in Marx’s prediction of unlimited capital accumulation.
Figure A-7. Mechanical labor produces Energy, which produces more Mechanical Labor. The role of Organic Labor is diminished. This process will continue until something else (insufficient demand? pollution?) restrains it.

Although this expansion of mechanical labor would take time, 150 years is not much in the scheme of things. Human labor would eventually find it role as prime mover greatly reduced; its new task would be as manager of mechanical labor. Animal labor would eventually be nearly completely replaced. The impact of mechanical labor on transportation (railroad, and highways) is a dizzying story onto itself.

A Florescence of Animate Labor

An interesting aspect of the advancement of machine technology was that it made all types of labor more efficient, and thus expanded the potentially profitable applications of horse-powered machinery. Throughout the 19th century, the use of the horse as a prime mover actually expanded. This came about as a result of the falling price and improved efficiency of complementary goods. Engineering did not advance to the point where horses could fly, but it did give them profitable opportunities to able to walk on water: consider the horse-powered ferries developed in the 1800’s.

---

601 See Beaudreau
602 See McShane and Tarr The Horse in the City.
While the advanced organic economy of the 1600’s was able to improve agricultural productivity, it only modestly improved living conditions. Living conditions would have drifted into a steady (stagnant) state, except for an important second development: the use of mineral based fuels.\textsuperscript{663} Mineral based fuels were able to avoid the constraints that would have eventually limited any organic improvements in real incomes.

\textit{About System Dynamics and causal loop diagram conventions}

Causal loop diagrams can be useful to illustrate conceptual models. They visually display the structure of a dynamic system, at least my interpretation of it. By breaking a logical argument into a series of causal relations, inconsistencies can be exposed (at least the glaring ones). When trying to explain dynamic behavior, the goal is to identify the “feedback loops”, sometimes call “vicious circles” (occasionally “virtuous circles”), which drive dynamic behavior.

Arrows show the direction of causality. The relationship between two is either “positive” or “negative”. In a positive relationship, an increase in the quantity of the first item will increase

\textsuperscript{663} Note that coal was the historical energy source in Britain; elsewhere in the world, many areas had not yet used up the thermal potential of their organic resources (for example wood-fuel in the Eastern United States).
the quantity of the second. Take for example a population of rabbits: the more adult rabbits in a population, the more baby bunnies are produced; this adds to the rabbit population, which in turn produces even more baby bunnies. Positive loops produce growth.

A “negative” relationship is where an increase in the first activity decreases the second. An example would be the food available, per rabbit, for a given habitat. The first few rabbits in a new meadow might find plenty of food available. However, the more rabbits there are the less food available per rabbit. Eventually, the available food per rabbit is so low that additional rabbits must move on or starve. Negative loops balance systems and restrain, or halt, growth loops. These two relationships are signed using “+” or “-”. The goal of this type of modeling is to complete a causal loop, showing the dynamics created by the structural elements of a system.

A model is NEVER intended as THE way a system works. Its task is to illustrate an argument being put forward by the author, with whatever insights or flaws inherent in the author’s ideas. The diagram shows in an explicit way how an author suggests a system is organized to produce an observed behavior. In this way, inconsistencies in the explanation are exposed and (hopefully) remedied.

For further background, see:


Also, a good on-line introduction has been put together by the US Energy Department (some of the graphics they have used for illustration are a bit curious but the introduction is excellent). http://www.systemdynamics.org/DL-IntroSysDyn/start.htm