# The Collier Problem: Toward a Definition and Application

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## Abstract

The collier problem of the nineteenth century boiled down to coal-powered ships being too inefficient to economically carry a cargo of coal to the globe-spanning network of coaling stations required for their operations. Thus, coal-carrying windjammers were a required piece of the infrastructure which made their nominal replacements' operation possible, as they did not burn any coal in transit. While this is occasionally mentioned by other scholars, this problem has not been examined in itself as a historical and technological paradox, frequently intertwined with the myth of progress and other social phenomena. This paradox wherein a new technology absolutely requires the support of the technology it nominally replaces due to efficiency limits is the "collier problem." The same type of problem exists in today's energy transition, especially with renewable energy generation equipment which is produced and moved using almost entirely fossil fuels. Conventional (internal combustion–engined) ships will require alternative, zero-emissions fuels to carry these fuels to their point of use, thus burning the limited and critical resource they are carrying. By understanding the collier problem's roots and the solutions which can be learned from its solution, the twenty-first century energy transition can be both clarified and accelerated.



## Keywords

maritime transport; alternative fuels; wind propulsion; energy transition; collier problem

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Figure 1. Solon F. M. Badger, *Six-Masted Schooner George W. Wells*. Oil painting, ca. 1900. The six-masted schooner pushed both economic and technical limits for sailing vessels at the dawn of the twentieth century, mostly revolving around the collier trade. Many were capable of carrying over 3,000 tons of coal at a time, and worked as tramps on the spot market. Mystic Seaport Museum 1978.117

## Introduction

The collier problem is a rarely discussed but critical paradox in how steam- and fossil-fueled propulsion came to dominate the world's maritime trade. Early steam vessels (1800–90) were coal-fired, fuel-inefficient vessels which relied on both wind-assisted propulsion and frequent stops for fuel when undertaking long voyages. Otherwise, they were bounded only to local routes which allowed them to return to their coaling port within one bunkering. In order for steamships to take over the world, more efficient steam engines had to be developed, and coaling stations had to be created across the globe at the appropriate distances along the world's maritime trade routes. Steam vessels were too inefficient to carry an economical load of coal to these stations, and thus were dependent on sailing vessels (specifically, coal-carrying sailing vessels, called colliers) for the supply of coaling stations in order to motor across anything but coastal routes. The new technology could not function without the old, and thus steam could not truly replace sail until these efficiency limitations were overcome.

Scholars have noted this paradox before, for example, Carter et al. in 2023: "During the nineteenth century, Welsh steam coal came to be the preferred fuel for the growing fleet of steamships, both those in the liner trades and naval vessels. This led to worldwide exports, paradoxically with large sailing vessels often transporting the coal needed by steamships, as they were more economical to operate on long oceanic sea routes."[1] Others have asserted that the P&O fleet required "170 sailing colliers to 'feed' 50 steam ships . . . The carriage of coal out to worldwide bunkering stations by sail, is a study in itself."[2] While little work on this transport of coal by sail has been undertaken, at least it is recognized and occasionally commented upon. However, no one has attempted to apply this lesson and paradox to modern challenges or to define it as a specific class of problem faced in technological transitions. Further, there has been no significant treatment of the collier problem in and of itself, and its effects on the rise of steam propulsion. An attempt to define and delimit this paradox is long overdue.

This paradox is tied up in some debate about the history of technology and the role of technology in society. With steamships comprising a major part of the narrative of technological progress which allows humanity to control and overcome natural limits, there was a philosophical reason to ignore that this new shining beacon of civilizational triumph relied absolutely on what it was supposed to replace. Further, due to the incentives of the emerging technological society (one which places technological development above most other goals),[3] paired with capitalist imperatives for economic growth and ever-expanding markets, new technologies drove out the old if they could be used more intensively to make more money. These human elements are inseparable parts of the collier problem.

This paper covers not only the historical background and philosophical origin of this technological problem, but its applicability to the energy transition currently underway. Though the basics of the historical situation are covered, with an emphasis on the merchant shipping situation, a detailed analysis is not necessary to understanding the paradox and its implications. By understanding the root of the collier problem historically, we can apply the same theoretical principles to modern problems, recognize them as having similarities to problems solved before, and then find a way to use lessons of the past to reach a desirable future. The main methods used for this paper include examining casualty returns to gauge the amount of coal actually carried under sail, determine its destinations, and how long this practice lasted. Additionally, philosophical analysis through the lens of Ellulian Technique and Mumfordian technics is paired with a closer look at generally well-understood modern parallels to the collier problem.

The structure of this paper is somewhat unorthodox, and divided into sections for various elements of the collier problem. Starting with historical background, it progresses through a proposed problem definition and application. These sections are followed by two modern examples, an exploration of the philosophical and social elements of the collier problem, and then conclusions and lessons which can be learned from this initial study and more advanced research on the collier problem.

## Historical Background

Sailing colliers have been in use since at least the thirteenth century, supplying medieval London with coal from Newcastle upon Tyne and elsewhere in the British Isles as a preferred fuel for the growing city.[4] By the late nineteenth century, a long chain of sailing vessels supplied cities and steamship coaling stations with coal, and the availability of coal worldwide was considered a topic of national security and heated debate in every government with ships underway on the seas, for both mercantile and military reasons. For almost seventy years before the transition to efficient steam engines and oil fuel, there were intense debates about the importance of coaling stations to national power and prestige within all the great imperial powers.[5] Directories of coaling stations with approximately what to expect at each were published by Naval Intelligence offices, and naval captains were required to report to these offices all the information they could about coal stockpiles in every port they visited.[6]

The debate about coaling stations for commercial and military purposes was heated and long lasting. Multiple positions were posited as to how this should be handled, but it was acknowledged that "to our modern vessels, the coaling station [is] as necessary as her crew. The modern ship [is] a hundred times as useful as any number of old ships so long as she [has] coal; but without coal she [is] infinitely more useless. This should be borne in mind when coaling stations [are] discussed."[7] Overseas empires were a big reason for wanting a large number of coaling stations, but national defensive interest was also a priority, especially in the US.[8] The sixty-six-page *Pall Mall Extra* entitled "The Truth About the Navy and its Coaling Stations" published in the 1880s gives a general snapshot of the debates around coaling stations in the UK, which were calculated both to support empire, and to deny others mobility in time of war. International law prohibited a neutral power from bunkering a belligerent warship with more coal than was necessary to reach the nearest home or allied port, meaning these concerns were significant for all world navies.[9] These discussions and efforts were not of merely theoretical importance, as shown in the tragicomical operations of the Russian Navy during the Russo-Japanese War transiting from the Baltic and Black seas to the Sea of Japan.[10] The debate continued into the 1920s, when naval architects still debated which type of propulsion was superior, "Coal, Oil or Wind?," especially across the merchant fleet where costs were to be kept to a minimum.[11]

Bulk cargoes like coal need not arrive on a strict schedule, and sailing vessels offered a low price per ton, especially over long routes where a large amount of fuel would be burned by a steamer. On favorable routes, sailing vessels could even outperform tramp steamers for speed and cost into the twentieth century.[12] The coastal collier trade in England waited until the middle of the nineteenth century for steam propulsion to supersede sail,[13] and steam did not completely replace sailing colliers until after the First World War on both coastal and transoceanic routes.[14] The massive schooners of Downeast Maine in the late nineteenth and early twentieth centuries were primarily colliers, working mostly coastal routes between the major coal-exporting ports of Virginia and Texas and the coal-burning regions of northeastern North America such as Boston, Portland, and the Canadian Maritimes. The advantage of small crews and free propulsion meant low costs and low freight rates, even into the late 1920s.[15]

The nineteenth-century collier problem was a side effect of the proliferation of steam propulsion for ships on long-distance routes from the 1850s forward. Essentially, the use of steam required coal, but steamships were not fuel efficient enough to carry sufficient coal to travel long distances, especially with an economically viable cargo, even when wind-assisted ship propulsion (WASP) was employed. They required a worldwide network of coaling stations with the equipment to rapidly deliver hundreds or thousands of tons of coal at a time as intermediate ports of call in their long-distance trade routes. The second part of this problem was that for much of the nineteenth century steamers could not carry enough coal to these stations to leave a significant load and retain enough in their bunkers to return to the source of the coal (though this was obviated in the case of some rare coaling stations which had sufficiently developed coal deposits nearby). Sailing ships which did not burn any coal en route were absolutely required to keep these coaling stations supplied, and made long range transoceanic steam navigation possible. Sailing vessels still traded on very long-distance routes with little competition from steam at all until after the opening of the Panama Canal. Frequently the only factor limiting the range of a windjammer (a sailing vessel with no mechanical propulsion) was the store of food and water aboard, and some were capable of up to five-month voyages from Australia to Europe without touching land.

These windjamming colliers were an essential part of the overall infrastructure required to make steam navigation economically competitive.

Figure 2. *Unloading coal from a collier on a beach in England*. Photograph, March 8, 1912. Note the complete lack of facilities necessary for the delivery of coal in small volumes under sail as late as 1912. Kolforn (Wikimedia Commons)

The Suez and Panama canals (among others) were critical pieces of monumental infrastructure for steamshipping, making it competitive with sail by drastically reducing distances between ports, and thus placing them within range of a steamship with only a handful of coaling stops.[16] Coaling stations themselves were not simple coal piles on shore, and often had complex and advanced coaling facilities built along the shore to minimize the time required for bunkering. The size of steamships by the early twentieth century had become large enough that dredging harbors and building large, complex wharves became necessary, which embodied more energy into the system every year due to maintenance requirements. This very high level of infrastructure dependency is typical of high-tech solutions today, even if we do not routinely recognize or see this infrastructure, and it seems to intensify with each new technological advance (i.e., proliferation of buried fiber-optic cables, ethernet switches and routers, and satellites to support ubiquitous internet connectivity). By contrast, windjammers required almost no support, relying on lightering,[17] beaching, and very primitive accommodations well into the twentieth century.[18]

As late as 1914, before the Panama Canal was opened, there were significant economic costs incurred by steam vessels trading with South

America or from the East to West coasts of the United States. As explained in a 1912 hearing on the subject:

> The coaling facilities along the South American route are less adequate than on the Suez and South African routes because native South American coal is not available until Coronel, Chile is reached. The usual practice of vessels sailing from ports on the eastern seaboard of the United States to points on the west coast of South America is to take on sufficient coal at the port of clearance to carry them to Coronel where a large supply of inferior Chilean coal is obtainable. Ships may coal at St. Lucia, St. Thomas, or Montevideo, but the price of the American and British coal at those stations is so high that most steamship companies sacrifice as much cargo space as may be necessary to secure room for the coal required for the run to Coronel.[19]

This "run to Coronel" is a leg of some 8,141 nautical miles at a great sacrifice of cargo space: 1,400 tons of coal, which, at a stowage factor[20] of 40 cubic feet per long ton, would take up 560 Register Tons,[21] a number which would make only a vessel of over 1,000 net register tons (NRT) economically effective on this route. In 1890 the average US steamer was only 747 NRT, and 1,169 gross register tons (GRT), meaning the amount of coal to be bunkered would absorb 132 percent of the space in the ship dedicated to engines, crew quarters, and fuel bunkers on such an average vessel if the hold were full of cargo; in other terms, 47.9 percent of the ship's *total enclosed volume* would need to be used to store this coal. By 1900 the situation was only slightly improved at 105 percent of the average steam vessel's GRT-NRT margin, meaning at least some revenue tonnage was still lost to coal.[22] Clearly, only a larger than average steamer could attempt this leg while carrying a significant cargo, and a much larger ship would turn more profit. The run to Coronel required 40 percent more coal than any other leg of the voyage. The same voyage from New York to Coronel is 4,821 nautical miles via the Panama Canal, as opposed to 8,141 nautical miles to go around Cape Horn, offering a spectacular 41 percent reduction in distance.[23] The breakeven distance for steam versus sail, where it became more expensive to operate a steamer than a sailing vessel, started at as little as 2,500 nautical miles in 1850, and reached 8,600 nautical miles in 1890.[24] The distance to Australia from Europe was beyond this range, as was most of the west coast of South America, necessitating calls at multiple coaling stations for any steamer on those routes. These are the routes where windjammers remained economically important for all merchant cargoes, as steamers could not compete due to the cost of fuel and coaling time. With the effective ranges of steam increasing with efficiency improvements and an increasing average tonnage and average speed for steamers, the economic balance on the vast majority of routes finally flipped solidly against sail between 1910 and 1915, just as the Panama Canal opened.

The data examined in this paper are for the turn of the century, but the half century before this was far more dependent on sailing vessels for cargo transport generally and coaling stations in particular; in 1880 "a net steam ton for carrying purposes was considered equal to three net sail tons. It is believed that net steam tonnage may be multiplied by 3 in 1890 and by 4 in 1900 to reduce it to a common basis of efficiency with sail tonnage."[25] With the proliferation of the compound steam engine and iron hulls, steam vessels gained a lot of range and speed, which then increased significantly with developments after the 1880s. Most steam vessels without auxiliary wind propulsion before the 1850s had a range limited to well under 1,000 miles, and the first transatlantic steam packet service[26] was not started until over thirty years after Robert Fulton's experimental steamship first navigated the Hudson River in 1807; these pioneers both had auxiliary sails. The initial transatlantic packet was government subsidized, carrying mail and passengers, not large, bulky cargoes such as cotton from the US South, which fed the cotton mills of London and Europe. It would be another forty years before steam started to seriously challenge sail on the same route for these cargoes due to the cost of fuel and range limitations. The trade-off was that a windjammer of the same tonnage could make fewer voyages and move less paying cargo than a steamer each year, offsetting savings from free propulsion.

There is anecdotal support for the assertion that bulk cargoes were carried by sail, including a large amount of coal for coaling stations the world over. However, this has not previously been quantitatively examined as far as the author's research has revealed. Lloyd's casualty returns were used as a reasonably comprehensive contemporary sample of vessels with their cargo listed, though this only contains vessels lost or damaged during each quarter of a given year.[27] Reading the 1890 return (the earliest available) shows windjammers with coal cargoes are frequent and mostly to destinations listed in the 1892 directory of *Coaling, Docking, and Repairing Facilities of the Ports of the World* published by the US Office of Naval Intelligence. Looking at these records, it becomes clear these sailing vessels were intended to supply the coaling stations: the 5,663 NRT of vessels wrecked on the way to Valparaíso in coal[28] during 1890 would have been able to provide up to 14,158 tons of coal, or 28 percent of annual importations of coal to that port in the 1892 guide (if they had reached their destination).[29]

Data from 1900–1904 in Lloyd's casualty returns give a total of 2,436 sailing vessels lost over those five years. 623 of these windjammers had no listed cargo, comprising 25.57 percent of the entries in Lloyd's casualty returns; these were mostly vessels condemned or broken up, and were removed from the study. This leaves 1,813 vessels in the sample, which is used in the following calculations. In order to make results more coherent, cargoes were grouped by type, and only the first cargo listed was used for each vessel's entry. "Coal" cargoes encompass coal,

**Windjammer Cargoes 1900–1904**

Taken from Lloyd's Casualty List. Excluding vessels with unlisted cargos.

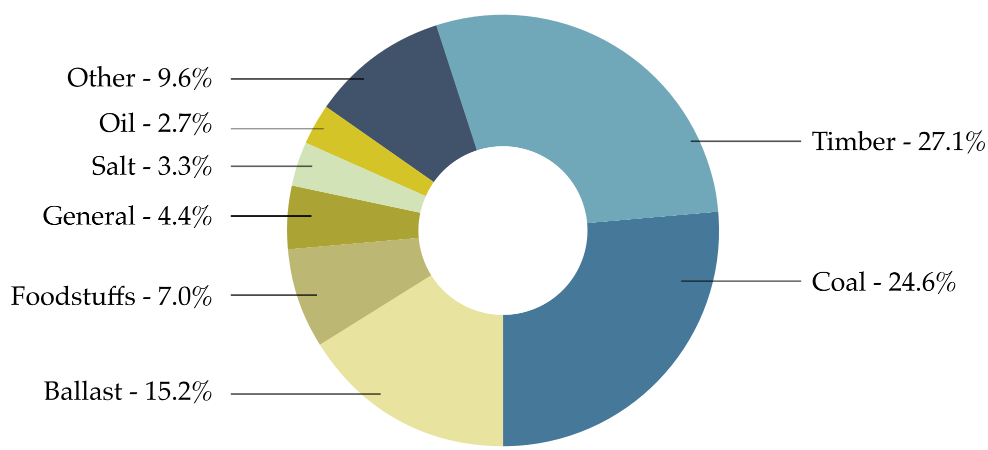


Figure 3. Windjammer cargoes by vessel, 1900–1904, from Lloyd's casualty returns. Vessels with unlisted cargoes are ignored. Energy cargoes made up approximately 28.8 percent of windjammer cargoes in this period.

charcoal, and coke; 24.6 percent of laden windjammers in the casualty returns were carrying coal.

When examined by tonnage, coal is by far the dominant cargo in 1900, consisting of over 30 percent of tonnage, 8 percentage points higher than the nearest competitor, timber. There were nearly 71,000 NRT of vessels in coal represented in the 1900 casualty return, which, at the aforementioned stowage factor of 40 cubic feet per ton, would give up to 177,500 deadweight tons of coal moved by just the 4.5 percent of the windjammer fleet which was lost that year.[30] Not all of the coal moved by windjammer was consumed by steamships, but the frequency with which destinations line up with coaling stations listed in Naval Intelligence publications indicates steamship use was the primary market for this coal in the majority of cases.

The picture is slightly muddled due to a few issues in the records. For example, Japanese vessels, while listed among the wrecks and other casualties, rarely have cargoes listed. Another risk is the possibility of a nonrepresentative sample of vessels being lost over the five-year stretch 1900–1904, but this seems unlikely. This cursory study should still give a good overview of the types of cargoes being carried by windjammers, and their relative share of the windjammer business at the turn of the twentieth century.

A cursory examination of steamers lost carrying coal in the 1900 Lloyd's casualty return indicates they were primarily on shorter runs within 1,000 miles, with only a small number making intercontinental runs with coal. All of these later vessels were significantly larger than average, the vast majority being over 1,000 NRT. A transition to steam colliers carrying the majority of fuel to coaling stations and cities for local use had only been effected on short routes, many of them domestic coastal legs which fed the major ports from distributed sources of coal (for example, Newcastle upon Tyne to London or Copenhagen). Even at this late date in the supposed decline and disappearance of working sail, windjammers were an important economic engine which fueled the mechanical engines of imagined progress in maritime commerce.

**Cargoes in Lloyd's Casualty Register by Tonnage, 1900**

Imcluding only vessels with listed cargoes. Tonnage in Net Register Tons.

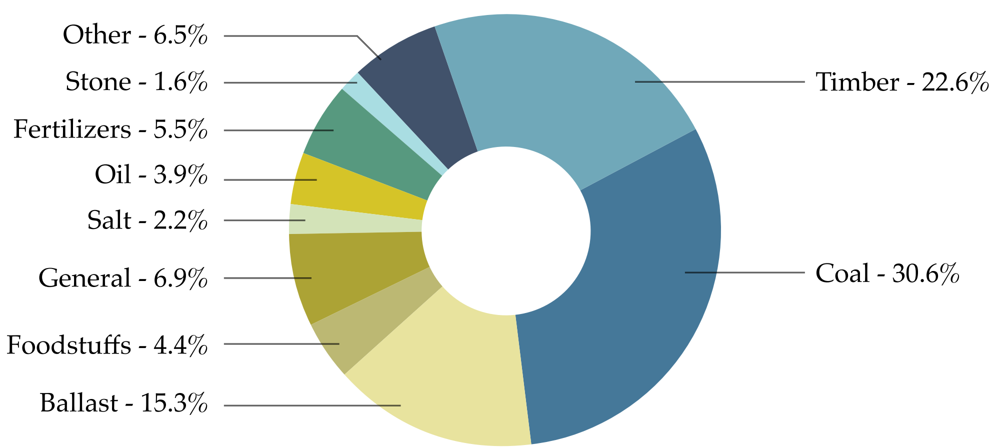


Figure 4. Windjammer cargoes in Lloyd's casualty register by tonnage, 1900. Vessels with unlisted cargoes are ignored, data by net register tons. Energy cargoes made up approximately 35.5 percent of windjammer cargo tonnage in this year, with coal making up 30.6 percent.


Figure 5. *Barque Nicaragua of Whitby Capt. Price Discharging Coals at Algiers May 1878*. Watercolor. Algiers was a major coaling station for steamers on the Suez Canal route in the second half of the nineteenth century, and even as late as 1878, the coal there was being provided by windjammers. Note the extremely simple methods of cargo discharge by basket off a stern ramp. Image courtesy Mystic Seaport Museum

## The Problem Definition

The collier problem is very applicable to the present energy transition, in both maritime and other contexts. However, it has not yet been defined as a class of problem, nor has the historical paradox been studied in and of itself. I propose the following as a working definition:

A collier problem occurs whenever a new technology requires the technology it nominally replaces to function due to efficiency limits. The collier problem is normally associated with energy supply requirements, but can be applied to other situations.

The cost in coal of supplying coaling stations by coal-burning steamship in order to replace sailing vessels was larger than the amount of coal delivered by early steam vessels. Sailing vessels which did not burn coal underway were required to supply the coaling stations which enabled steamships to "replace" windjammers. Within a certain radius of action from a coal supply, no collier problem exists, because the need to refuel can be met at one or both ends of a round-trip voyage: this was the case with the Newcastle steam collier fleet of the late nineteenth century which supplied the city of London with fuel. However, to bring steam


Figure 6. Detroit Publishing Company, *Norfolk and Western Coal Piers, Norfolk, Va.* Postcard, 1913–30. The postcard shows a six-masted schooner tied up at the coal chutes of the Norfolk and Western Coal Piers in Norfolk, Virginia. The very large schooners of Downeast Maine were primarily colliers, including the *Wyoming*, the largest wooden sailing vessel ever built, which carried up to 8,000 tons of coal (constructed 1909). The Miriam and Ira D. Wallach Division of Art, Prints and Photographs, The New York Public Library, 74235

vessels beyond that relatively short range would require support by windjammers or a local source of coal, though frequently both were required to meet demand for fuel at major coaling stations.

There are at least three types of limits which can create a collier problem: physical, economic, and environmental. Physical limits are those which would prevent the newer technology from functioning at all, such as an absolute inability to deliver even a single ton of coal outside a certain range from the port of origin, if the ship carried nothing but coal (or insufficient coal could be provided due to limits on mining). Economic limits are based upon costs to supply coal by steam vessel, which, outside a given range, cannot make a (sufficiently enticing) profit, though no physical limit prevented it. Environmental limits would include existential, unmitigable harms to the environment and earth systems, such as the anthropogenic climate change from fossil fuel emissions we face today (though there are others).

A collier problem can be solved by operating within the constraints of the technology, and the more those constraints are lifted, the wider this range will be. In the original example, this would involve using steamships only on short passages with a reliable coal mine on each end, or within returning range of their homeports, assuming no WASP systems are used. Historically, the collier problem was solved by a combination of the Bessemer steel process (1857), the triple-expansion steam engine (1880s), the steam turbine (1890s), oil fuels (1910s), diesel cycle engines (1920s), and steady improvements to the screw propeller through the nineteenth century. All of these technologies allowed for ever-larger motor vessels and more efficient engines working at higher steam pressures and energy efficiencies. Additionally, steam vessels were given the ability to "cheat" against windjammers due to monumental projects such as the Suez and Panama canals, which reduced voyage distances by many thousands of miles. Without these shortcuts, even more coaling stations would have been necessary, with a larger supply of coal moved by even more windjammers for steamships to accomplish the same mission, and more steam fleet tonnage would have been required to provide the same level of service.[31]

Eventually the transition to oil fuels after the First World War curtailed the need for coal, and thus colliers, while allowing more efficient energy use and storage onboard. The war itself force-retired many of the older and less efficient coal-powered ships due to naval action, especially submarine warfare, which also decimated the Atlantic windjammer fleet.[32] Together, these factors created massive efficiency gains for steam and motor vessels, a growth in tonnage and speed for steamers, and thus an increase in capacity through the economy of scale experienced by motor vessels. Through using less coal and being able to carry more of it, the steam collier eventually took over almost all major routes worldwide until the need for coaling ports effectively vanished as diesel cycle engines and oil turbines began to dominate in maritime commerce. This, however, did not occur until after the dual interventions of the Panama Canal and First World War in 1914 stacked on top of earlier advantages such as the Suez Canal and other developments mentioned above.

Part of the challenge with identifying a collier problem is its paradoxical nature: steamships replaced sailing ships, but without windjammers the steamships could not function. Solar panels replace fossil fuel power generation capacity, but require fossil-fueled energy to construct and deploy them. The internet relied for decades on sending software and hardware through physical media and the postal service, with connectivity provided through telephony networks. Alternative fuels for ships can eliminate fossil fuels in shipping, but we are making most of them from fossil fuels, and moving them with fossil fuels (explored in more depth below). Fossil fuel–free ships without internal combustion engines aboard have been designed, but they require shore power which is generated mostly by fossil fuels.[33] Researchers and energy transition professionals should (and frequently do) carefully examine their fields for potential collier problems, and then specifically plan to either negate them or find a substitute for the fossil-fueled element using a more fundamental technology, such as wind propulsion or human power over internal combustion or electric power. While this is understood to some degree, there is no recognizable term for this type of paradox in the historical or sustainability literature. Securing a term for this paradox will also make communication efforts around this problem more understandable and simpler than at present.

Collier problems arguably include multiple historical and modern cases, some well known and understood, some emerging. Moving alternative maritime fuels is one of them, as there is a very limited amount of alternative bunkers available, and important reasons to limit their production. For example, methane and ammonia need to be limited in use and production due to toxicity and climate-forcing emissions from leaks,[34] while other renewable fuels have a very low energy return on


Figure 6. Allan C. Greene, *Muscoota*. Photograph, undated. The *Muscoota* is shown at the head of a long line of large windjammers moored at coal wharves in Australia, awaiting cargo. Australian coal was a major fuel for the Pacific basin during the late nineteenth to early twentieth century, mostly carried by windjammers like these. State Library of Victoria, H91.250/226

energy invested (EROEI), or low energy density, both undesirable when energy consumption must be drastically reduced and energy storage space is limited.[35] Manufacturing biofuels at a scale sufficient for the maritime industry incurs climate-forcing emissions due to the land use changes required to grow feedstocks. The imperative not to burn these fuel stocks in transit creates a collier problem for the alternative maritime fuel sector almost identical to that of the nineteenth century. Another historical example from the nineteenth century, especially in the UK and US, but elsewhere to a certain degree, is early railroad networks, which were almost entirely reliant on the coastal sailing vessels and animal-powered canal boats the railway was supposed to replace for transporting fuels, materials, and machinery. While this was a relatively short-lived collier problem, the rail network had to become sufficiently efficient and capacious to overcome it before the problem went away. This required a sufficiently complex railway network and sufficient rolling stock to move both its customers and their goods, and the fuel required at their various depots.

Because the collier problem is so common in high-tech answers to the renewable energy transition, it needs to be considered and addressed in the planning stages for a technology's implementation. If a different technological mix is used, this limiting efficiency factor can be either eliminated or reduced to a manageable level. The new collier problem with alternative maritime fuels is effectively the original collier problem resurgent, with fossil-fueled motor vessels taking the place of windjammers (until windjammers take their place again). However, the solutions are fundamentally the same: installing WASP systems on ships reduces fuel requirements and extends ranges, while using windjammers for fuel transport minimizes consumption en route to end users. The first of these is being done already, while the second can be implemented over the coming decades on a replacement basis for the current generation of liquid bulk tankers and bunkering vessels.

A point of clarification is necessary for this problem statement to prevent every technological transition from falling under the definition of a collier problem: simply needing an older technology for initial production does not constitute a collier problem, such as making light bulbs by candlelight, or fabricating the first metal lathes with hand files. The collier problem only arises when *continued operation* of a technology is underpinned by what it nominally replaces, as given in the examples above. While the problem may not be as prolonged as it was for steamshipping, it may still be present for the time required to build a sufficiently efficient replacement system.

### A Modern Example: Supplying Alternative Maritime Fuels

The nineteenth-century collier problem is relatively obvious for modern maritime trade in the supply of alternative fuels, such as ammonia, methane, biofuels, methanol, and other supposedly "zero-emissions" fuels (as opposed to fossil fuels such as marine diesel oil or heavy fuel oil). All of these fuels present various risks and challenges, ranging from environmental pollution or greenhouse gas effects if leaked, to large environmental impacts of producing feedstock, low EROEI, lower energy density, and so on.[36] To use these fuels, they have to be produced, which, in many cases, gives a poor return on energy invested, and uses energy from fossil fuels.[37] Second, fuels must be transported to bunkering facilities by either burning this very limited and valuable supply of renewable fuel, or by using fossil fuels. These fuels are likely to be produced in the Global South, and consumed to a large degree in the Global North, meaning maritime transport will be absolutely necessary for their deployment and widespread adoption. Further, engine and fuel compatibility issues in a diverse renewable fuel environment may mean ships have to be capable of using many different types of fuel to trade worldwide, or will be restricted to only serving specific routes where compatible fuels are available. To avoid this, an especially complex network of green bunkering stations and extremely efficient fuel carriers will need to be developed and deployed in the very near future.[38]

The volume of alternative fuels needed for maritime shipping is enormous. To meet the requirements for 2050 net zero emissions from shipping, the primary energy required would be about the world's entire renewable energy supply in 2022.[39] This is for producing shipping fuels alone, exclusive of their transportation, with nothing left over for the decarbonization of every other sector of the world economy, meaning there will undoubtedly be fossil-fueled energy used in the production of theoretically zero-carbon alternative fuels. As mentioned above, there are other risks to producing these fuels, aside from the energy density and EROEI problems, which will most likely limit the bounds of available fuel resources.[40] This adds additional pressures for energy efficiency in ship design, much like those seen with the expense of coaling and the loss of revenue-generating potential from bunkering space requirements among nineteenth-century steamers, and the revival of interest in WASP systems during the last oil crisis.[41]

As in the nineteenth century, the answer to these challenges can simply be to use windjammers to transport fuel, or only operate motor vessels within a range where they can return to their alternative fuel–producing homeport on a single bunkering. A primary wind-propelled tanker vessel such as the one evaluated by Perez et al. in 2021 could, with a very restricted engine use strategy and some patience, traverse the seas under wind power carrying alternative fuels and deliver them wherever necessary.[42] A simple increase in system-wide efficiency solves the problem for fuel transportation, and, if wind propulsion is applied to a large enough portion of the fleet, it may even obviate the need for much of the predicted fuel requirement through the end of this century. Making all new-generation ships more efficient through wind-assisted propulsion and other design elements will assist in overcoming the resurgent collier problem of the twenty-first century.

### A Modern Example: Electric Vehicle Propulsion

Electric vehicles of any type (road, rail, maritime, or aircraft) rely on grid electricity for charging and operation. The grid is still fundamentally powered by fossil fuels, with only 21 percent of US electricity generated from renewables, and 59 percent from coal and natural gas in 2022.[43] Vehicle manufacture and charging is powered by the same fossil-fueled grid. If we limit our production and operation of electric vehicles to only use renewable energy resources, we will not be able to effectively transition the transportation system, thus creating a collier problem involving efficiency limits which force the new technology to rely on the old.

The increased efficiency of electric motors and battery charging performance means that the grid power requirements to replace internal combustion engines which can at maximum reach 60 percent thermodynamic efficiency is actually significantly smaller: electric motors can reach above 98 percent efficiency, little to no energy is consumed while idling, and transportation of the energy to the vehicle is through distribution wire, far more efficient than the combination of pipeline, trucking, and rail transport used for fossil fuels like diesel and gasoline. As more renewable energy becomes available, the collier problem will be reduced automatically. For a better result from the same amount of resources and a higher overall system efficiency, prioritizing the most efficient types of electric vehicles such as electric-assisted bicycles and pedal-electric cargo bike sets in urban areas should be an obvious policy choice worldwide.

There is a simpler solution to get out of this collier problem, however, which is to use far fewer self-propelled vehicles of any type. The push for active transport such as walking and bicycling, wind propulsion, and other types of technologies which do not require either fuel or electricity to operate would be just as effective as increased motor vehicle fleet efficiency in reducing absolute energy demands. Substituting less resource-intensive technologies for others as a conservation measure is a proven method when dealing with strategic materials in wartime.[44] Overall, reliance on charging stations and fossil fuels, along with an obsession over charging times, makes this implementation of electric vehicles very reminiscent of nineteenth-century military and commercial debates around coaling time for ships.

## Philosophical and Social Elements of the Collier Problem

As observed by Koltz over forty years ago: "Steam propulsion was not encouraged because sail was failing as a mode of transport. To the contrary, sailing ships were continually improving. Steam was simply a different technology which proved itself superior by virtue of the difference. This new type of marine propulsion surpassed sail by reason of speed, maneuverability, and increase in potential ship size. The qualities of sail were never disproved, only challenged."[45] People believed, by the nineteenth century, that there was a new and supposedly better way of doing things, which is a social and philosophical element of any technological transition. While the discussion to this point has been focused on technical aspects of the problem, it is important to include the social aspects thereof. This is related to the myth of progress-inspired techno-optimism and techno-utopian views of the modern energy transition, which rely on unproven or yet to be discovered technologies to end the climate crisis in the indefinite (but supposedly ever-imminent) future.[46] This is contradicted in many places by people solving problems through a lower-tech solution, as frequently seen in farming, despite a much-heralded fourth agricultural revolution happening in real time through the power of digitization and autonomous farming solutions.[47] This type of use-centered view of technology and transitions is similar to David Edgerton's work in *The Shock of the Old*, but Edgerton only touched upon the nonexistence of the supposed "sailing ship effect" on innovation, not the absolute reliance of some new technologies on the old due to inefficiencies.[48]

As an example within the transportation sector, warehousing is an essential part of any polytechnic[49] economic system powered by the weather, as observed by Kris De Decker. Warehousing in this case is a form of energy storage when contrasted to modern just-in-time delivery, because it allows a society to use natural forces when they are available to produce and preposition goods near the point of end use; these stocks are then drawn upon when needed across a smaller hinterland.[50] This is not a conventionally modern view of the warehouse's role in society, but it is an important one: the collier problem was partly solved because massive stockpiles of coal for scheduled steamers were dropped off at these ports by windjammers when the forces of nature got them there. The energy was moved without a demand on the fossil-fueled energy system, and was available on demand for scheduled vessels. Readopting this mentality in trade and transportation, while critical to reducing fuel and energy demands, will be very difficult, because warehousing is now looked at only as a cost to be avoided; shifting the mindset of an economic system obsessed with maximizing financial efficiency to take on an additional expense will be a difficult nontechnical barrier to overcome, as was the cost of building coaling stations in the nineteenth century.

Collier problems are frequently induced or driven by these philosophical paradigms, such as the myth of progress which has clutched humanity since the seventeenth century and "boasts of effacing, as fast and as far as possible, the technical achievements of earlier periods."[51] The Ellulian idea of Technique (the social use and effects of technology) also fits in this philosophical space, where "a purely mechanical discovery may have repercussions in the domain of social techniques or in that of organizational techniques."[52] Technique is defined by Ellul as "the quest for the one best means in every field" and, in a technological society, "technical activity automatically eliminates every nontechnical activity or transforms it into technical activity."[53]

Since the nineteenth century, we have been living in an increasingly technological society which has discarded all but the most technically efficient means of accomplishing a given task in order to maximize financial returns. As observed by both Mumford and Ellul, this results in ever-increasing global technical and sociocultural uniformity, especially in technological forms such as measurement and machinery.[54] The replacement of sailing colliers with steamships can be seen as part of the self-augmentation of Technique, where technological advancement changes in form from individual acts of invention to systematic engineering, with individuals becoming ever less important to developing and directing technological advances, and the pace of advances continually increasing. This is encouraged by the uncritical embrace of the latest technology characteristic of and celebrated by technological societies captured by the myth of progress.

In the nineteenth century the collier problem was increased by the rebound effect in steamshipping, which increased demand for coal and coaling stations at a greater pace than steam propulsion itself improved in efficiency and capability, demanding ever more steamshipping, and the associated windjammer capacity to fuel these steamers. The collier problem can also be exasperated by the religious dedication to economic growth, inducing ever more consumption, and thus shipping capacity, per capita.[55] Increased demand for shipping could be met at a higher level of financial efficiency using steamers which have a higher effective tonnage than windjammers of the same size. This need for financial efficiency sacrifices others such as energy, resource, labor, and environmental efficiencies when examined at a systems scale. This is a case of the rebound effect (or Jevons paradox), where a technology becoming more efficient leads to increased use, thus increasing aggregate resource consumption, with coal consumption forming the classic case. Jevons specifically mentioned consumption of coal in his 1865 book on the coal question in the UK.[56] This is a lesson we can learn and apply today to similar circumstances, and should encourage engagement with theories of degrowth which actively attempt to counter the rebound effect while increasing energy and resource efficiency. Most of the techniques advocated by the degrowth movement are nontechnical and include a focus on redefining prosperity and success away from increased material consumption and into what economists refer to as "relational goods." This is a social answer to a technical challenge which shows promise, provided the social narrative can be changed in time.[57]

This philosophical motivation describes the impetus behind the Suez and Panama canals, and the drive to constantly build larger and faster motor vessels at any price in energy, money, infrastructure, environmental harms, and lives.[58] In order to make the new technical method the one, true, and only method in its field, entire continents and oceans were (and are still actively being) modified to suit it, instead of suiting the technology to the existing environment. This led to the current maritime transportation system and other world systems which it supports being entirely reliant on fossil fuels and internal combustion engines, with all the human and ecological consequences of prioritizing these technologies and systems over human needs or wants. Similar parallels can be seen in the reengineering of US cities in the second half of the twentieth century to accommodate high levels of car use to the detriment of walkability and human-scale activity. The rise of containerization in international shipping is another example of self-augmenting Technique and the rise of megamachine tendencies in most technological fields which are influenced by the myth of progress.[59]

## Conclusions and Lessons

The collier problem is unique to eras of massive or rapid technological change, and is only seen in transitional phases. Whether this transition is sudden or slow is as immaterial as the reason for the transition itself: whether a previously plentiful resource has been exhausted or a new, more convenient technology has come about does not seem to influence the likelihood of a collier problem arising. It is evident these problems occur when a technology which nominally replaces another is not yet efficient or advanced enough to fully displace its antecedent, and is reliant upon it to function, and this state of affairs is not uncommon over the last five hundred years.

Some transitions do not create collier problems at all: the bicycle, for example, did not require horses to function and still enabled riders in the 1880s to 1900s to transport themselves in the local area. Telephones replaced telegraph without any reliance on telegraphy to make phone networks function. While bicycles relied on roads which had been developed for foot and animal traffic, and used developments pioneered for use in carts and wagons, these are not the same types of reliance as steamships upon windjammers. Similarly, the telephone used the copper-wire infrastructure of the telegraph network and many of the techniques originally used in telegraphy, but it applied a different theory of operation; no one needed to send a telegraph in order to make a phone call. Other transitions do create a collier problem: steamships relied on sailing vessels to provide their fuel. Renewable energy replaces fossil-fueled energy, once the renewable energy production technology is built using fossil fuels and becomes efficient and prolific enough to generate society's energy needs. Electric cars replace fossil-fueled cars, drawing their energy requirements from fossil-fueled power grids. Accessing the internet for a long time required software on physical media and connection via the telephony network.

There are a number of lessons which can be learned from the past for application to current challenges. Because the collier problem is fundamentally about efficiency limits, these must be the root of any technical solution, and can be addressed in several ways. First, and possibly most obvious, is to favor technologies with lower infrastructure intensity, which generally means choosing a lower-tech option for a given task. The easiest and cheapest way to do so is to avoid building out an overcapacity of infrastructure for high-intensity options, and supporting the lower-intensity option instead. Second is to require high efficiency in transitional technologies through regulation, such as setting maximum size and minimum range per energy unit in electric vehicles and vessels. Third is to encourage the use of technologies within their natural limits, which will reduce their infrastructure demands and increase efficiency.

Possibly the most important of these adaptations for any collier problem is to use technologies within their natural limits and maximize their usefulness in this role. For example, the zero-emissions motor vessel fleet of the future can become more efficient overall by changing hull designs, slow steaming, working primarily local and mid-distance routes, and adding WASP systems such as Flettner rotors. If this sounds suspiciously similar to steam propulsion in the 1860s, that's because it is. Long-distance routes can be left to primary wind-propulsion vessels, and goods moved on seasonal winds into warehouses at hub ports within reasonable motor vessel range of their final destination. Through such a systems- and fleet-level change, the overall maritime fuel and grid electricity requirement can be significantly curtailed and brought within reasonable economic and safe environmental limits, while still allowing for a reasonable volume of international trade. Whether this type of change will be achieved through economic competition or governmental regulation is yet to be seen, but both forces have a role to play in this transition.

Breaking free of older technologies is rarely an easy process because it is never purely technical. While the technical solution to the alternative marine fuels collier problem is quite simple, the behavioral shifts required are significant. Technology dictates our expectations and habits in many ways, and the cheap availability of fossil fuels has made us expect regular schedules and just-in-time delivery, which wind propulsion cannot reliably provide. In fact, this is a fundamental reason why sail fell out of use, alongside the ability to use a steam vessel more intensively due to its higher consistent speeds. Sociocultural adjustments to deal with collier problems are likely to be more difficult than technical adaptations, but just as necessary. These adjustments can start by both pointing out the existence of this class of problem, and then undermining the current uncritical sociocultural narrative of rapid and revolutionary technological diffusion which fuels delaying tactics based on techno-optimist dreams of future technological saviors capable of instantly solving current challenges.

The collier problem lays bare one of the most fundamental lies of the myth of progress in the nineteenth century and today: the poster child technology of steam navigation, the progressive conqueror of natural forces, the seas, and the globe, was only an illusion propped up by a more fundamental low technology which is over five thousand years old. It took the creation of two massive shortcuts which cut through continents, a fundamental chemical discovery, three industrial revolutions in shipbuilding, and four highly important engineering breakthroughs to finally make the motor vessel economically competitive with sail on transoceanic routes, and these propulsion systems took over a century to be adopted. Even into the 1920s there were significant debates about the best form of propulsion for economic and energy efficiency, with four options given: coal, oil, and wind, or some combination of the three.[60] Dozens of commercial vessels were still being built which used option number three, the wind, as their sole form of propulsion for another decade.

This type of paradox affects other types of technological transitions, and must be kept in mind. This is especially important when looking at a techno-social crisis such as the great energy transition the world is now facing in an attempt to fend off catastrophic climate change: there is a very limited budget of carbon and time in which a transition must be made, and the underlying technology (fossil fuels) must actually be eliminated within a generation to ensure the next generation can survive on the planet.

This paper is not nearly ambitious enough to claim a comprehensive view of the collier problem on a technical or philosophical level, and more research is needed on all aspects of this topic. This initial attempt to name and define the type of paradox involved in a somewhat limited set of technological circumstances is very limited, and a comprehensive treatment of the subject would require a treatise. Future research should cover at least the following major questions, which are generally applicable to current challenges:

1. In areas which did not transition to steam propulsion during the coal-fired era, what technological path was taken instead?

2. Where sail held on until after the widespread adoption of the diesel cycle engine and oil fuels,

how did this transition starting at higher efficiency affect the transition to motor vessels?

3. The decline of WASP installation and use on steamers in the nineteenth century compared to landmarks such as average tonnage, average voyage distance, and major steps in engine efficiency should be examined. Framing the question in the form of "When did the collier problem disappear on a specific route?" with reference to these technological diffusions may indicate the efficiency level needed to end the paradox in a given case.

4. Where and under what *relative* economic and energy supply conditions did sail propulsion endure, and where was it revived in times of fuel stress such as wartime, the 1970s oil crisis, etc.? There is some research available on this topic, but it has mostly been considered as an economic problem, not as part of a revolutionary energy transition.

5. Is there a correlation between collier problems and the infrastructure intensity of a technology? While steamships required widespread and capital-intensive fixed and mobile infrastructure for their support, that is not necessarily the case for other technologies which could still be subject to collier problems.

Understanding and applying the models developed from the nineteenth-century collier problem can not only assist in understanding historical energy transitions, but also the critical transition facing us today. Since the current transition's success or failure will dictate the fate of life as we know it, any tool which can be applied to understanding and hastening it should be taken in hand and put to use immediately. In the context of maritime trade, this means minimizing the use of all fuels through efficiency measures and the use of wind propulsion, the development of a new generation of windjammers for renewable energy transportation, and ensuring that any alternative fuel adopted at scale is neither dependent on fossil energy sources, nor more dangerous than the fossil fuels it replaces for other reasons.

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**Endnotes**

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20 Stowage factor is a measure of the space (normally measured in cubic feet) required to carry one long ton of cargo. See *Stowage Factors for Ship Cargoes*, 2nd ed. (Washington, DC: Government Printing Office, 1919).
21 Register tons, both net and gross, are regulatory units of 100 cubic feet, used to measure ship volume in many jurisdictions from the mid-nineteenth century until the International Convention on the Tonnage of Ships (ICT) was ratified in 1969. Ship tonnage is a study all its own, but gross tonnage reflects total vessel volume, while net tonnage gives the hold space of a vessel which can be used to generate revenue. Gross tonnage less net tonnage gives the machinery, crew, and bunker space of a vessel.
22 US Bureau of Navigation, *Annual Report of the Commissioner of Navigation to the Secretary of Commerce* (Washington, DC: Government Printing Office, 1900), 12–15. By doing the math on these average vessels, it is apparent that an average steamer in 1900 has a "maximum collier range" of 10,227 nautical miles, assuming all the interior space of the ship was filled (based on a coal stowage factor of 40 cubic feet per long ton and 1407 GRT). Obviously, this is not possible as some space must be allowed for buoyancy, crew quarters, provisioning, engines, and other machinery and working spaces. This assumes 5.8 nautical miles per ton of coal burned (8,141 nautical miles/1400 tons of coal = 5.8 NM/LT), and a cargo of 1 ton to drop at the coaling station. Clearly an economic range would be much shorter, with 6,322 nautical miles being the maximum based on 872 NRT for the same average steamer in 1900. Clearly, above-average size steamers would be able to overcome this; even the 1900 average steamer is losing 64 percent of its cargo space for the voyage from New York to Coronel. Any sailing vessel's "collier range" is effectively unlimited, regardless of era.
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27 Lloyd's Register of British and Foreign Shipping, *Returns of Vessels Totally Lost, Condemned, &c.* (London: Lloyd's Register, 1890–1905).
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44 Strategic materials include copper, nickel, oil, and other materials absolutely necessary for wartime production. A classic example of their conservation and intentionally avoiding their use is the minting of steel nickels and pennies in the US during the Second World War. See Steven Woods,

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49 Polytechnic systems are "able to promote and absorb many important changes without losing the immense carryover of inventions and skills from earlier cultures. In this lies one of its vital points of superiority over the modern mode of monotechnics, which boasts of effacing, as fast and as far as possible, the technical achievements of earlier periods, even though the result . . . may be far less flexible and less efficient than the more diverse and many-paced system which preceded it." See Lewis Mumford, *The Myth of the Machine*, vol. 2, *The Pentagon of Power* (New York: Harcourt Brace Jovanovich, 1974), 140–41.

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52 Ellul, *The Technological Society*, 90. "Technique" should not be confused with "technology" when talking of Ellul's work and insights: technology is the tool itself, an inanimate object designed to complete a task; Technique is concerned with the human employment of and relationship to technology, in both specific cases (here, steamships) and in general, at a societal level. Capitalization of *Technique* as a distinguishing characteristic between this idea and the skilled manipulation of a tool is copied here from Ellul.

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57 Relational goods are nonmaterial "goods" generated through community, such as the group enjoyment of concerts, friendship, etc., and are exclusively subjective experiences. A good overview of the economic degrowth movement's logic and theories can be found in Giorgos Kallis et al., *The Case for Degrowth* (Cambridge: Polity Press, 2020).

58 This impetus is still with us, as seen by the trends in naval architecture which have seen the construction of the new locks in the Panama Canal, the advent of ChinaMax vessels displacing nearly 400,000 tons, and container vessels with a capacity of over 24,000 TEUs (Twenty-foot [container] Equivalent Units). All of these have required massive dredging operations, ever-decreasing margins of error in canals, ever-fewer ports where these vessels can call, and massive risks to bridges and other vessels from collisions, in addition to increasing fuel consumption and induced demand for international shipping. There is no indication this two-hundred-year-old trend is anywhere near stopping unless an absolute engineering or resource limit is met, no matter how vulnerable to disruption this system becomes or how poorly it serves human wants and needs.

59 Mumford, *The Pentagon of Power*, 263–99.

60 Liljegren, "Coal, Oil or Wind?"