Energy 35 (2010) 1730–1740

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy, industry and politics: Energy, vested interests, and long-term economic growth and development

Espen Moe [1]

School of Policy Studies, Kwansei Gakuin University, Kobe-Sanda Campus, Sanda, Hyogo, Japan

ARTICLE INFO

Article history:
Received 7 April 2009
Received in revised form
24 October 2009
Accepted 21 December 2009
Available online 27 January 2010

Keywords:
Structural economic change
Vested interests
Energy-industry symbiosis
Energy and growth
Joseph Schumpeter
Mancur Olson

ABSTRACT

The article seeks to explicate a link between energy and long-term economic growth and development. While in many ways intuitive, attempts at sketching theoretical frameworks explicating this link have been few and simplistic, typically limited to technology and economics. This article emphasizes the importance of politics as well, fostering a symbiosis between the dominant industries of a historical epoch and the energy system that enabled them to flourish. The framework combines Joseph Schumpeter and Mancur Olson, emphasizing 1) the importance of structural economic change for long-term growth and development and 2) vested interests. The framework yields one theoretical proposition: In order to rise, states must prevent vested interests from blocking structural change. States that are unable to do this will get locked into yesterday's technologies, industries and energy systems, effectively consigning themselves to stagnation and decline. A brief empirical section provides historical data from 6 historical epochs (including present-day renewables) over a period of 250 years to demonstrate the usefulness of the approach. While no exhaustive test, the data suggests that countries that have prevented vested interests from blocking change have been far more successful in fostering a symbiosis between energy and industry than those countries that have not.

1. Introduction

The link between energy and economic growth may seem obvious. There is a strong and well-documented correlation between energy (as in total primary energy supply) and long-term economic growth and development [1,2]. There is little doubt that steam power, electricity and oil have been essential to long-term growth processes.

On a different level, the link is not equally obvious, far more complex and capricious. A multitude of social scientists and historians have emphasized structural economic change as the cornerstone of long-term growth and development. If not for structural change, we would all still be hunter-gatherers, or farmers, or industrial workers. Structural change is what makes the economy leap from one economic trajectory to another. Hence, the economic history of the world, at least since the Industrial Revolution, can be viewed as one of core industries based on new and generic technologies serving as locomotives of economic growth during different historical epochs [3–12].

A number of scholars [4,5,13–17] have gone one step further and noted how each industrial wave has been accompanied by the discovery and rapid exploitation of a new source of abundant energy – a new resource. And from technological progress, this resource has become rapidly more exploitable and cheaper. Hence, what arises is a symbiosis between energy and industry, fostering long-term economic growth and development. Without new sources of energy, structural change and renewed growth in new core industries would have been more or less impossible. But equally important, without technological change and industrial progress, there would have been little pressure to find and develop new sources of energy.

It is this symbiosis and the political economy that drove it, that I draw a very brief sketch of here. The importance of structural change begs the question how and why such change occurs. The symbiosis between energy and industry owes much to politics. In some countries, politics has enabled it to happen; in other countries it has prevented it. It was never obvious that the industrial and economic development experienced by the West would just happen by itself, and that steam engines, electricity and oil would have the revolutionary impacts that they had. In most countries they did not (or only very belatedly)! But in the countries with success, the reward was major industrial advantage and a new foundation for long-term economic growth.

E-mail address: esp.moe@gmail.com

[1] Mailing address: Espen Moe. Department of Sociology and Political Science, Norwegian University of Science and Technology, 7491 Trondheim, Norway.

0360-5442/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2009.12.026

In my book [10] on the rise (and fall) of core growth industries, one of the conclusions was that only states that managed to prevent vested interests (e.g. Ref. [18]) from gaining control over economic policy-making stood much chance of pursuing policies of structural change. In this article I suggest the same theoretical framework and core variable(s) for an explanation of structural change that combines energy and industry.

I first sketch a theoretical framework explicating the link between energy, industry, and growth. This framework outlines how the symbiosis between energy and industry is contingent on politics, and how vested interest structures means that success does not automatically follow just because of the existence of new technologies or resources. I then provide historical empirical evidence from five time periods to substantiate the fruitfulness of the approach, showing how the state has been instrumental in fostering – or preventing – structural change in the energy sector. This also includes the potential role of renewable energy in driving a future wave of growth.

2. A theory of long-term economic growth and development

A theory of growth and energy requires more than just positing the importance of energy for growth. Over the past years, this journal has hosted five articles by Robert Ayres (with or without coauthors) [19–23], dealing with different aspects of the relationship between energy[2] and economic growth. They all identify weaknesses in the approach of neoclassical economics towards energy, for instance criticizing how it depicts resource consumption as an effect, not a cause of growth [20,21]. To Ayres et al. a growth engine like technological change is no exogenous black box, as in much neoclassical theorizing. Rather, physical resource flows is a major factor of production, with coal and steam power evidently driving the first industrial revolution through declining fuel and mechanical power costs. Electric power did the same a century later. Hence, in this journal, Ayres et al. have sought to bring the focus onto energy inputs, or *useful work*, as the long-term driver of the economy.

The conceptual link between useful work and economic growth takes the shape of a feedback cycle where growth generates growth. Energy and growth is linked by technological progress making the conversion from exergy (as in fuel) to useful work more efficient, leading the cost of useful work to decline. This yields increased demand for useful work, thus bigger production units and production volume. Which requires more capital investment. While supply and demand drive each other, the long-run trend sees increasing exergy conversion efficiency drive growth through declining prices, increasing all sorts of demand and fueling new investments, further economies of scale, learning-by-doing, R&D, further price declines, etc., in other words growth generating further growth [20,21,23].[3]

The above description is one that most economists would recognize. It works through the markets, by supply and demand stimulating each other, fueled by technological progress, in a process that seems quite linear and driven by the normal equilibrium dynamics of neoclassical economics. Yet, Ayres et al. [23] are quite correct in emphasizing how macro-economists have underestimated the importance of energy, as well as in lamenting how attempts to explain the residual encountered in traditional works of neoclassical economics has consistently neglected to take account of energy. And they are correct in attacking present-day economics for its often tacit assumption that "changes in the supply of energy or the demand for energy services have no impact on economic growth" [23].

The framework outlined here goes further, accentuating the breaks, the disequilibria, the path-dependencies and lock-ins of the political economy. It stresses how in describing structural change and long-term growth and development, technology and economics cannot by themselves provide sufficient explanatory leverage. For that, *politics* – or the political economy, with its focus on actors and decision-makers, on institutions and regulations, and on past and present interactions – must be included. And thus, technology, economics, and politics constitute a triangle, with all sides of the triangle capable of preventing structural change from occurring. While agreeing with the criticisms of Ayres et al. [20,21,23], and accepting the conceptual link that they provide, a theory of long-term economic growth and development needs to go further.[4]

Structural change is crucial in energy as in industry. Joseph Schumpeter and Mancur Olson provide separate parts of a framework emphasizing the importance of structural change for long-term growth and development, and how the impact of vested interests on policy-making affects the capacity of political decision-makers to implement policy [10,24]. This applies to energy policy as well as industrial policy.

A framework stating that different time periods have been characterized by different growth sectors may seem trivial. It would have been odd if the cotton textiles of the early Industrial Revolution were still the main engine of growth. In a different sense, it is not trivial. It is an argument that privileges certain sectors over others in deeming them more important for growth: These were sectors drawing on generic technologies, with multiplier effects through their contribution to other sectors, and they have drawn upon technological breakthroughs, allowing major productivity improvements and giving rise to entirely new economic activities.

While growth invariably consists of different components, the framework employed here is one of Schumpeterian growth. The focus on structural change, and on the political economy of vested interests in resisting such change, represents a distinctly Schumpeterian view of growth and development; that is, growth based on technological innovation and knowledge.[5] Schumpeter's world is

[2] 'Energy' really is a misnomer [19]. The term that should really be used is 'available energy', or the more technical term 'exergy'. Available energy is defined as that fraction of total energy that can converted into 'useful work', hence the above use of that term. Technical misnomer or not, I use the term 'energy' as it is being used in the general parlor.

[3] Ayres [20,23] refers specifically to his own work on the US economy, which is where he derives most of his empirical material from, and claims great success for his model in explaining 20th century US economic growth.

[4] Ayres should not be averse to this [1]. He recognizes that the economy has cycles, with long-waves coinciding with shifts in major energy sources. Speculating around the potential end to exponential growth, he references the same Kondratieff long-waves (popularized through Schumpeter) that are an integral part of the framework presented here.

[5] Without downgrading other types of growth, Schumpeterian growth is important. Standard neoclassical theories only account for a modest amount of long-term growth. Abramovitz [25] and Solow [26] provided early attempts at growth theories, but with the model only explaining 10–20% with the remaining 80–90% a residual, these only illustrated the inability to provide a satisfactory explanation. The approach has since been refined (e.g. Ref. [27]), but economic analyses routinely attribute such significant shares of overall growth to technological change that Schumpeterian growth is a good starting point [10,28]. Other types of growth [29]: 1) Investment-led, or Solovian growth (after Robert Solow); capital accumulates more rapidly than the growth of the labor force. 2) Smithian growth, based on commercial expansion, also known as gains from trade. 3) Growth based on scale or size effects. All growth processes are invariably a mix (Schumpeter [30] for instance recommends savings and investments – in entrepreneurially promising sectors – which overlaps with Solovian), but Schumpeterian growth has gradually become ever more important. (Ayres [1] even hints that in the industrial world most of the gains from the other three have already been captured, with technology the only remaining viable driver of growth.) Schumpeterian is also at the core of structural change, as in this article.

cyclical, in flux, and characterized by shocks and disequilibria rather than a steady walk towards economic equilibrium, with the world economy going through successive waves of industrial revolutions of empirically 50–60 years each. While this is too deterministic a view, there is considerable consensus about core industries and technologies that have been particularly important for growth and prosperity through different historical epochs.[6]

Schumpeter's long-term economic cycles are driven by the growth of one or a few leading industries. As these saturate, the world economy drifts into a structural depression ultimately only resolved when new growth industries provide the economy with a new industrial engine. In Schumpeter's [31,32] own terminology: The world economy goes through 'waves of creative destruction'. Depression leads to the destruction of old firms and industries, but also to the creation of new ones. When the core industries of the past no longer yield the profits and investment opportunities they once did, the country has to move on. Seeking to prevent the phase of destruction only leads to the silting up of economic rigidities and long-term stagnation.

Technologies and institutions change over time, and what drives growth in one era will not be equally important in the next. New technologies and industries have different requirements – be it in terms of knowledge and education, capital, linkages between academia, government and industry, patenting systems, etc. – and the degree to which these are met is what is crucial with respect to structural change and long-term growth and development. Hence, institutions well suited for an earlier paradigm may be completely inappropriate for the new one [5,33–35].

Schumpeter provides the emphasis on structural change. However, the *mechanism* by which his shocks, macrotrends and creative destruction occur comes from Mancur Olson [18,36]. Olson understands how structural change is a thorny process that routinely meets with resistance from *vested interest* groups.[7] As an economic sector becomes economically prosperous, it typically also acquires political influence. Institutional stability leads to institutional rigidity, as vested interests seek to preserve the institutional status quo that served them in the past.[8] And so, societies that have had to start over again, reforming their institutions and breaking up old monopolies of power and economic vested interests, are the ones that have become prosperous [36].

If the economy is controlled by vested interests, it loses its ability to change, adapt and to shift the status quo. Olson starts with institutional rigidity, Schumpeter with technological change. When technological change is allowed to persist, Olson's silting up of institutional rigidities will not occur. When the process of creative destruction is blocked, it will. Applying Olson to Schumpeter, rigidities silt up when the implementation of new technologies gives rise to a new status quo defended by new vested interest groups. Hence, the state needs to actively protect and promote new technologies and industries, but only while they are young and vulnerable. If protection becomes permanent, we are back in an Olsonian trap, vested interests again having been allowed to grow powerful. Towards the end of a technology or an industry's product cycle [40], it must *not* be supported, as this will impede upon structural change and obstruct the rise of upcoming industries. This provides for a distinct role for politics and for the state.

I do not make any pretensions as to whether structural industrial change fuels structural energy change, or the other way around. (Most likely, the effects are reciprocal, with positive feedback loops, hence *symbiosis*.) However, without structural breakthroughs in energy production and supply, the industrial changes that have materialized over at least five economic waves, could hardly have occurred. Radically new industries, challenging existing energy systems, would not have had the same societal impact if not for a new energy system that allowed them to live up to their potential. Similarly, without the growth of new industries, there would have been little impetus for structural change in energy, as the old and trusted solutions would have sufficed. The early 19th century iron industry could never have developed into the engine of the world economy if not for the structural change in energy leading to the phasing out of charcoal and the introduction of coke. Britain could have chopped down every one of its trees and still not be able to meet demand.[9] Hence, it is fair to assume that similar causal mechanisms apply to structural change both in industry and in energy.

Industrial change does not happen simply because of the availability of new and better technologies. In any society there are a number of vested interests seeking to preserve the status quo, which includes an energy structure [29,37]. These are at least as capital-intensive as regular industrial structures,[10] giving rise to what Unruh [35] labels techno-institutional complexes (TIC) – large technological systems embedded through feedback loops between technological infrastructure and institutions. Once locked in, they are not easily replaced. Hence, today's oil companies are the biggest industrial giants on the planet,[11] part of a TIC that perpetuates a fossil fuel-based infrastructure, exacerbated by government subsidies and institutions, resulting in "carbon lock-in". It typically takes strong political action, beyond mere market mechanisms, to displace a TIC and implementing a new energy structure [10,35]. And so, the countries that have managed to implement energy structures that fit the industrial demands of the future are the ones that have enjoyed success.

There is of course nothing revolutionary *per se* about linking energy, or more generally, resource endowments, and economic growth. A number of scholars have. Jared Diamond [43] has written about how different peoples have destroyed their own resource bases and doomed themselves to falling. Several scholars have written about climate/resources and growth, in particular regarding the colonizing of America [44,45]. In explaining the lack of Chinese industrialization, Kenneth Pomeranz [46] claims access to coal as the one relevant strategic difference between China and Britain. Whereas Michael Ross [47], in phrasing the term 'resource

[6] Numerous scholars have identified the same core industries. Freeman and Perez [5] single out five *technoeconomic paradigms*, of 50–60 years each, since the Industrial Revolution, based on cotton textiles, iron, steel, electric industry (including chemicals), oil and consumer durables, and computers and microelectronics. Similar core industries can be found with Bairoch [3], Gilpin [6], Hobsbawm [7], Landes [8], Modelski and Thompson [9], and Rostow [12].

[7] There will always be vested interests resisting change. New knowledge displaces existing skills and technological change leads to losses for those that have invested in the old technology. Hence, potential losers have routinely sought to curb innovation [29,37]: 1) Outright physical resistance against new technology – riots, strikes, physical destruction of machinery. 2) Laws and regulations restricting implementation of new technology, as well as barriers of entry – guilds, trade unions, labor unions, lobby groups, state monopolies. 3) Lobby groups that manage to shield themselves against competition through protection and favorable treatment.

[8] Institutional theory tells us that institutions create stability. They are the rules of the game, leading to path-dependencies, acting as bulwarks against radical change [18,38,39].

[9] By 1815, the total amount of trees on the British Isles could have produced enough charcoal for 100,000 tons of pig iron. But by 1815, Britain was now producing 3–4 times that amount [41].

[10] Energy structures can of course also be industrial structures. There is no doubt that there is an oil *industry*. And so, the distinction is somewhat artificial. Still, there are certain kinds of industries that primarily exist because they provide fuel for other industries, as opposed to providing goods *per se*, and these are the ones here being treated as energy rather than industry.

[11] Of the world's 12 largest companies, 6 are fossil fuel providers, one is an electricity company, and 4 are car manufacturers [42].

curse', instead suggests that countries richly endowed in resources may face underdevelopment.

Scholars have also made the observation that the previously mentioned industrial waves have coincided with shifts in the major energy sources [5,11,17]. Authors like Phillips [13] and Rifkin [16] suggest that the rise and fall of the great powers is linked to their ability to benefit from a new energy system (and their refusal to restructure as new sources of energy become available). Industrial waves have been accompanied by the discovery and exploitation of a new source of cheap and abundant energy – which has then rapidly become cheaper because of new technologies and methods of extraction and because of the building of a new infrastructure facilitating its use. These are the waves that I sketch out in the empirical section.

While economic historians have dwelled on parts of this, the analysis provided here is an attempt at synthesizing efforts belonging to two strands of literature, and from a social science point of view: One strand of literature focuses on case studies of specific periods of structural change, like the Industrial Revolution in Britain, or the electrification of the US, but with less of an effort at causal inference about the general phenomenon of structural change. A second strand analyses structural change in general, seeking to outline its contribution to a specific country or to the world economy in different time periods. What is often lacking is an explanation for change *per se*, leaving this process as something that is essentially taken for granted – as the starting point of the analysis, as cause rather than effect. (It also often lacks a comparative and an institutional perspective.) It is these two strands that I try to bring together. A full empirical treatment would require a book. The purpose here is to provide a brief, but plausible sketch of a general pattern of structural change – beyond time and space – outlining the role of the state in promoting such change, and suggesting a specific and traceable causal mechanism through which structural change occurs, in both industry and energy.

True, there are potential differences between structural change in industry and in energy. Changing energy structures requires access to a specific resource. Thus, countries with access within their own borders start out with a resource endowment advantage. Britain certainly benefited from access to coal, the US to oil. But resource determinism overlooks that Britain and the US could utilize their resources because their economies had developed such that these resources were now essential for economic growth. It is dubious, despite Pomeranz' assertions [46], that China would have become an industrial nation if it only had easy access to coal [8,29,41]. As we now know, China has an abundance of coal. Hence, resource determinism also overlooks the role of the state in working around such problems. A state that actively pursues infrastructural policies to enable resource endowments to come to good use is even more important in countries with difficult starting conditions. And because energy structures are often both bigger and more fundamental than regular industrial structures, the vested interest focus is at least as important here as it is for regular industry. Schumpeter himself felt that rather than resource endowments, the reason why the US thrust ahead of Europe in the interwar years was the way in which it made good use of its resources [30].

It still makes for a potential role for geopolitics in securing access to resources, in a way that is hardly the case for regular industry, whether by securing access to particular geographic areas or by securing open, global markets, and by peaceful or less peaceful means. They are processes that may significantly change the international system and economy. Thus, we should not expect structural change in energy to exactly replicate industrial change. However, the importance of an autonomous state, preventing vested interests from obstructing structural change is as important here as in industrial affairs. The same theoretical mechanism applies, even if we have to do the actual casework to find out how the precise process played itself out.

3. Methodology

While no major methodological pretensions go into this article, it has a clear comparative and historical design. Vested interests are obviously not the sole relevant economic growth variable, but space constraints make it impossible to present a more exhaustive framework.[12] It is also a variable that is hard to operationalize, hence the qualitative approach taken here. For each time period we need to identify major energy-related political issues, relevant vested interest groups, to what extent they were successful in influencing policy, and the extent to which political elites were receptive to upcoming energy actors, or whether these were at the mercy of policies designed to protect more established actors. The variable is deductively derived from theory, but since there invariably is a multitude of vested interests we cannot *a priori* determine which will be the most important for each time period. This can only be established inductively, based on the historical record. The same goes for the actual policy-making influence of these vested interests. No large-scale data can tell us whether or not vested interests actually mattered in any large array of cases. Ultimately, I must rely on assessments based on my own reading of the literature. For this, I have tried to shy away from controversy, relying on data and interpretations that the overwhelming majority of scholars in the field should agree with.

With only one independent variable, this is a simple model. Vested interests tied in with the existing industrial and energy regime is the main factor standing in the way of structural change (thus long-term economic growth and development) and the state the main actor capable (or incapable) of dealing with these vested interests. The success of an energy regime gives rise to vested energy interests seeking to perpetuate the existence of that regime. The stronger the interests, the harder it is for the state to pursue structural change. The expectation is that a state controlled by vested energy interests may only reluctantly and belatedly change its energy structure. A lack of structural change in the energy sector yields a state that is sooner or later incapable of providing new industries with sufficient power or an energy infrastructure that serves their needs. Instead, new industries will rise in countries where the energy structure *has* changed, leading to structural industrial change and new growth engines in these countries.

The cases are selected such that each time period juxtaposes one positive and one negative case – the leading power of the day and a great power that was more of a relative failure – employing Mill's Method of Difference [48]. This is complemented with the historical method. Mill for all practical purposes leaves us with a set of correlations without a large enough sample to make valid inferences. Hence, the historical method is crucial, tracing the micro mechanisms specified by the macro variables in the theoretical framework, thus creating the foundation for causal inferences about the correlations discovered through the comparative method. For a far more extensive treatment, see Ref. [10].

First, while the early Industrial Revolution to a major extent was driven by the maturing of well-known technologies like water power and wind, coal was crucial to the rapid growth of the

[12] For instance, without a proper knowledge base, none of the breakthroughs would have occurred. They might also not have occurred without social cohesion, as policies of structural change are hard to implement without a solid public mandate. But fitting this into the format of an article seems impossible. The model can be found in [10].

second wave, fueled by the early to mid-19th century iron industry, constituting an industrial complex comprising iron, coal and steam, and the building of a new railroad infrastructure. For both these periods, I compare British success with French relative failure. Third, the late 19th century saw the beginning of an electricity revolution, boosting growth in a number of upcoming industries like chemicals, electric motors, and injecting new life into older ones like steel. Britain now is the waning power vs. a rising Germany. Fourth, without the growth and maturing of the early 20th century oil industry, car manufacturing would probably never have developed into the mass production industry that it became. This period compares US success with British reluctance.

The fifth period is conceptually trickier. Many assumed that nuclear power would become *the* new source of energy. This only to some extent happened, and marked among other things by Chernobyl, the 1980s saw a reversal in the fortunes of fission. Instead, two other developments mattered. First, oil remained crucial. The 1970s oil crises subsided, prices dropped, and until very recently remained relatively low. Second, the growth of the 1980s onwards was not based on manufacturing. The new, abundant resource enabling growth was not an *energy* source. Instead, breakthroughs in computing power led to microelectronics serving as a cheap and abundant *re*source fueling growth in the services. This section pits US success against Japanese failure.

Sixth, the days of cheap and abundant oil may be at an end. It is not unlikely that increasing demand for petroleum, together with the exhaustion of resources and climate change, may put new and obvious constraints on growth. This final section looks at whether it is conceivable that renewables will provide future industrial paradigms with the cheap and abundant energy required to trigger yet another economic wave.

The design ensures variation on the dependent variable, for each time period and for the article as a whole, allowing more reliable inferences to be made. The point of the empirical section is primarily to demonstrate the fruitfulness of the approach. Yet, the values on the dependent variable are systematically matched by the values on the independent variable and supported by the historical narrative. This is no conclusive test, both because the independent variable is only loosely defined and because space constraints severely limit the amount of empirical material that can be included. Methodologically, it is a *plausibility probe*; the results are not conclusive, but sufficiently rooted in data to warrant more rigorous testing [49].

4. Some empirical examples

4.1. Water, wind and the early Industrial Revolution

The early Industrial Revolution was to a great extent powered by already known technologies. The waterwheels of the late 18th century had become far more effective and sophisticated than the ones of a century earlier. The giant Versailles waterwheels of Louis XIV yielded no more than 7 kW. By 1750 maximum effects were around 40 kW. By the 1850s the largest British installation provided a full 1.5 MW. Change *did* take place, to an extent that should not be underrated. Still, most of the change occurred within the existing energy-industrial framework of the time, and even without the introduction of the steam engine could have kept going for decades still, particularly in cotton textiles. True, in Britain, already by 1800 the transition to coal had largely taken place, but in France and much of the rest of Europe, coal did not start surpassing wind and water until the 1850s [17,50–52].

For the early Industrial Revolution, no firm energy policies were in place, no major vested energy interests needed pushing aside or energy infrastructure erecting. Hence, in terms of energy little Schumpeterian growth occurred, unlike in industry which for its day experienced major structural change. Yet, comparing Britain and France, there are suggestive differences, even if these apply more to the nascent and gradually evolving energy infrastructure based on coal rather than the waterwheels. British ruling elites possessed a far greater degree of political autonomy than French elites. This made independent policy-making far easier. Hence, in the struggle between cotton textiles and the dominant wool industry, the British state very effectively clamped down on vested interests in wool (although for political, not economic reasons), whereas the French state very much did not [24,53]. More specifically on energy technology, in one sense the British state was not laissez-faire. It vehemently protected the new industry against physical resistance (tampering with mines was made a capital offense), and against petitions to create legislation to ban new technology. And in this, it distinguished itself from France, which had neither the autonomy nor always the willpower to go against vested interests, whether in the shape of physical attacks on machinery, guilds, bureaucratic interests, clergy, craftsmen or merchants [30,54–58].

Also, while not the most active of states, British infrastructure efforts were far more extensive than the French. In the 1760s and 1770s, Parliament passed an average of 40 Turnpike Acts a year, and as importantly, canal building routinely cut the cost of transporting coal by 50%, in some cases as much as 80%. By 1820, England and Wales had twice the internal waterways per square kilometer of France [4,7,54,59,60].[13]

The outcome was a Britain that protected its new industries and the machinery and power technologies through which these thrived, and a France that did not. And consequently, Britain's industrial landscape changed whereas France's to a far lesser extent did.[14]

4.2. Coal, steam and iron

The iron industry was the second main engine of the Industrial Revolution, rising to prominence in the 1820–1830s as cotton textiles were running out of steam [62]. What made this industry so important was its many linkages with coal, steam power and railroads. It would never have become the economic boost that it was if not for the steam engine, for the transition to an energy system based on coal, and for the railroad infrastructure soon crisscrossing Europe.

Here as well, there were telling differences. The advantage that Britain held in terms of having iron and coal located in close proximity to each other should not be underestimated. Britain was well-endowed in coal and benefited from it. On the other hand, the reason why Britain turned to coal in the first place was not its abundance, but the scarcity of charcoal. Increasing demand for iron and bottlenecks in iron production led ironmasters to search for new methods of production. Demand was initially met by imports, with British per capita wrought iron consumption more than twice that of France. In France, timber was abundant and iron scarce. Thus, resource endowments can say something about why France did not make a transition towards new methods of production earlier, but *not* why demand for iron, and the willingness to use it despite its prohibitive price, was so much higher in Britain. Britain

[13] 1760–1789 saw a French canal fever, but political and financial constraints meant that the only major canal built was the Saône-Loire [61].

[14] Also, the Napoleonic Wars made diffusion of technology across the Channel far more difficult, even though it took until Napoleon before French industry could finally rely on some kind of (momentary) calm.

had a resource problem, and found a way around it. France did not [61,63,64].

What France did not do was erect an infrastructure suited to the requirements of the new industry. True, the role of the British state was modest, typically limited to letting private interests invest where they perceived of a need for railroads – which could work in a country flush with capital. But in setting up this infrastructure, Britain was not devoid of vested interests. The Liverpool–Manchester railroad was heavily fought by a vested interest coalition including the shareholders of the three Liverpool–Manchester canals, the local landowners and even the Archbishop of York. This was "a straightforward confrontation between long established vested interests and newcomers" [65] at a time when "railway mania" had yet to overwhelm investors. A government decidedly ambivalent towards industry (Lord Liverpool's Tory cabinet) came down on the side of the railroads, against a wealth of experts brought in by canal supporters [4,65].

In France, similar vested interests created a very costly compromise. While iron and coal were not located close to each other, no government succeeded in working around this. Instead, caving in to vested interests worsened the problem. Some of the most powerful of these were deeply entrenched inside the state apparatus. Hence, the railroad bureaucracy (*Corps des Ponts et Chaussées*) insisted on an expensive solution whereby canals would parallel railroads and be the primary means of goods transports. Attempts to scrap canal building were vehemently and successfully fought on several occasions [66]. In a country where the state should have played a role in providing a railroad infrastructure, the influence of the railroad bureaucracy centralized construction and held it to such high standards that it was far slower and costlier than anywhere else, even regularly bypassing industrial areas, with all (rail-)roads leading to Paris, rather than being at its densest where economically the most beneficial. Consequently, France was slow in producing an infrastructure linking iron and coal [61,66,67].[15]

Finally, in a country scarce in the crucial natural resource of the day – coal – and highly dependent on imports, pressure from domestic coalminers, bolstered by the powerful mining bureaucracy (*Corps des Mines*), tariff restrictions were placed on coal imports. Thus, a tax on coal was imposed by *the* European power in most desperate need of such fuel, worsening the situation for iron miners depending on it. The state also kept promoting wood for iron-smelting not to go against charcoal iron producers, and throughout the century French coal-mining remained an industry of small private producers using conservative and old-fashioned methods [61]. While the transformation of Britain's energy structure was swift, comprehensive and crucial to structural industrial change, France did not undergo change that to any great extent could be described as Schumpeterian. Instead, creative destruction was practically shunned.

4.3. Electricity and the second industrial revolution

The end of the 19th century saw growth driven by industries considerably more knowledge-based than in the past and depending on a very different infrastructure. Fueling this revolution, both as a resource and as an industry *per se* was electricity and the electricity industry (with certain other industries, like chemicals). Electricity is obviously a very different source of power than coal, produced *using* primary sources of energy. Thus, while revolutionizing the economy, it could never replace coal. But the electric engine had major advantages: As Brose [68] puts it, it freed the machine and the tool from the bondage of the place. It made power ubiquitous. The electric engine was flexible, easily applied to large factories, small businesses and home workshops. Power could easily and efficiently be transmitted over long distances, enabling unheard of economies of scale as machines did no longer have to be located close to the prime mover. Also, electric engines could be easily started and stopped without having to make costly adjustments. It gave new life to large and small businesses through cheap power. It revolutionized the railroad, heavy electro-chemistry, electro-metallurgy, and had its maybe most important impact in the application of small, fixed electrical engines [52,64]. This was very much a structural energy change, giving rise to structural industrial change.

Britain took an initial lead,[16] but squandered it, due to institutional and vested interest problems. The most obvious and glaring failure of the state was the unwillingness to provide mass and higher education, hence suffering a massive lack of electrical engineers (and chemists). By 1913, Germany produced 10 times as many engineering students and their universities were vastly better funded [69,70].[17] In Britain aristocratic vested interests was one obstacle. Education reform would cost a fortune. Conservative politicians did not see the usefulness in sponsoring education for the masses – it had not been necessary earlier (and it might lead to revolution). Also, there was no pressure for education reform from the industry. Britain fell behind from a mix of disinterest and hostility [71–74].

Also, strikes, not specifically directed at electric equipment, but typically against the newest and most labor-saving machinery, like electric machinery, blighted Britain around the turn of the century, strongly affecting the introduction of electrical cranes in dockyards [68].

Most importantly, a lack of integration made the introduction of electricity a hodge-podge of standards and efforts. Municipal gas networks were partially successful in opposing electrification. Often, cheap coal meant that electricity was met with limited enthusiasm. The Electric Lighting Act (1882) limited operating licenses to 7 years and gave local authorities the right to take over assets after 21 years. And because of local autonomies Britain was stuck with a multitude of power networks, with separate voltage arrangements and hardware. None of this was helped by attitudes like those of the president of the British Institute of Mechanical Engineers who saw the chief purpose of electricity to be lighting rather than industrial power [8,64,68,75].

Compare this to Germany, which had no strong existing vested interests to hem it in. It had for its day the best and most heavily sponsored education system in Europe, set up deliberately by the state, with a particular onus on technology and science. The initial rivalries between pure and applied sciences were in the past, and industrial linkages were strong. The state actively sought to foster cooperation between industry and academia and cater to the needs of new industries. The electrical industry crucially depended on formal instruction in scientific and vocational-technical schools rather than old-fashioned on-the-job training [8,68,69].

Also, the emphasis on industrial use meant that even if Britain was ahead in lighting, Germany was the undisputed leader in electrical equipment and appliances. The German electrical industry was smaller than its American counterpart, but exports

[15] This did not change until Napoleon III (1852–1870), railroads being amongst his pet projects [61,66].

[16] The first European public power station was erected in Godalming, England in 1881 [64].

[17] By the end of the 19th century, the British government spent £26,000 on universities for all purposes. Prussia alone spent £476,000. By 1911/12 the corresponding figures were £123,000 and £476,000 respectively [70].

were 3 times that of the US and 2.5 times that of Britain [64,68]. Success was also helped by German laws favoring large business and banking combines and cartels – the electric industry was only one of several new industries to feature major investments and huge sunk costs.[18] Finally, the German power network that arose was an integrated one, most unlike the British mess. Distribution nets were larger, their characteristics more uniform and their performance more efficient [75]. The German state had a very obvious hand in all these development, pursuing structural change through human capital, infrastructure and institution building, whereas in Britain, Schumpeterian growth was stifled by a political economy at best lukewarm towards electrification.

4.4. Oil, cars, and mass production

The early to mid-20th century saw growth driven by mass production industries. Of these, the car made the biggest impact, transforming people's lives both in how it fueled imaginations and through the sheer overall growth impact of the industry. It is hard to underestimate both the importance of oil for the car industry and the car for the oil industry.

Yet, during the early years of the car, gasoline was only one of three main fuels. In 1900, the US market was split three-ways between gasoline, electricity and steam.[19] Also, the early oil industry had very little to do with cars. Instead, kerosene gas for lighting was its revolutionary new mainstay, gasoline essentially a waste product. But by the 1880s, electricity, successfully lobbied by amongst others Thomas Edison, was making kerosene look old-fashioned. Instead, the fledgling car industry became the new outlet for petroleum (helped by breakthroughs in refining and thermal cracking) [77,78].

The US was no early leader in car manufacture, but quickly rose through Smithian factors like demand, capital and market size. By the 1920s (with Canada) it accounted for 90% of world car production [9,79].[20] By the second decade of the 20th century, gasoline had become the primary fuel. Kirsch [80] claims numerous benefits for the electric car and emphasizes how cities made political choices favoring gasoline over electricity and that the prevalence of electric cabs and trolley buses shows that electricity could have had a future. Black [81] goes further, citing the deal that Henry Ford in 1914 made with Thomas Edison to mass produce half a million electric cars. This would have made for economies of scale unheard of in electric vehicle production, and presumably to cost reductions and the acceleration of technological progress. The deal was never completed and the opportunity lost that same year as a massive fire blazed through Edison's uninsured factory. Hence, it is not obvious that technology alone made for gasoline-fueled car transportation, even if evidence from most countries makes this seem the more obvious outcome.

The role of the state in fostering this symbiosis can be gauged in a few different ways. In terms of industrial policy, early 20th century US was distinctly laissez-faire. However, in terms of road infrastructure, during the 1920s the US thoroughly changed. While most expenses were at the state and local levels, road building "gave the auto industry a larger government subsidy than railroads received in their entire history" [82].[21] This would continue throughout the interwar years, accentuated further by President Roosevelt's New Deal, and culminating in 1956 as President Eisenhower, after years of lobbying, started the building of the Interstate Highway System [13].[22] This completed an entire infrastructure around oil as the main source of energy.

After some early teething troubles, the federal government happily encouraged oil and automobiles. This was partly because of an absence of strong vested coal interests. Coal was never very big as the steady opening up of new land meant that Americans could always rely on firewood.[23] Instead, it was the oil barons that caught the nation's imagination. This was where fortunes were won, not in coal [13]. Schumpeterian change thus occurred quite seamlessly, much unlike in Britain, which with its abundance of coal stuck with a political economy dominated by coal fields and miners, iron and railroads. Here, structural change was both late and reluctant. In Persia, Britain found oil as early as 1908, but despite the formation of the Anglo-Persian Oil Company (later British Petroleum), did not pursue it with much eagerness [77,78]. Instead, strategic concerns, not economic, determined the outcome, as in 1911 Winston Churchill, as First Lord of the Admiralty, insisted that British battleships switch from coal to oil. From the 1920s, Britain chased oil in the Middle East and did its best to keep others out. Yet, until the 1950s, the domestic economy was to a degree of 90% fueled by coal, all mined domestically [13].[24]

In the US, oil also became a strategic resource. Self-sufficient until the late 1940s, the US did not equally actively partake in the hunt for foreign oil. However, from then onwards oil became crucial to foreign policy, President Truman signing an National Security Council document stating that nothing should be allowed to interfere seriously with the availability of oil from Venezuela and the Middle East. When Arab countries demanded greater concessions, the US for all practical purposes subsidized them by allowing them to deduct oil royalties paid to foreign governments from their taxes [77]. Hence, strongly encouraged by the American state, the symbiosis between oil and automobiles happened for industrial and geo-strategic reasons. It benefited both industries, Maugeri [77] arguing that the link was crucial also to the Post-war rise of Western Europe, especially until 1973, as the oil price remained low and reserves kept increasing.[25] The oil and car industries grew to become the biggest industrial giants on the planet, driving growth in a world where oil by 1970 even in nominal terms was cheaper than in 1914.

[18] AEG and Siemens-Schuckert being two of the most impressive and successful giants, sharing 75% of the domestic market between them [64,68].

[19] Gasoline cars accounted for 22% of US sales, electricity 38% and steam 40%. Steam cars were more economical than electric cars and more reliable than petrol cars. However, steam engines were unsuitable for dry areas, and electric cars were slow [76].

[20] In terms of technological breakthroughs, Europe did the early running. Germans Karl Benz and Gottlieb Daimler both manufactured their first automobiles in 1886. The Otto and Diesel engines were also German inventions. European cars remained technologically superior, suggesting that first-mover advantage was less important than scale. Hence, chances are that the rise of oil and cars may have had a solid Smithian growth component.

[21] By 1929, total expenditures on roads and streets (local, state and federal) amounted to $1.4 billion a year, or a full 2% of US GNP. Only education received more money [83].

[22] Eisenhower's administration was heavily predisposed towards both oil and cars. It hosted a Texas oil executive as secretary of the treasury (Robert B. Anderson) and a General Motors president as secretary of defense (Charlie Wilson) [13]. However, ever since 1921, when federal planning for a national highway begun, defense concerns were at least as important an impetus as interest group lobbying.

[23] In 1876, the US derived twice as much energy from firewood as from coal [13].

[24] For strategic, rather than industrial, reasons, the same deliberations were being made by the other European great powers. Germany, without recourse to resource-rich colonies, tried to remedy its lack of oil by using its chemical expertise to develop synth-fuels.

[25] Between 1948 and 1973 the world's proven oil-reserves rose from 70 to 667 billion barrels – probably even a conservative figure as many companies systematically underreported reserves [77].

4.5. A new resource? Microelectronics and information and communication technologies (ICTs)

Conceptually, this time period is trickier. Nuclear power was once envisioned as the energy of the future. A number of countries derive significant amounts of their energy supply from nuclear, with the nuclear lobby typically hugely influential with respect to electricity policy, like in Japan [84,85]. But nuclear dwindled in popularity following Chernobyl, and energy-wise the world economy has kept relying on oil. The late 20th century did see strong new growth, but uncharacteristically, not based on manufacturing, but services. Services not being very energy-intensive, the existing energy structure still held, with growth instead fueled by breakthroughs in computing power and microelectronics. Not a new source of *energy*, I will only touch lightly on it below. Still, it did represent a new *re*source, one providing computing rather than manufacturing power, and structurally thus representing a huge shifts in the world economy.

The main spur did not come from ICT producing manufacturing. True, productivity growth in ICT-manufacturing has been staggering.[26] But this sector is not very big, accounting only for roughly 3% of Gross Domestic Product (GDP). Instead, at about 30% of GDP, *ICT using services*, have been crucial [86]. Here, the US can show for dramatically higher productivity growth than for instance Japan. The far more active US take on liberalization and deregulation is the main reason why the US has been so much better at utilizing ICTs. With the present financial crash in mind, developments may obviously have been taken too far, with visions of ICT-based perpetual growth in the so-called "New Economy" particularly naive and ill-fated. Yet, chances are that since the 1970s, overall effects of liberalization and deregulation have been decidedly beneficial.

While there is an obvious knowledge and education component to the US advantage in this area [88–90], vested interest structures seem more important. Rather than being curbed by vested interests, the US ICT sector received numerous favors from the state. And over the past two decades, in a certain few areas, US politics has been broadly bipartisan, namely in terms of liberalization and deregulation, particularly within the knowledge-intensive services. IT and finance gained in particular by applying new ICTs [87,91,92].

ICTs enjoyed favors in Japan too. But while highly proficient at mass-producing high quality ICTs, Japan has failed to utilize them, and stubborn resistance from an "iron triangle" constituted by the Liberal Democratic Party, the bureaucracy and vested interest groups has actively presented extreme resistance towards deregulation, liberalization and any structural reform, protecting a dual economy of highly efficient and competitive exports vs. a distinctly low-productivity sheltered domestic manufacturing and service sector [93–95]. Sectors that in the US underwent dramatic productivity improvements have remained largely unchanged.

4.6. Renewables as the energy source of the future?

Can renewables, primarily wind and solar power, serve as the cheap and abundant energy of tomorrow? Regardless of the effects of the financial crash on renewables, there are things about the future that we can be fairly certain about, and in some respects our ability to make predictions is better than in the past. Energy demand has suffered a dent, but will rise again. The onus on producing energy will only get stronger, and climate change and peak oil combined with continually increasing demand for energy makes it unlikely that renewable technologies and industries will be less in vogue in the future than today. Technologies like carbon capture storage may reduce emissions from fossil fuels, but they still merely prolong the life of an energy system that must eventually be phased out. At current rates, oil consumption will increase by 37% (2005) to 2030, from a current 84 millions barrels per day (mb/d) to 116 million, and by 86% by 2050, to 135 mb/d [96,97]. While there is little consensus as to when reserves will exhaust, continually increasing demand ensures an accelerated dwindling of existing reserves [96–98].[27]

Normative and political concerns also matter: First, energy security concerns are becoming more important, as East Asia guzzles up ever more of the available oil, and as the West strives to disengage itself from the Middle East. Second, a number of countries, particularly in the EU, have spent heavily on creating a competitive advantage within solar and wind. Third, climate change has become an accepted fact. Hence, domestic and international framework conditions are likely to impose more stringent regulations on polluters, while countries will need to increase their renewable energy production in order to meet their climate commitments. And fourth, energy derived from fossil fuels will eventually have to be replaced. By 2030, there will be less time remaining to replace a volume 37% larger than today [96], with climate change probably having intensified. The sooner the transition gets underway, the better, both from a climatic and an economic perspective.

Until now, growth in renewables has primarily resulted from government support. Major new export industries have been built, but technological progress, employment and exports have come at a financial cost [99].[28] Continued growth will most likely remain dependent on support. In pure market terms, these industries cannot compete against established energy actors, even if some analyses suggest that renewables, in particular wind and thermal, will eventually be competitive with fossil fuels, and that underinvestment in R&D in renewables is the reason why this has not happened yet [100].

Also, in many countries some of the world's most powerful energy lobbies strive to uphold the energy status quo. Unruh [35] reports fossil fuel subsidies of $200 billion worldwide, EREC and Greenpeace put the figure for conventional energy at $250–300 billion [101].[29] Unsurprisingly, resource-scarce countries with major unresolved energy-issues are the ones that have done the most to promote renewables [102]. In contrast, over 30 years a petroleum exporter like Norway has built a huge infrastructure to support and aid its most powerful industry, to the at least partial detriment of renewables [103,104]. But even a country like Japan, with no domestic oil resources, has a tangled web of vested interests encompassing electric utilities and nuclear, which for all practical purposes use their influence to push wind power into the periphery [84]. Most likely the biggest breakthroughs will come in countries with major energy problems, minor vested interest lobbies and a strong state. In Japan breakthroughs have been stifled.

[26] Between 20 and 40% a year. However, US manufacturers of microprocessor chips and computers only account for 0.23% of US employment, and so their impact on the overall economy is limited [86,87].

[27] The IEA [96] holds that world oil resources are sufficient to meet projected demand until 2030. However, of the estimated 135 mb/d by 2050, conventional oil may not account for more than 92 mb/d. The rest will have to be provided by heavy oil, tar sands, shale oil, arctic oil and biofuels [97].

[28] For Denmark, even with a carbon price set at DKK 270 (€36) per ton, the support for renewables in the 1990s represented a negative investment. At this price, net present value of the 1992–1999 wind subsidies was DKK -3 billion (€ −0.4 billion). This includes DKK 25 billion worth of subsidies and preferable taxation, offset by DKK 20 billion in environmental benefits, with a bonus of DKK 2 billion from the growth of a Danish windmill industry [99].

[29] Germany for instance subsidizes every coal miner with more than $85,000 [101].

In China, renewables are rising rapidly because of the country's insatiable urge for energy. In the US, for energy security reasons as much as anything else. In much of Europe, from a lack of domestic petroleum, a tradition of state intervention, and a lack of strong vested energy interests.

While starting from a small base, growth figures are impressive.[30] For the past 10 years (1997–2006), annual growth has averaged 29% [106]. In 2006, the global market for renewable energy had a turnover of $38 billion, up 26% from 2005 [101]. 2004–2008, wind power capacity increased by 250%, capacity in solar photovoltaic 16-fold, and annual investment in renewables increased fourfold to $120 billion [107]. With 20% of total global investment (2008), the US is the new leader, but is rapidly being challenged by China, which in 2008 for the 5th year running doubled its wind power capacity. In 2007, the global wind turbine market increased by 30%. In the US, installed capacity of wind power equalled more than 30% of total installed capacity, in the EU, 40% [108,109]. In 2008, for the first time, the US and Europe added more power capacity from renewables than from conventional sources [107].

Renewables hold great promise. How great depends as much on politics as anything else. We cannot say that it will become *the* economic driver of the future. There is growing recognition that the current energy system needs phasing out, and that it has ceased to provide cheap and abundant energy. But if a phase-out were to happen, alternative energy providers would have to grow so fast that we would be witnessing one of the world's greatest industrial transformations – which may seem less likely. Also, if renewables could just about be competitive on price with oil at $150 a barrel, we are hardly yet looking at either cheap or abundant energy. Even optimistic scenarios puts renewables by 2030 at less than 30% (including hydropower) of total electricity generation (up from 18.7% (2005)) [110]. But because of the increase in energy demand, it is not even obvious that at 87% the share of fossil fuels in the energy mix will have dropped much by 2030 [111]. Thus, even if the highly impressive growth rates of renewables persist, it started from such a low base that without revolutionary breakthroughs it will not be a quick-fix to the current energy problems. Thus, we might instead easily be staring at something akin to Michael Klare's predictions of a race for the planet's remaining fossil fuel resources [111].

In one sense, that renewables will not short-term trump fossil fuels, is no challenge for the theoretical framework. People routinely fail to realize how much coal we still consume today despite having lived in a petroleum era for 50–100 years.[31] And so, growth in renewables *may* fuel the world even without fossil fuels fading away. In another sense, we are facing a radically new situation. First, because it is doubtful whether a *cheap and abundant* new source of energy is anywhere near – renewables are still quite expensive. Second, we *are* running out of fossil fuels – with demand increasing. This might trigger a race for the remaining resources that beats anything from the past. Klare [111] uses terms like resource nationalism and neo-mercantilism to describe the way most visibly China has sought to secure stable energy supplies by virtually partly re-colonizing African countries, how Russia is using its oil and gas to get concessions out of countries like Ukraine and Belorussia, and how the US seeks to pressure Saudi-Arabia into increasing production. True, Britain used to have coaling stations all around the world – this is not exactly a new game. Yet, the potential scale and scope of present-day and future energy geopolitics outshines the past. Third, if renewables cannot meet demand in a world running out of fossil resources, countries that are self-sufficient in energy hold the upper hand, which could de-stabilize world politics. Fourth, climate change will make a resource race look ever more absurd (although no less likely), as the race to secure access to the final fossil resources simultaneously worsens our predicament. Finally, this means that there might actually be life in the nuclear option still, 50 years belatedly. Numerous countries are rethinking their nuclear policies. However, it is not obvious that with an accompanying increase in demand for nuclear, uranium and plutonium deposits will last much longer than the petroleum [111].

Hence, while it is hard to credibly claim that renewables will *not* be *among* the most important growth industries of the future, it is not obvious that industrial success will be enough to fuel major economic growth. It is certainly possible to conceive of problems on a scale that makes a new growth wave less likely. In this sense, Robert Ayres [1] in predicting the end to exponential growth may have a point, the mechanism he suggests even partly overlapping the one here. That said, our framework still holds: Vested interests will determine which country benefits the more from new energy sources like renewables. And with geopolitics an X-factor, it is also overwhelmingly likely that politics will have a major say in the success or failure of renewables. But it just might be that success may in itself not be enough to create a new growth cycle based on renewables, while preventing the planet from sliding into major ecological problems.

5. Conclusions

This article has sought to demonstrate the usefulness of a theoretical framework for long-term economic growth and development. The framework links energy and industry, with the state and the political economy as the prime mover. Technological breakthroughs in energy and industry have been at the core of structural economic change for at least 250 years, driving the world economy in spurts of 50–60 years each. But these breakthroughs have not just come about by themselves. Behind the symbiosis between energy and industry lies politics. Not always as in prescient and far-sighted politicians making enlightened choices, but there is little doubt that in some cases politics has fostered symbiosis whereas in others it has patently not. And with energy giants being among the biggest industrial actors on the planet, their potential for influencing politics has been massive, for better and for worse.

While not drawing overly strong conclusions from data provided primarily to illustrate the theory, the cases do exhibit the necessary variation on the dependent variable for tentative generalizations to be made, suggesting that in those cases where the state was able to ignore its vested interests and independently pursue policy, structural change and a symbiosis between energy and industry happened, whereas the states that were at the mercy of their vested interests only weakly and belatedly managed to do the same.

While there are obviously non-Schumpeterian aspects to all of the cases described – growth is invariably a mix between different processes – I have looked for periods characterized in particular by structural change. This, inscribed in a political economy of vested interests places this article firmly within a Schumpeterian growth tradition. The degree to which Schumpeterian growth characterizes different economic epochs obviously varies. It has for instance become more important as the world has gotten more knowledge-intensive. However, looking at periods of structural change also invariably means looking at periods where technologies have

[30] In 2004, solar power's share of world total primary energy supply was a mere 0.039%. Wind power accounted for 0.064% [105].

[31] Coal accounts for 25% of total world energy demand (2005) and is even projected to rise by 2030 (to 28%). Oil accounts for 35%, and is projected to fall to 32% [96].

changed and where radically new skill-sets have been required for success.

Hence, with the early Industrial Revolution, it is the British state which protects entrepreneurialism and machinery against riots and uprisings, and not the French. During the early to mid-19th century, it is Britain that ends up with a massive railroad infrastructure to deal with the requirements of coal and iron, and not France, even though the French state was far more interventionist and the role for this interventionism far more obvious in terms of overcoming geographic obstacles. It was in Germany that electricity flourished towards the late 19th century, and not in Britain, where the state was less than interested in the technology itself, or in making institutional arrangements that would foster its growth. It was in the US that the oil industry and the automobile industry rose to become the world's largest companies, and it was in the US that ICTs made their late 20th century economic breakthrough, and not in Japan, which was at least as good as the US at ICT-*manufacturing*. Finally, it is too early to say where renewables will go, but market forces alone will not be able to fully predict the direction of these technologies and industries, and there is a firm role for the state in supporting them. And vested interests may to a large part end up deciding which countries will prosper within renewables and which will not.

It may be easier to make the point about vested interests for the negative cases. Here we can actually see the state being bogged down by interests that it is either unwilling or incapable of going against. First, in the absence of strong vested interests, the state still has to make the right kinds of policy-decisions, which is obviously not a given. Hence, the absence of vested interests can never be a sufficient condition for success, even if its presence will easily suffice for failure. Second, there are different patterns through which structural change can be pursued. 19th century iron and coal interests in Britain had to struggle with powerful established interests in water power, but with both German electricity and US oil, existing vested energy interests were fairly weak, which made supporting upcoming energy actors a lot easier for the state. Nevertheless, in all three cases, whether because of dealing with vested interests or being fortunate enough to a lesser degree to have to, it provides for a role for the state in pursuing policies of structural change in order to present rising industry with an energy structure that allows it to grow and prosper. These policies differed between countries and historical epochs. There are some obvious similarities, among others in human capital, but this will have to be the topic for a later article.

Yet, despite empirical differences, an overall pattern emerges. That energy and industry are inextricably linked is no surprise to readers of this journal. Neither should be the fact that this link has changed over time and between industries. History does not replicate itself, but sometimes patterns play themselves out over large spans of time, and while they never do so in exactly the same fashion, the existence of a pattern may still be detected. This is a pattern of energy, industry and politics, through the political economy of vested interests, and it is a pattern that very much still exists.

References

[1] Ayres RU. From my perspective: turning point: the end of exponential growth? Technological Forecasting and Social Change 2006;73:1188–203.
[2] Smil V. Energy at the crossroads. Cambridge: MIT Press; 2003.
[3] Bairoch P. International industrialization levels from 1750 to 1980. The Journal of European Economic History 1982;11(2):269–333.
[4] Freeman C, Louçã F. As time goes by. Oxford: Oxford University Press; 2001.
[5] Freeman C, Perez C. Structural crisis of adjustment, business cycles and investment behaviour. In: Dosi G, Freeman C, Nelson R, Soete L, editors. Technical change and economic theory. London: Pinter; 1988. p. 38–67.
[6] Gilpin R. The political economy of international relations. Princeton: Princeton University Press; 1987.
[7] Hobsbawm EJ. Industry and empire. London: Penguin; 1969.
[8] Landes DS. The wealth and poverty of nations. New York: W.W. Norton; 1998.
[9] Modelski G, Thompson WR. Leading sectors and world powers. Columbia: University of South Carolina Press; 1996.
[10] Moe E. Governance, growth and global leadership. Aldershot: Ashgate; 2007.
[11] Reinert ES. Catching up from way behind. working paper 8/93. Oslo: Fremtek; 1993.
[12] Rostow WW. The world-economy. London: Macmillan Press; 1978.
[13] Phillips K. American theocracy. New York: Penguin; 2007.
[14] Reinert ES. Det tekno-økonomiske paradigmeskiftet [The techno-economic paradigm change]. Report 3/96. Oslo: Norsk investorforum Report See also, http://www.nifo.no/dokumenter.htm; 1996.
[15] Reinert ES. How rich countries got rich…and why poor countries stay poor. New York: Public Affairs; 2007.
[16] Rifkin J. The hydrogen economy. New York: Jeremy Tarcher; 2003.
[17] Smil V. Energy in world history. Boulder, CO: Westview; 1994.
[18] Olson M. The rise and decline of nations. London: Yale University Press; 1982.
[19] Ayres RU, Ayres LW, Martinás K. Energy, waste accounting, and life-cycle analysis. Energy 1998;23(5):355–63.
[20] Ayres RU. The minimum complexity of endogenous growth models. Energy 2001;26(9):817–38.
[21] Ayres RU, Ayres LW, Warr B. Exergy, power and work in the US economy, 1900–1998. Energy 2003;28(3):219–73.
[22] Ayres RU, Ayres LU, Pokrovsky V. On the efficiency of US electricity usage since 1900. Energy 2005;30(7):1092–145.
[23] Ayres RU, Turton H, Casten T. Energy efficiency, sustainability and economic growth. Energy 2007;32:634–48.
[24] Moe E. Mancur Olson and structural change. Review of International Political Economy 2009;16(2):202–30.
[25] Abramovitz M. Resource and output trends in the United States since 1870. The American Economic Review 1956;46(2):5–23.
[26] Solow RM. A contribution to the theory of economic growth. Quarterly Journal of Economics 1956;70:65–94.
[27] Mankiw NG, Romer D, Weil DN. A contribution to the empirics of economic growth. The Quarterly Journal of Economics 1992;107(2):407–37.
[28] Kim J-I, Lau LJ. The sources of economic growth of the East Asian newly industrialized countries. Journal of the Japanese and International Economies 1994;8(3):235–71.
[29] Mokyr J. The lever of riches. Oxford: Oxford University Press; 1990.
[30] McCraw TK. Prophet of innovation: Joseph Schumpeter and creative destruction. Cambridge: Belknap Press; 2007.
[31] Schumpeter JA. The theory of economic development. Cambridge, MA: Harvard University Press; 1934. Reprinted, London: Transaction Publishers, 1983.
[32] Schumpeter JA. Capitalism, socialism and democracy. New York: Harper Torchbooks; 1942.
[33] Nelson RR. Recent evolutionary theorizing about economic change. Journal of Economic Literature 1995;33(1):48–90.
[34] Gilpin R. Economic evolution of national systems. International Studies Quarterly 1996;40(3):411–31.
[35] Unruh GC. Understanding carbon lock-in. Energy Policy 2000;28:817–30.
[36] Olson M. Power and prosperity. New York: Basic Books; 2000.
[37] Mokyr J. The political economy of technological change. In: Berg M, Bruland K, editors. Technological revolutions in Europe. Cheltenham: Edward Elgar; 1998. p. 39–64.
[38] March J, Olsen J. Rediscovering institutions. New York: Free Press; 1989.
[39] North DC. Institutions, institutional change and economic performance. New York: Cambridge University Press; 1990.
[40] Vernon R. International investment and international trade in the product cycle. Quarterly Journal of Economics 1966;80(2):190–207.
[41] Marks RB. The origins of the modern world. Lanham, MD: Rowman & Littlefield Publishers; 2002.
[42] Bradford T. Solar revolution. Cambridge: MIT Press; 2006.
[43] Diamond J. Collapse. New York: Viking; 2005.
[44] Acemoglu D, Robinson JA. Economic origins of dictatorship and democracy. Cambridge: Cambridge University Press; 2006.
[45] Engerman SL, Sokoloff KL. Factor endowments, institutions, and differential paths of growth among new world economies. In: Haber S, editor. How Latin America fell behind. Stanford: Stanford University Press; 1997. p. 260–304.
[46] Pomeranz K. The great divergence. Princeton: Princeton University Press; 2000.
[47] Ross M. The natural resource curse. In: Bannon I, Collier P, editors. Natural resources and violent conflict. Washington, DC: World Bank; 2003.
[48] Mill JS. A system of logic: ratiocinative and inductive. London: Longman's; 1904.
[49] Eckstein H. Case study and theory in political science. In: Greenstein FI, Polsby NW, editors. Handbook of political science. London: Addison-Wesley; 1975. p. 79–137.
[50] Magraw R. Not backward but different? In: Alexander MS, editor. French history since Napoleon. New York: Oxford University Press; 1999. p. 336–63.
[51] Reynolds TS. Power technology. In: Mokyr J, editor. The Oxford encyclopedia of economic history, vol. 4. New York: Oxford University Press; 2003. p. 246–53.
[52] Smil V. Transforming the twentieth century. New York: Oxford University Press; 2006.

[53] O'Brien PK, Griffiths T, Hunt P. Political components of the industrial revolution. The Economic History Review 1991;44(3):395–423.
[54] Mokyr J. Editor's introduction: the new economic history and the industrial revolution. In: Mokyr J, editor. The British industrial revolution. Boulder: Westview Press; 1999. p. 1–127.
[55] Bossenga G. Protecting merchants. French Historical Studies 1988;15(4):693–703.
[56] Furet F. Revolutionary France 1770–1880. Oxford: Blackwell; 1995.
[57] Morgan K. The birth of industrial Britain. London: Longman; 1999.
[58] Wright G. France in modern times. New York: W.W. Norton; 1995.
[59] Hudson P. The industrial revolution. London: Edward Arnold; 1992.
[60] Mokyr J. The gifts of Athena. Princeton: Princeton University Press; 2002.
[61] Trebilcock C. The industrialization of the continental powers 1780–1914. London: Longman; 1981.
[62] Greasley D, Oxley L. British industrialization, 1815–1860. Explorations in Economic History 2000;37:98–119.
[63] Fremdling R. Transfer patterns of British technology to the continent. European Review of Economic History 2000;4:195–222.
[64] Landes DS. The unbound prometheus. New York: Cambridge University Press; 1969.
[65] Harris R. Political economy, interests groups, legal institutions, and the repeal of the Bubble Act in 1825. The Economic History Review 1997;50(4):675–96.
[66] Smith Jr CO. The longest run. The American Historical Review 1990;95(3):657–92.
[67] Mitchell A. Private enterprise of public service? The Journal of Modern History 1997;69(1):18–41.
[68] Brose ED. Technology and science in the industrializing nations: 1500–1914. NJ: Humanities Press; 1998.
[69] Keck O. The national system for technical innovation in Germany. In: Nelson RR, editor. National innovation systems. Oxford: Oxford University Press; 1993. p. 115–57.
[70] Murmann JP. Knowledge and competitive advantage. Cambridge: Cambridge University Press; 2003.
[71] Evans EJ. The forging of the modern state. Harlow: Longman; 1983.
[72] Hobsbawm EJ. The age of revolution. London: Weidenfeld and Nicolson; 1962.
[73] Hoppen KT. The mid-Victorian generation. Oxford: Oxford University Press; 1998.
[74] Lindert PH. Voice and growth. The Journal of Economic History 2003;63(2):315–50.
[75] Smil V. Creating the twentieth century. New York: Oxford University Press; 2005.
[76] Mowery DC, Rosenberg N. Paths of innovation. Cambridge: Cambridge University Press; 1998.
[77] Maugeri L. The age of oil. Westport, CN: Praeger; 2006.
[78] Yergin D. The prize: the epic quest for oil, money & power. New York: Free Press; 1990.
[79] Ruttan VW. Technology, growth, and development. Oxford: Oxford University Press; 2001.
[80] Kirsch DA. The electric vehicle and the burden of history. Piscataway, NJ: Rutgers University Press; 2000.
[81] Black E. Internal combustion. New York: St Martin's Press; 2006.
[82] Leuchtenburg WE. The perils of prosperity, 1914–1932. Chicago: University of Chicago Press; 1958. Reprinted Chicago: University of Chicago Press, 1993.
[83] Heilbroner R, Singer A. The economic transformation of America since 1865. Fort Worth, TX: Harcourt Brace; 1994.
[84] Iida T. Renewable energy policy and politics in Japan. 3rd Workshop of Japan-UK Joint Research project on low-carbon societies. Roadmap to a Low-Carbon World, 2008.
[85] Moe E. Vested interests and renewables in Norway and Japan, in press.
[86] van Ark B, Inklaar R. ICT production and use in Germany, Japan and the United states. See also, http://www.eco.rug.nl/medewerk/inklaar/papers/ictgermanyjapan.pdf; 2003.
[87] Castells M. The rise of the network society. The information age. Malden: Blackwell; 2000.
[88] Castells M. End of millenium. The information age. Malden: Blackwell; 2000.
[89] Langlois RN, Steinmueller WE. The evolution of competitive advantage in the worldwide semiconductor industry, 1947–1996. In: Mowery DC, Nelson RR, editors. Sources of industrial leadership. Cambridge: Cambridge University Press; 1999. p. 19–78.
[90] Mowery DC, Rosenberg N. The U.S. national innovation system. In: Nelson RR, editor. National innovation systems. Oxford: Oxford University Press; 1993. p. 29–75.
[91] Micklethwait J, Woolridge A. The right nation. New York: Penguin; 2004.
[92] Rosecrance R. The rise of the virtual state. New York: Basic Books; 1999.
[93] Grimond JA. Survey of Japan. See also. The Economist, http://www.economist.com/surveys April 18, 2002.
[94] OECD. OECD economic surveys: Japan. Paris: OECD Publications; 2001.
[95] Sakakibara E. Structural reform in Japan. Washington, DC: Brookings Institution; 2003.
[96] IEA. World energy outlook 2007. Paris: OECD/IEA; 2007.
[97] IEA. Energy technology perspectives 2008: scenarios & strategies to 2050. Paris: OECD/IEA; 2008.
[98] Energimyndigheten. Oljens ändlighet – Ett rörligt mål! [The end to oil – a moving target]. Report no. 21. See also, http://www.swedishenergyagency.se/web/biblshop.nsf/FilAtkomst/ER2006%2021w.pdf/$FILE/ER2006%2021w.pdf?OpenElement; 2006.
[99] IEA. Energy policies of IEA countries: Denmark 2006 review. Paris: OECD/IEA; 2006.
[100] Schilling MA, Esmundo M. Technology S-curves in renewable energy alternatives. Energy Policy 2009;37:1767–81.
[101] EREC, Greenpeace. Energy [r]evolution. See also, http://www.energyblueprint.info/fileadmin/media/documents/energy_revolution.pdf?PHPSESSID=58b8970bb06e00dbb5cfec0ac8ee6772; 2007.
[102] Eikeland PO, Sæverud IA. Market diffusion of new renewable energy in Europe. Energy & Environment 2007;18(1):13–37.
[103] Moe E. All about oil and gas, or a window of opportunities for the renewables industry? In: Fermann G, editor. Political economy of energy in Europe. Berlin: Berliner Wissenschafts-Verlag; 2009. p. 337–64.
[104] Zero. 40 års ventetid på vindkraftkonsesjon [40 year waiting list for wind power concessions]. See also, http://www.zero.no/fornybar/nve-ma-oke-konsesjonsbehandlingen/; 2008.
[105] Economist. The sunlit uplands. See also, http://www.economist.com/specialreports/displaystory.cfm?story_id=9217928; May 31, 2007.
[106] WWEA. New world record in wind power capacity. See also, http://www.wwindea.org/home/index.php?option=com_content&task=view&id=167&Itemid=43; 2007.
[107] REN21. Renewables global status. Report. Paris: REN21 Secretariat. See also, http://www.ren21.net/pdf/RE_GSR_2009_Update.pdf; 2009.
[108] EWEA. Wind energy leads EU power installations in 2007, but national growth is inconsistent. See also, http://www.ewea.org/index.php?id=60&no_cache=1&tx_ttnews[tt_news]=1270&tx_ttnews[backPid]=1&cHash=2711a06cdb; 2008.
[109] Teknisk Ukeblad. Vindkraft tar av – men ikke i Norge [Wind power take-off – but not in Norway]. See also, http://www.tu.no/energi/article137812.ece; 2008.
[110] Resch G, Held A, Faber T, Panzer C, Toro F, Haas R. Potentials and prospects for renewable energies at global scale. Energy Policy 2008;36:4048–56.
[111] Klare MT. Rising powers, shrinking planet. New York: Metropolitan Books; 2008.