Energy Research & Social Science 1 (2014) 74–82

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Original research article

Economics of energy, big ideas for the non-economist☆

Adonis Yatchew *,[1]

Economics Department, University of Toronto, 150 St. George Street, Toronto, Canada M5S 3G7

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 10 March 2014
Accepted 10 March 2014
Available online 15 March 2014

Keywords:
Energy markets
Market failures
Big ideas

ABSTRACT

The interdisciplinary nature of energy issues calls for a 'big ideas' approach to both energy teaching and research. To devise a suitable framework, it is necessary to develop simple narratives for relevant disciplines based on big ideas found therein, and to link them to other disciplines.

This paper focuses on energy markets, their successes and failures, and outlines basic remedies for the latter. It suggests that the tension between market forces and market failures is not only a focal point of today's most pressing energy issues, but that it also provides a central geopolitical narrative of the 20th century. The importance of understanding energy policy logic within a broader political context, both domestic and global, is also emphasized.

Finally, the paper illustrates, through examples, that the search for interconnections between energy economics and ideas in the sciences, humanities and other social sciences can only deepen our understanding.

1. Introduction

If, as Norbert Weiner said, "Change comes most of all from the unvisited no-man's land between the disciplines", then the interdisciplinary nature of energy calls for a 'big ideas' approach to both energy research and teaching. Many fields inform our understanding of energy. The theoretical and applied sciences underpin the fundamental potentialities of energy and its impacts – beneficial and detrimental, constructive and destructive. Humanities document and elaborate the human consequences of energy. Indeed, the pursuit of energy is a fundamental driver of human history. The social sciences analyze societal aspects. Energy has shaped world economics and politics, and even the social structures within which humans live.

To devise a suitable framework for the interdisciplinary study of energy, it is necessary to develop simple narratives for relevant disciplines based on big ideas found therein. Constructing a narrative of the economics of energy for the non-economist is a daunting task.[2] What are the 'big ideas'? There are many. We will try to content ourselves with focusing on two: markets and their failures.

In devising energy policies, nations worldwide are attempting to balance competing objectives of economic growth, environmental protection and energy security. The instruments vary depending on cultural and historical roots.[3] Economics, and more generally political economy, inform these debates. In this discussion, markets are critical, both economically and politically. But how does one integrate sound (social) science into good (social) policy? There are alternate economic and political approaches to advancing environmental and economic objectives. There are various economic instruments for promoting innovations that can increase energy efficiency, as well as encouraging the search for needed breakthrough technologies (such as carbon sequestration, large scale storage of electricity, or integration of renewable resources).

This paper is organized as follows. Section 2 outlines two 'big ideas' – markets and their failures – illustrates these in the context of energy markets, and describes remedies for market failures. Section 3 demonstrates the power of these ideas, not only in framing discussions of contemporary energy issues, but also in

☆ The author is grateful to Ben Akrigg, Carol A. Dahl, Lester C. Hunt, David M. Newbery, James E. Pesando, James L. Smith, Yanqin Wu and four anonymous referees for helpful comments.

* Tel.: +1 4169787128.
E-mail address: yatchew@chass.utoronto.ca

[1] The author is Professor of Economics at the University of Toronto and Editor-in-Chief of *The Energy Journal.*

[2] One only need peruse texts on energy economics, such as Dahl [5] or Bhattacharyya [6].

[3] For example, carbon taxes have been resisted particularly strongly in the United States (think 'Tea Party') while Europeans have been more amenable to higher tax loads. Some leaders have attempted to promote a combined agenda of 'growth and the environment' by seeking to create jobs in renewables industries.

http://dx.doi.org/10.1016/j.erss.2014.03.004
2214-6296/

understanding tidal changes in history. We argue that energy issues are best understood within the broader economic and geopolitical context.

This paper is premised on the idea that a rich understanding of energy requires one to journey into other disciplines.[4] To this end, Section 4 provides several examples to whet the appetite. It illustrates how the Bernoulli Principle (a.k.a. the foil) contributed to globalization; it provides examples of connections between energy economics and literature and the arts; it demonstrates the elegance and concision of science in representing the hydrocarbon economy and its global warming externalities; and, it points to the benefits of viewing history through the lens of energy related developments, *energy qua history*, as it were.

In our view, a 'big ideas' approach helps to bridge the edifices that house academic disciplines (some would call them fortresses). By nurturing broad perspectives at the outset, the creative mind is more likely to take the leap into Norbert Weiner's "no-man's land".

2. Markets and their failures – two big ideas

2.1. Markets

The idea that humans respond to incentives is fundamental to economic thinking. The pursuit of one's interests is the departure point from which one builds theories of economic behavior, many of which deal with material goods.[5] To pursue their interests, individuals organize themselves into groups with common or related interests. The most basic of these in economics are firms. The process of self-organization is a direct consequence of self-interest.[6]

Two key variables which help to explain world-wide patterns of energy consumption are income (richer countries consume more energy), and prices (more energy is consumed where it is cheap and abundant). Geography also plays a central role. Heating is required in colder climates. Air conditioning is often relied upon in hotter climates. Where population density is lower and distances are greater, increased amounts of energy are consumed in transportation. Thus, demand for energy is a 'derived demand' resulting from our demand for energy services such as heat, light, refrigeration, washing and drying, various functions performed by commercial and industrial equipment, and, of course, transportation.

Alternative forms of energy may be substituted for each other. Heating and cooking may be accomplished using natural gas or electricity (or, biomass). Road vehicles, most commonly fueled by gasoline or diesel, may alternatively be propelled using natural gas or electricity. In some cases, energy use can be reduced by additional capital expenditures on more efficient engines, higher-efficiency furnaces or additional home insulation. However, such substitution usually takes time because of the long-lived nature of many capital investments. (After the oil price shock of the early 1970s, the shift to more efficient cars was gradual.)

An especially useful visual representation of the supply of, and demand for energy is depicted in energy flow diagrams, such as in Fig. 1 where 'pipe' diameters are intended to be roughly proportional to energy flows. Even a cursory examination is fruitful.[7]

In this U.S. example, total 2012 energy use (at the bottom of the diagram) is 95.1 quads.[8] The boxes on the left margin depict supplies of energy from various sources. Adding up quantities of natural gas, coal and petroleum yields a value of 78.1 – that is about 82% of U.S. energy is derived from carbon based sources. Coal is predominantly used in the generation of electricity. Renewable sources – hydraulic, wind, solar, geothermal and biomass – together yield 8.8 quads, about 9% of the total. The remaining 9% is produced from nuclear sources.

Next, consider the demand side which is divided into residential, commercial, industrial and transportation uses. The energy in each sector either produces 'energy services' or is lost in the form of 'rejected energy', the latter comprising over 60% of total energy. The least efficient sector is transportation where almost 80% of the energy is 'rejected'. The most efficient is the industrial sector where only 20% is 'rejected'. Overall, it might appear that humans are very inefficient, 'wasting' well over half of the energy we produce, but this is primarily a reflection of the state of technology and the second law of thermodynamics which we will discuss below. In fact, we have already come a long way. Fires used to heat and cook in the pre-industrial era 'wasted' 95% or more of the energy embodied in the wood they burned.

Markets provide a remarkably responsive and adaptive mechanism for supplying energy. Coal is available in many parts of the world and is the cheapest hydrocarbon. Because there are many suppliers, coal prices are determined by competitive forces and price differentials across the world mainly reflect differences in quality and the costs of transportation. Easily accessible oil, so-called conventional oil, is concentrated in relatively few places on the planet, enabling the exercise of market power, OPEC being the prime example. Nonconventional oil, such as that extracted from shale using horizontal drilling and hydraulic fracturing (fracking), is much more widely distributed and has already had a material impact on prices. (There will very likely be significant geopolitical consequences if, as a result of shale oil, dependency on Middle Eastern oil declines.) Natural gas markets vary depending on where one is located. In North America, they are competitive, in part as a result of the shale gas revolution. Continental Europe, on the other hand, is supplied to a significant extent by Russia which exercises market power in setting prices.

2.2. Market failures

In broadest terms, the historically unprecedented successes of the industrial revolution are testament to the efficacy of markets in general, and energy markets in particular. Why then should governments be involved in energy markets? Why can't markets solve societal problems on their own? From the perspective of an energy economist, there are three primary reasons. The first is the presence of consequences to market activities that are not borne by parties to the transaction, that is external effects or externalities (think pollution and today's challenges of global warming).[9] The second is the presence of market power, in the extreme case monopoly power (think OPEC or the Standard Oil Trust). The third involves goods that are not produced in sufficient

---

[4] Indeed, a central objective of this journal is to provide a venue for interdisciplinary analyses of energy issues, Sovacool [7].

[5] Although rarely acknowledged explicitly in economics textbooks, the idea is implicitly understood to be rooted in evolutionary concepts. After all, natural selection rewards self-preservation.

[6] The idea that humans can be motivated or incentivized to take a certain course of action is also fundamental to neighboring social sciences, such as political science and sociology, as well as psychology, which has played an increasingly important role in economics.

[7] The earliest known example of this type of diagram is attributed to Henry Harness who in 1837 used it to show volumes of passenger flows along railway segments. In 1869, Charles Minard used a similar diagram to show the decrease in Napoleon's troops over the course of the Moscow campaign. In 1898, Matthew Sankey used this type of diagram to show energy flows in a steam engine. Such diagrams have come to be known as Sankey diagrams. Those in Figs. 1 and 2 may be found at https://flowcharts.llnl.gov/.

[8] A 'quad' is a quadrillion BTUs. For our purposes, what will matter are proportions or relative quantities, not actual levels.

[9] In this issue, Hodbod and Adger [8] discuss the importance of considering externalities in a broader ecological context.

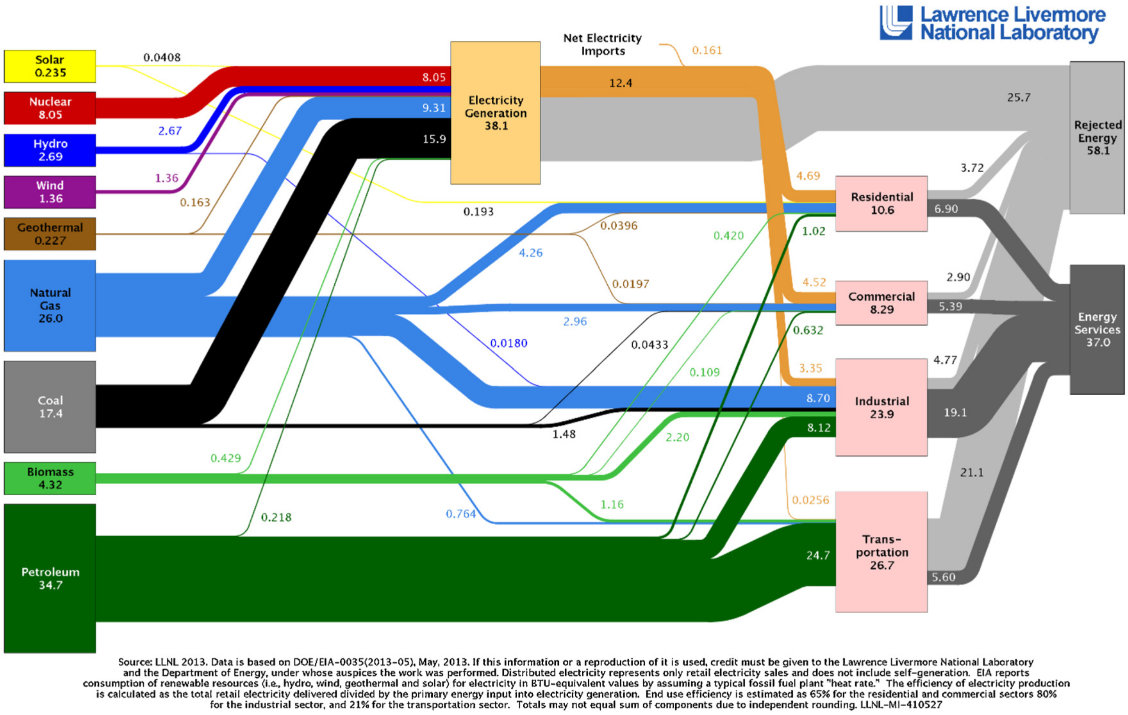

Fig. 1. Estimated U.S. energy use in 2012: ~95.1 quads.

quantities by the marketplace. Economists call these public goods (think *basic research* which is needed to solve our energy-environmental problems). We will focus on externalities, but other market failures will also be touched upon.

The macroeconomist would add a fourth deficiency of markets, and that is their inadequacy in creating sufficient employment under certain conditions, such as during the Great Depression. The political economist, historian, sociologist and philosopher would add a fifth shortcoming by pointing to places and times when markets and capitalism have not produced just societal outcomes or fair distributions of income.

2.2.1. Externalities

Today, the most prominent example of an adverse energy-related externality is the production of greenhouse gases from hydrocarbon combustion. Fig. 2 illustrates the levels of U.S. carbon dioxide emissions arising from the various energy sources depicted in Fig. 1. One might think of the two diagrams as fraternal twins – the first mapping supply and demand in U.S. energy markets, the second illustrating an important corresponding externality. The twins reveal important information about each other.[10]

Compare coal and natural gas. Although considerably more natural gas is used than coal (26.0 v. 17.4 quads in Fig. 1), natural gas produces less carbon dioxide (1370 v. 1660 million metric tons in Fig. 2).[11] In fact natural gas has about 55% the carbon footprint of coal. Petroleum has about 67% the carbon footprint of coal and natural gas about 81% the carbon footprint of petroleum.[12]

These figures suggest that switching from coal to natural gas in electricity generation can have a material, perhaps dramatic impact on CO_2 emissions. Even switching from oil to natural gas in transportation may provide some carbon relief. The availability of shale gas, exploitable at low production costs, combined with its carbon advantage, would seem to herald a 'golden age of gas'. Some argue that natural gas is the bridge fuel that will take us from the hydrocarbon era to a future low-carbon world (see e.g., [1]).

2.2.2. Internalizing externalities

Should we have the right to pollute? Before the reader turns away in indignation, keep in mind that whenever you drive your car, turn on a light or air conditioner, leave your refrigerator on (would you ever think of turning it off?), you are contributing to pollution. The issue is how much pollution we should be producing. Suppose then that a market activity creates a negative externality to the point where it is detrimental to the interests of society. Many years ago, the economist Cecil Pigou [2] suggested that such activities be taxed to the point where the level of the externality is, on balance, not deemed to be harmful to the public interest. By embedding the externally imposed costs within the price, the level of the externality can be reduced to an acceptable level. The basic idea is to internalize the externality through a tax.

Many economists favor the imposition of carbon taxes to reduce our reliance on hydrocarbons. Coal in particular would attract a high carbon tax because it produces the most carbon dioxide per unit of energy. However, economic rationality does not necessarily translate into political feasibility. Carbon taxes are often opposed

[10] The meticulous reader might ask why in Fig. 2, biomass produces zero carbon dioxide. Biomass is considered to be carbon neutral because the CO_2 that is released during combustion has been previously absorbed through photosynthesis.

[11] These figures do not incorporate the release of greenhouse gases during the extraction process. Methane molecules have over 20 times the greenhouse impact of carbon dioxide and methane which escapes into the atmosphere (so-called fugitive methane) may substantially increase the overall carbon footprint of methane.

[12] For example, natural gas produces about 52.7 million metric tons per quad of energy, while the corresponding figure for coal is 95.4, the ratio is about 55%.

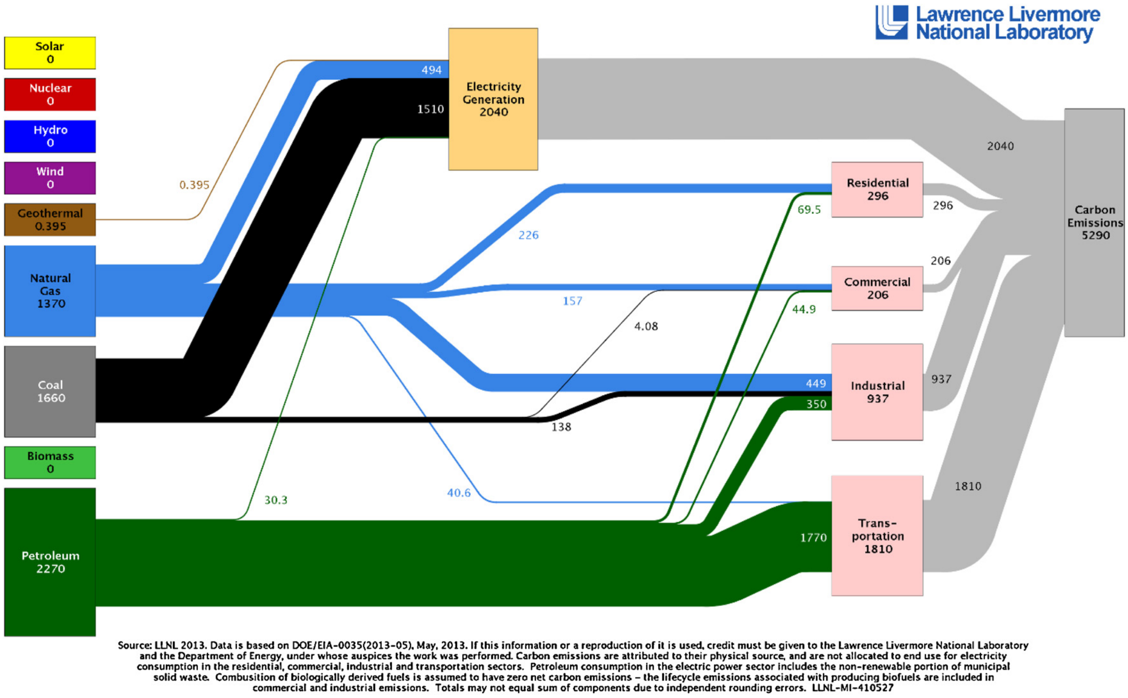

Fig. 2. Estimated U.S. energy-related carbon dioxide emissions in 2012: ~5290 million metric tons.

on the grounds that they are just another 'money grab' by government. Taxes are very difficult to reverse.[13] An important advantage of carbon taxes is that they are relatively easy to implement. A disadvantage is the difficulty in predicting resulting reductions in the targeted externality. One needs to fiddle with tax rates to arrive at an appropriate calibration.

Enter economist Ronald Coase, who published only a handful of papers, but which were so insightful that he was awarded the Nobel Prize. His contribution to the externalities issue was to recognize that by *capping* the total societal level of a pollutant, and *distributing* that right, the pollution that *is* produced will be allocated to its most efficient purposes, [3].

For example, suppose as a society we decide that we want to limit CO_2 emissions to a certain level. Emissions quotas are then allocated and permits distributed to individuals and firms. Permit owners can sell their rights to those who need them. Ronald Coase's work forms the foundation of cap-and-trade/emissions trading systems. Indeed, the European Union implemented a cap-and-trade system for CO_2 in 2005 and emissions rights are traded on a market. As long as the externality can be measured and emitting parties identified, then the market (in this case for emissions permits) will lead to efficient outcomes regardless of how the rights are allocated.

The essential *difference* between these two approaches is that Pigou seeks to directly influence price while Coase limits the quantity. The *common* feature is that both seek to correct the market externality by internalizing it. Both recognize the efficacy of markets and therefore seek to modify them, rather than replace them, for example, with bureaucratic decision-making or some other centralized approach.

[13] In Canada a temporary tax on income was imposed during WWI to finance the war effort. I am still patiently waiting for the revocation of this 'temporary' arrangement.

2.2.3. Market power

Economists dislike monopolies. Concentration in an industry for a product that has no close alternatives results in prices that are too high, and quantities too low. One option is to break up the monopoly (or dominant firm) into smaller firms that compete against each other. An historically important example is Rockefeller's Standard Oil Trust which sought to dominate the U.S. oil industry in the late 19th century. It was broken up into many successor companies and the initials S.O. (spoken aloud), eventually gave way to the name Esso. Western democracies have legislation that is intended to protect against monopoly abuses and that limits industry concentration where appropriate.

In some cases, it is more efficient to have a single firm providing a good or service than many firms (so-called natural monopolies). In energy, certain network industries such as electricity transmission and distribution are leading examples. (It would make no sense to have several different companies delivering electricity on your street.) In these cases, regulation is required to protect against monopoly abuses.

There are also broader political arguments against concentration of market power as economic power often translates into political leverage. In extreme cases, disproportionate economic power can influence legislation, domestic policy and even foreign relations.

2.2.4. Public goods

Some goods are not produced in sufficient quantities by markets. For example, basic research that leads to findings that are not patentable and can be readily copied by other companies is not likely to be conducted by private firms. But basic research brings societal benefits and is an important example of a public good. It merits support by governments through universities, laboratories, research institutions and perhaps public–private partnerships. In the energy industry, it may be that cost-effective carbon sequestration or large-scale storage of electricity awaits a deep insight that comes through publicly supported research.

3. The power of these big ideas

3.1. Markets – avoiding the Silk Road

To appreciate the power of markets in bringing about geopolitical change, consider the 'age of discovery' when European empires expanded around the world. This period was propelled by many energy-related innovations that enabled navigation out of sight of land, sails and rigging that enabled sailing against the wind, and weaponry, such as cannon, which would subdue the non-compliant.

Until the 15th century, trade between Europe and the Far East was mainly overland via the Silk Road, a network of routes which was especially open to trade during the Han Dynasty (206 BCE to 200 CE) and later during the Yuan Dynasty (1271-1368 CE), the Mongol rulers of China that followed the conquests of Genghis Khan. The Mongol Empire which expanded west into Europe ensured relatively safe passage, to which the legendary travels of Marco Polo bear witness.

But the Yuan Dynasty was short-lived and the expansion of the Ottoman Empire (Constantinople fell in 1453) made passage more difficult and costly. In part, as a result of the desire to *avoid* the Silk Road, European powers sought ocean routes. Columbus sailed west seeking a shorter route to the Far East, and thinking that he had reached India, called the inhabitants 'Indios' (Indians), a term that has persisted for centuries. A few years later, Vasco da Gama sailed south and east to find the ocean passage to India around the Cape of Good Hope.[14]

The story of the discovery of America is less one of adventurism (as it is often depicted) than it is one of economic competition for markets and resources among European Powers and the need to avoid the centuries-old overland route.

3.2. Markets and their failures – The Central Drama of the 20th century

The industrial revolution, driven by coal and the steam engine, had brought about capitalism – the accumulation of financial and physical capital – which was required for ever greater productivity. But along with capitalism came profound changes in social conditions. Workers had moved from farms to work in city factories, many lived in utter poverty and destitution.

Dickens writes of the misery and destitution of workers and their families in Oliver Twist and Hard Times. Victor Hugo, who spends a lifetime battling injustice, anticipates a central theme of the 20th century in his enduring novel, Les Misérables. Although loosely translated to mean "The Wretched", Hugo defines the meaning of his title much more precisely:

> ". . . those are rare who fall without becoming degraded; there is a point, moreover, at which the unfortunate and the infamous are associated and confounded in a single word, a fatal word, Les Misérables. Whose fault is it?"[15]

In this passage, Hugo is asking: how do we draw the line between individual responsibility and responsibilities that belong to us collectively, and therefore to society, the state and its institutions?[16]

Karl Marx and his disciples argue that systems based on capital, private property and markets can only ultimately fail to produce equitable outcomes and will inevitably be abandoned. They argue that communal ownership and central economic planning is the way of the future. The Russian Revolution leads to the first communist state and the ideological competition between markets and central planning begins.

During the 1930s, market-based economies are devastated by the Great Depression. Proponents of central planning see the Great Depression as the ultimate 'market failure' and await the demise of capitalist market-based economies.

From the 1930s onward, *the political pendulum in market economies swings to the left*. In an attempt to rectify the 'market failure' of unemployment, governments develop 'stabilization policies'. In a separate but parallel attempt to correct inequities, governments introduce social security, unemployment insurance and other programs to attend to the public welfare, the 'welfare state'.

And then come the 1970s, a period of stagflation (the combination of a high unemployment, a stagnant economy and inflation), and government policies become ineffectual. This is seen as a major '*government failure' and the political pendulum begins to swing to the right*, first with the election of Margaret Thatcher and Ronald Reagan. China and South-East Asia begin to introduce marketization policies, and privatization and liberalization (i.e., the freeing of markets) becomes ever more popular. Then, to the surprise of the world, the Soviet Union dissolves. By the early 21st century, some of these liberalization policies appear to have gone too far, as evidenced by the financial market meltdown of 2008.

3.3. The importance of understanding energy policies in the broader political and historical context

Why is this political, economic and historical narrative useful, even essential, for understanding energy in the 20th century? The reason is that energy policies are typically a reflection of broader political and ideological trends. If an increased government role is warranted in managing the macro-economy, why would it not be the case in specific industries, especially those that are literally the driving force in the economy?[17]

Thus, each of these periods has parallels in energy industries. Major government energy-related infrastructure programs are undertaken during the Great Depression as part of economic stabilization and job creation. Ever increasing regulation from the 1930s onward culminates in energy price controls during the 1970s. The period of stagflation is exacerbated, perhaps even triggered by the acute rise in oil prices orchestrated by OPEC in 1973.

Deregulation of energy, for example, natural gas and even electricity, follows in the 1980s and 1990s. By the early 21st century, it becomes clear that deregulation is not a cure-all. The

[14] It would be centuries before the eastward and westward ocean routes to Asia from Europe would be dramatically shortened. The 200 km Suez Canal opened in 1869 and the 80 km Panama Canal in 1914. But these were short compared to the Grand Canal, a series of linked waterways extending 1700 km from the Beijing area to near Shanghai during the Sui Dynasty, circa 600 CE.

[15] Victor Hugo (1862), Les Misérables, Volume III, Book VIII, Chapter V.

[16] The central character in Les Misérables is imprisoned for stealing a loaf of bread. He steals the bread to feed his sister's children during hard economic times. He is imprisoned and then pursued relentlessly by Police Inspector Javert, who is the symbol of authority, and who officiously upholds laws that he believes are just. Is Jean Valjean "unfortunate" and therefore deserving of help from us, or is he "infamous" and therefore should be punished?

[17] This comovement (econometricians would say correlation or even cointegration) of policies across strata of decision-makers occurs for complex reasons, some of which relate to political marketability of ideas that can be reduced to simple terms. This, economists argue, is due to the limitations on rationality of human, so-called 'bounded rationality'. See, in particular, Simon [9].

Enron collapse is sizeable, but tiny in comparison to the financial precipice that the world stands before in 2008.[18]

More importantly, oil, the energy lifeblood of the 20th century, shapes events, domestic and foreign policies, and even military strategies. The Japanese attack on Pearl Harbor was part of a larger strategy to secure oil supplies in Indonesia (Japan has little in the way of hydrocarbons, hence its later reliance on nuclear energy). Stalin's defence of Stalingrad ensured that Hitler did not reach the oil-fields of the Caucasus. (Europe has much coal, but little oil.) These global paroxysms and convulsions during the most acute attacks of fascism are also a very major theme of the 20th century. But even these are at times motivated by an avowed desire to fight central planning and communism. Such was the case in Germany, Italy and Spain.

Once the Cold War begins, arguably the third world war of the 20th century, there is constant strategic tension between the two protagonists – the U.S.A and the U.S.S.R – a goodly portion of which is focused on oil and the Middle East. The Soviet Union, a major oil exporter, benefits considerably from the OPEC driven price increases in the 1970s. But by the 1980s, oil prices fall, reducing revenue flows to the Soviet government and, some have argued, contributing to its ultimate dissolution.[19]

3.4. *The principle of subsidiarity*

How does one who is not an expert in economics, political theory and government begin thinking in a sensible way about the proper role of government in energy? As a departure point, consider the principle of subsidiarity: Decisions should be taken and tasks should be performed at the lowest level at which they can competently be decided and completed. The government should undertake responsibilities only if individuals or groups of individuals cannot fulfill them competently on their own.[20]

There is great room for debate on the meaning and precision of this statement, but the general thrust favors decentralization which promotes a variety of approaches to problem solving and hence innovation. It also suggests citizens should, as far as possible, take responsibility for themselves, lest their ability to do so in a 'nanny state' decline over time.[21] Centralization of control and decision-making concentrates power, which may require checks and balances to ensure that it is not abused. Unnecessary centralization can also lead to inefficient resource allocation.

The principle may be used to justify markets and to think rationally about regulatory boundaries. It is useful in delineating boundaries between local, provincial and federal government responsibilities. (Why is defense a federal responsibility while garbage collection is at the municipal level?) In a different variant, it is a cornerstone of Maastricht Treaty which establishes the European Union – there, the principle limits infringement of national sovereignty.

On the heels of the 'government failures' of the 1970s and the ensuing movement toward deregulation, a succinct dictum which echoed this principle was articulated as "Competition where possible, regulation where necessary." This slogan is repeated in many settings, but particularly during deregulation of various industries in the United Kingdom.

As a current application, consider alternative approaches to decarbonization policy. Carbon taxes and cap-and-trade approaches seek to restrict the production of carbon, but leave the choice of technology to individuals, firms and markets. For example, an electricity company seeking to reduce its cost of carbon might switch from coal to natural gas, hydraulic, wind or solar generation. This represents a relatively decentralized approach. Feed-in-tariff programs, as implemented to date, have typically required the government, through the regulator, to select the technologies it prefers, and to set prices and contractual terms for the electricity generated therefrom. This approach is more centralized. Are governments better qualified to place bets on technologies than firms? The principle of subsidiarity would suggest otherwise. Feed-in-tariffs *may* be justified if a more decentralized approach is politically infeasible, administratively too costly, or if there is some other market failure that cannot be readily overcome.[22]

3.5. *Necessity is the mother of invention*

Today's energy challenges require innovations if they are to be met successfully. Economists study the role of incentives and institutional arrangements in promoting innovation.[23] Material rewards, allocated through decentralized and competitive market mechanisms provide powerful incentives so long as the benefits can be captured by those that are investing in innovation.

But the motives for innovation can reach beyond material rewards. Sadi Carnot, often described as the father of thermodynamics, died of cholera at the age of 36, seventeen years after Napoleon's final defeat. His belongings, including most of his papers were burned. But his work on the Carnot Engine, which provided a theory of the maximal efficiency of heat engines, survived. Carnot's research was motivated by his disappointment in Napoleon's defeat and by the belief that the British prevailed in part because of their more efficient use of energy.[24]

Some of the most dramatic, even fearsome, energy-related innovations have been driven by the need to prevail in conflict. The Manhattan Project, which resulted in the development of atomic weapons, comprises a particularly salient example.

4. Searching for clues, making connections

The interdisciplinary nature of energy studies implies rich networks of connections between the many related disciplines. Whatever the *resident* discipline of a student or researcher interested in energy, connections to other disciplines may readily be found. For example, the archeologist might ask: Could the Iron Age have preceded the Bronze Age? To which the metallurgist might provisionally respond: The ability to sustain high temperatures is essential to the smelting process. The components of bronze (copper and tin) have lower melting points than iron and so the Bronze Age logically precedes the Iron Age.

This paper hopes to beckon to non-economists from the perspective of economics. The objective of this section, therefore, is to provide a few examples of connections to the *economics* of energy from other disciplines. Some are obvious, others less so.

---

[18] Both California and Ontario, Canada took unsuccessful forays into deregulated electricity markets.

[19] The history of oil and its transformation from a commodity to a strategic resource that shapes national security planning throughout the 20th century may be found in the works of Daniel Yergin. See, in particular Yergin [10,11].

[20] Goldthau [12], also in this issue, discusses ideas closely related to the principle of subsidiarity.

[21] In a completely different setting, 'helicopter parents' are criticized for micromanaging their children's lives, thus thwarting normal development.

[22] See, for example, Green and Yatchew [13].

[23] Industries that effectively promote innovation are said to be 'dynamically efficient'.

[24] In 1815, the United Kingdom was producing more than 20 times as much coal as France. See Daemen [4], Table I.

4.1. Globalization foiled

Consider the Bernoulli Principle in fluid dynamics which explains the *foil* – a structure whose shape allows a fluid to pass at different rates across its two main surfaces. Perhaps the most transformative *foil* in history is the triangular or lateen sail (in this case, the 'fluid' is air, hence a sail is an airfoil).

During Roman times it took about a week to sail from Sicily to Alexandria. The return trip, against the prevailing winds, would take a month or more. The foil, invented sometime during the first millennium, permitted the harnessing of wind energy, even when sailing *against* the wind, thus enabling much more efficient and controlled sea travel over ever longer distances. It was used by Arab traders in the Indian Ocean, leaving a lasting legacy of Islam along Africa's east coast.

Globalization is a 20th century word (according to the Oxford Economic Dictionary). But the first 'globalization', which saw rapid expansion of global trade and the ascendency of global empires began in the late 1400s, was, in no small measure, due to the art of sailing. European powers expanded their domains across the oceans of the world, and trade patterns changed dramatically as empires grew, redefining the course of history. The underlying principle of fluid dynamics was articulated by Daniel Bernoulli in 1738, but by that time the European 'age of discovery', which was so dependent on sailing ships, was well underway.

In the 20th century, the foil enabled powered flight, furthering globalization. In this case, wings constitute yet another airfoil, and engines provide airflow. Hydrofoils exploit the same principle to elevate boat hulls out of the water, thus dramatically reducing drag and increasing efficiency.[25] Even wind turbines exploit the principle to increase the quantity of electricity that is generated.

Thus, the reach of this big idea – the foil – extends into many corners of the humanities and social sciences. Understanding that a simple engineering principle, arrived at by accident, affected trade, the migration of peoples and ultimately the influence and reach of civilizations is not only of academic interest, it alerts us to the complexity and unpredictability of impacts of forthcoming energy innovations.

4.2. Rembrandt and Peat, Conrad and Bicycles

Motivating, inspiring and deepening one's understanding of energy can be aided by the arts and literature. Art and artifacts residing in galleries and museums provides a vast historic reservoir of knowledge about the origins and uses of energy and related inventions. For example, questions such as who was the first to develop the lateen sail have been informed by ancient artifacts depicting triangular sails. Searching for such connections between art and energy can be a most enriching museum pastime.

Envision for the moment the extraordinary art of the Dutch Golden Age, exemplified by Rembrandt, Vermeer and many landscape painters. The great wealth that supported this great art was based on an economy engaged in world trade through a world class sailing fleet, an extensive domestic canal-based transportation system (canals were often depicted in Dutch landscape paintings) and the availability of fuel in the form of peat (a precursor to coal). Indeed canals were often constructed to facilitate the transportation of peat. But, peat has a much lower energy density than coal, and so the energy base of the 17th century Dutch economy was soon surpassed by England's coal-based economy.

There are numerous examples in literature depicting the human consequences of technical progress, some of which are crucially dependent on energy-related innovations. Joseph Conrad's *Heart of Darkness* and Mark Twain's *King Leopold's Soliloquy* excoriate the exploitation of Africa in the 19th century. But how many are aware that the horrors of the Belgian Congo were in major part a result of the economics of rubber markets? The invention of the modern bicycle had led to a 'rubber boom'.

There are also examples in film which relate to the subject matter of energy. Godzilla was spawned by the atomic bombings of Hiroshima and Nagasaki in a nation that eventually chose atomic energy, despite its history. The Battle for Iwo Jima, symbolized by the iconic statue, has been memorialized in numerous books and films, yet few are aware that this military objective was crucially linked to the delivery of the Hiroshima and Nagasaki bombs. The China Syndrome, a 1978 Hollywood movie about a nuclear meltdown, eerily preceded the 'Three Mile Island' incident by a scant few weeks.

Contemporary art sometimes serves to document energy use and its human and environmental impacts. For example, Ed Burtynsky's work focuses on how nature has been transformed through industry. His photographic exhibitions and books, most notably *Manufactured Landscapes*, *Oil* and most recently *Water*, provide a remarkable visual record of human impacts.[26]

4.3. Energy qua history

Historians eschew mono-causal theories of history. Still, energy has profoundly shaped human history, civilization and its institutions. In the rich tapestry of history, energy threads are found everywhere. Empires, from ancient times to the present, have been fundamentally shaped by their access to, and use of energy. The historical evolution of energy and energy related innovations have deeply affected technological and civilizational progress.

The Promethean revolution initiated human control over chemical energy. The wheel provided for more efficient use of human and animal energy, and eventually chemical energy. The agricultural revolution led to more efficient caloric production allowing higher population density and 'civilization' itself (in the sense of living in cities). The bronze and iron ages were propelled by ever higher smelting temperatures.

The expanding use of coal led directly to the invention of steam engines and the industrial revolution. The oil age, the internal combustion engine and the age of electricity accelerated productivity growth and living standards in industrializing countries. Alongside these epochs, the extraordinary histories of solar, water and water energy are woven throughout. Viewing history from the perspective of energy – *energy qua history*, as it were – provides a remarkably far-reaching account.[27]

4.4. The hydrocarbon economy

The theoretical and applied sciences are fundamental to the understanding of energy. The elegance, precision and concision of science allow one to express and link complex phenomena, often in simple ways.

---

[25] Today's fastest sailing vessels combine foils in multiple ways – a traditional sail, a rigid sail which effectively acts like a wing mounted vertically, and a hydrofoil which raises the hull entirely out of the water. See, for example, http://www.nytimes.com/newsgraphics/2013/09/07/americas-cup-boat/, "America's Cup: Racing Above the Water" *New York Times*, September 7, 2013.

[26] See http://www.edwardburtynsky.com/ and Mitchell and Rees [14].

[27] Vaclav Smil's many contributions explore this theme extensively. See for example, Smil [15]. In this issue, Jones and Hirsh [16] discuss how historical insights can inform our understanding of contemporary energy issues.

To illustrate the unifying elegance of science, consider our current energy epoch – the hydrocarbon era. About 80% of the energy produced worldwide comes from hydrocarbons which are molecules consisting of carbon C, and hydrogen H. More formally, hydrocarbons are molecules of the form C_xH_y where 'x' and 'y' are numbers. Small values generally correspond to gases (e.g., methane CH_4, propane, pentane), larger values to liquids (e.g., various components of crude oil such as octane, kerosene, diesel and bitumen) and very large values to solids such as coal, though these may also contain small quantities of oxygen, nitrogen and sulphur.

Past – biomass combustion:

$C_xH_yO_z + \text{oxygen} \rightarrow \text{carbondioxide} + \text{water} + \text{energy}$

Present – hydrocarbon combustion:

$C_xH_y + \text{oxygen} \rightarrow \text{carbondioxide} + \text{water} + \text{energy}$

Possible future – hydrogen combustion:

$H_2 + \text{oxygen} \rightarrow \text{water} + \text{energy}$

Now, consider three epochs in human history: the age of biomass when wood was a primary energy source, the age of hydrocarbons in which we presently live, and a future possible world where hydrogen provides much of our energy. Science provides an elegant representation of these three periods.

The quantity of energy available from biomass combustion (the first equation, where biomass molecules also contain oxygen) is generally much lower than that available from hydrocarbon combustion (the second equation). This idea is fundamental to the industrial revolution, with all its technological, social, political and economic ramifications.

Unfortunately, hydrocarbon combustion produces carbon dioxide, the main culprit in global warming. Widespread use of hydrogen as a fuel (the third equation) would alleviate this problem, but the economics of hydrogen production preclude large-scale deployment given present-day technology.[28],[29]

Thus, the simple but scientific representation of combustion elegantly summarizes not only whence we have come, and our main source of energy today (hydrocarbons), but at the same time points at our common challenge – global warming driven by ever increasing CO_2 production.

4.5. Energy efficiency and the second law of thermodynamics

'Big ideas' in science often have prominent counterparts in economic or public policy. Consider, for example, the Second Law of Thermodynamics which states that an isolated system will tend to a state of maximum entropy. (Is this sufficiently intimidating to the non-scientist?) And yet policy-makers and politicians lay multi-billion dollar programs at the feet of the second law when they speak of 'energy efficiency'.

A variant of the law states that whenever energy is transformed from one form to another, some of it is dissipated (this is entropy at work). A key objective of efficiency is to reduce the amount being dissipated. For example, a typical car engine transforms the chemical energy in gasoline into mechanical energy at an efficiency of less than 25%, the remaining portion is lost in the form of heat. Incandescent light-bulbs have an efficiency of about 3%, while the highly touted compact fluorescents raise that figure to 12%[30] – we have a long way to go. On the other hand, natural gas furnaces can operate at an efficiency of 95% because the energy that is being created – heat – is exactly what is required. No further transformation is necessary.

5. Concluding comments

This paper advocates a 'big ideas' framework for promoting an interdisciplinary approach to energy. No individual can be an expert in all areas of the sciences, social sciences and humanities relevant to energy issues. But the inquiring and persevering mind can gain a much broader perspective by apprehending big energy ideas from other disciplines.

For the economics of energy, a basic understanding of the efficacy and efficiency of markets is the departure point. The next important step is to understand the limitations of markets, what economists call 'market failures'. It is the tension between these two that underlies many ongoing policy debates. We also suggest that it is this tension that underlies the fundamental ideological drama of the 20th century – markets vs. central planning.

An appreciation of sweeping political trends is central to understanding energy policies, the latter often being an articulation or instantiation of the former. During the 20th century, energy policies were to a great degree influenced by the political movement between the proverbial left and right, as well as a global Cold War competition for political space and for resources. As the political pendulum swung to the left from the 1930s to the 1970s, energy industries became ever more regulated. Following the 'government failures' of the 1970s, the political pendulum began to swing to the right and deregulation of energy industries followed.

An understanding of the big ideas in the science of energy cannot be circumvented by energy researchers in the social sciences or humanities. Science is too powerful, too fundamental and too elegant. As illustrations of big energy ideas in science we draw upon hydrocarbon combustion, the second law of thermodynamics and the foil.

What features might one expect a 'big idea' to have? First, it should illuminate – the foil (or the Bernoulli Principle) explains sailing to windward. Second, it should connect apparently unrelated phenomena – the foil connects sailing to flying. Third, it should unify – the Bernoulli Principle provides a common abstract framework for analysing an expanded range of phenomena and is capable of application to new ones. Fourth, in the context of interdisciplinary analysis, a big idea should reach beyond its native territory, perhaps far beyond. In that vein, interdisciplinary journals such as this one become far more than simple depositories for work that fails to fit within a single discipline. They become an instrumental part of the process of finding these next few big ideas.

References

[1] MIT. The future of natural gas; 2011. http://web.mit.edu/mitei/research/studies/naturalgas.html
[2] Pigou AC. The economics of welfare. New York: Macmillan; 1920.
[3] Coase R. The problem of social cost. J Law Econ 1960;3:1–44.
[4] Daemen J, History of coal industry In: Cleveland C, editor. Encyclopedia of energy. New York: Elsevier; 2004.
[5] Dahl C. International energy markets. Tulsa: PennWell; 2004.
[6] Bhattacharyya S. Energy economics. New York: Springer; 2011.

[28] The third equation also reveals why the element hydrogen has embedded in it the Greek word for water (hydros) – 18th century chemists discovered that this substance, when burned, generated water, and named it correspondingly.

[29] Einstein's iconic equation $E = mc^2$ powers an alternative future where the world relies to a large degree on nuclear energy. The practical force of this equation is that even a tiny quantity of matter m, yields an enormous amount of energy E, since c is the velocity of light, a large number that becomes much larger when squared. There was a time when nuclear energy was heralded as being too cheap to meter.

[30] For this reason, a 13 W compact fluorescent package will sometimes explicitly indicate the equivalence to a 60 W incandescent bulb – roughly a factor of four.

[7] Sovacool BK. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. Energy Res Soc Sci 2014;1:1–29.
[8] Hodbod J, Adger N. Social-ecological resilience in energy systems. Energy Res Soc Sci 2014;1(1).
[9] Simon H. Reason in human affairs. Redwood City: Stanford University Press; 1983.
[10] Yergin D. The prize. New York: Free Press; 1991.
[11] Yergin D. The quest. New York: Penguin; 2011.
[12] Goldthau A. Rethinking the governance of energy infrastructure: scale, decentralization and polycentrism. Energy Res Soc Sci 2014; 1(1).
[13] Green R, Yatchew A. Support schemes for renewable energy: an economic analysis. Econ Energy Environ Policy 2012;1:83–98.
[14] Mitchell M, Rees W. Edward Burtynsky: oil. Gottingen, Germany: Steidl; 2011.
[15] Smil V. Energy in world history. Boulder, USA: Westview Press; 1992.
[16] Jones CF, Hirsh RF. History's contributions to energy research and policy. Energy Res Soc Sci 2014;1(1).