ELEVEN

THE ECONOMICS OF INFORMATION IN A POST-CARBON ECONOMY

Joshua Farley and Ida Kubiszewski

> *The challenges we face are immense, and information will play a critical role in building a post-carbon economy—but today's markets are not equipped to produce the information we need to survive.*

Economics is frequently defined as the allocation of scarce resources among competing desirable ends. Most economists focus on markets as the ideal allocative mechanism. One critical resource required for any economic activity, from gathering edible plants to genetically engineering them, is information, or knowledge. As a result of the exponential increase in new technologies and knowledge, we now live in what is commonly called the information age. Another critical resource is energy, an essential input into any economic activity. Explosive advances in knowledge during the eighteenth century allowed human society to shift from the finite flow of current solar energy, available at a fixed rate over time, to the finite stock of fossil energy, which can be used virtually as fast as we like. We have become so dependent on fossil fuels that we could not feed ourselves without them—we currently use an estimated seven to ten calories of hydrocarbons to produce, process, transport, and prepare each calorie of food we consume (Pimentel & Pimentel, 2008). Access to such concentrated energy allowed humans to increase the rate of extraction of raw materials from nature and in waste emissions back into nature, with all the harm to ecosystems and human well-being inherent to both activities. The market economy emerged simultaneously with the fossil fuel economy. Though most economists attribute the explosive economic growth of the past two centuries to the magic of the market, it would have been impossible without the magic of fossil fuels.

Fossil fuel stocks are finite. Discoveries peaked during the 1960s then declined precipitously during subsequent years. In spite of amazing advances in technology, conventional oil production peaked around 2006 (International Energy Agency [IEA], 2010). We have likely used half the planet's finite supply already, and remaining oil is less accessible, of lower quality, and requires more energy to extract, offering a lower energy return on energy invested (Campbell & Laherrere, 1998). Even if fossil fuels were infinite, we have exceeded the planet's capacity to absorb their waste products, threatening catastrophic destabilization of the global climate. Whether due to source or sink constraints, if human society is to thrive, it must shake its dependence on fossil fuels and undo the damage it has caused.

Information will play a central role in this transition. Addressing climate change and peak oil will require major advances in low-carbon energy technologies. Creating sustainable food systems will require technologies that increase agricultural yields while reducing ecological impacts and dependence on fossil fuels. Addressing natural resource depletion and environmental degradation will also require new green technologies.

Given the central and growing importance of information in our economy, it is critical that we assess what types of economic institutions are most effective at allocating resources toward the production of appropriate information and that information among different users. Economists recognize that information has the unique characteristic that it improves through use. Information is therefore not a scarce resource in an economic sense, and we cannot assume that markets efficiently create and allocate new information. There has nonetheless been a tremendous global effort in recent decades to force information increasingly into the market economy, strengthening patent protection across international borders, lengthening patent and copyright duration, and extending intellectual property rights to ever more types of information (Boyle, 2003; Jaffe, 2000).

The goal of this chapter is to assess the effectiveness of market forces for producing the most potentially valuable information at the lowest costs, for maximizing its value among users, and to compare markets with alternative economic institutions. To achieve this, the chapter

- identifies appropriate criteria for assessing different economic institutions for the production and dissemination of information;
- analyzes the unique physical characteristics of information and the most pressing problems confronting human society that require new information and technologies in order to be solved;
- assesses the effectiveness of markets in producing the most desirable information, and in minimizing the costs of production;
- assesses the effectiveness of markets in allocating information among potential users; and
- explores alternative mechanisms for producing appropriate types of information at minimum cost that maximize its value after production.

Assessment Criteria: The Desirable Ends

Implicit in the definition of economics are the criteria for assessing economic institutions: How effectively does a given institution achieve some particular set of desirable ends? Economists have conventionally defined the desirable ends of economic activity as utility maximization, where utility is a measure of relative satisfaction, or "the greatest happiness," for the greatest number of people (Bentham, 1907; Mill, 1871). Conventional economists typically assume that consumption provides utility and what we pay for the goods we consume is an objective measure of the utility they provide. They also claim that we cannot meaningfully compare utility between people, and therefore our goal should be to maximize total monetary value in the economy.

Under certain rigid assumptions, markets achieve this goal. Markets use the price mechanism to decide how to allocate resources among different products and how to allocate those products among different users. The basic mechanism can be split into two parts: the allocative function of prices and the rationing function We can think of the allocative function as how raw materials are apportioned among different products. Many different firms are competing for raw material inputs into production, such as oil and steel, and whoever is willing to pay the most wins the resource. If I am able to convert the resource into a product of higher value than my competitor, I can afford to pay more than my competitor. This ensures that resources are allocated toward the highest-value products. The rationing function of price awards products to whichever consumer is willing to pay the most for them. This ensures that those products go to whoever values them the most in monetary terms. Markets therefore maximize monetary value on both the production and consumption sides. When economists state that markets are efficient, they mean that markets maximize monetary value. If maximizing monetary value is our goal, then markets would appear to be an excellent economic institution (Farley, 2008).

However, the "greatest number of people" should include future generations, in which case ensuring sustainability takes precedence over maximizing current monetary value. Future generations cannot participate in today's markets, and market values do not reflect their preferences. To ensure sustainability, we must not deplete renewable resources faster than they can reproduce, cannot deplete essential nonrenewable resources such as oil faster than we can develop renewable substitutes, and cannot emit waste into the environment faster than it can be absorbed (Daly, 1990). Our efforts to maximize monetary value for the current generation come at the cost of sustainability.

But even if we ensure sustainability, it is not at all clear that monetary value is what we want to maximize. Monetary value is determined by preferences weighted by purchasing power. Someone who is destitute and starving does not value food, someone who is destitute and ill does not value health care. The conventional economist's assumption that we cannot compare utility between individuals is unrealistic: a good meal obviously provides more utility to a starving person than to an overfed one by almost any metric besides that of monetary value.

This chapter will take the position that the desirable ends of economic activity must include the satisfaction of basic biological necessities for growing populations now and in the future. Concern for future generations means that we must ensure sustainability. The most serious threats to basic needs and sustainability include global climate change, peak oil, natural resource depletion, food security, biodiversity loss, and global pandemics, among others. Information must play an important role in solving any of these problems. Given the severity and urgency of these threats, we must ensure that our economic institutions are well suited for producing the required knowledge and disseminating it as effectively as possible.

The Nature of the Resource: Characteristics of Information Relevant to Its Allocation

Economics typically focuses on scarce resources. If I burn a barrel of oil, that oil is no longer available for you to burn; if ecosystems sequester the CO_2 I spew into the atmosphere, they have less ability to sequester yours. Because my use leaves less for you to use, we must compete for access to the resources. Economists use the terms "rival" or "subtractive" to describe such resources: use by one person leaves less for others. If society fails to ration access to scarce rival resources, anyone who wants them can use them. The likely result is unsustainable overuse or underprovision, unjust distribution, and inefficient allocation toward activities that do not generate the greatest monetary value or toward people who do not value them the most.

However, information is a nonrival resource: one person's use of information has no impact on the amount of information left for others to use. More accurately, information is actually an additive resource that improves through use (Kubiszewski, Farley, & Costanza, 2010), and this additive nature of information is what led to the rapid development of technologies and civilizations. If we look back over time, the rate of technological progress was exceptionally slow for the first two hundred thousand years or so of human existence—small bands of hunter-gatherers roamed the countryside looking for food, and technological advances were separated by millennia. The invention of agriculture, however, allowed denser populations and the more rapid circulation of ideas, which improved through use. Written language emerged, allowing ideas to be stored and transmitted more easily. As the rate of flow of information increased, so did the rate of technological change. Mercantilism and industrialization led to more rapid communication of ideas between cities and across cultures, contributing to an even more rapid rate of increase in knowledge (Diamond, 1997). For example, when Genghis Khan conquered most of Asia, the Middle East, and Eastern Europe, he adopted new technologies and spread them across his empire. Equally important, he opened up and protected trade routes, allowing people and ideas to continue to spread. As ideas spread, new users found ways to improve them. The spread of information through Genghis's conquest may have ultimately paved the way for the European Renaissance and the Industrial Revolution to which it led. Genghis Khan could be considered the father of the modern age (Weatherford, 2004).

Many low-carbon alternatives to fossil fuels are effectively nonrival. For example, no matter how many photons we capture for solar energy in North

America, it will have no impact on the number available in the rest of the world. If we freely share technologies for capturing solar energy with other countries, those countries are likely to burn less fossil fuel, improving everyone's quality of life. The more scientists and industries experiment with these new technologies, the faster they are likely to improve.

As many people in the commons movement point out, information is like grass that grows longer and more nutritious the more it is grazed upon, so everyone should be free to graze on it as much as possible. In reality, however, an increasing amount of information is patented or copyrighted. People are not allowed to use it unless they pay. The World Trade Organization's Agreement on Trade-Related Aspects of Intellectual Property Rights was the greatest expansion of intellectual property rights in history (Tansey, 2002). In spite of this expansion in intellectual property rights, neither patents nor copyrights can make access to information completely excludable, so that even those who do not pay may benefit. The result is that the private sector is likely to invest less in research and development (R&D) than is socially optimal (Arrow, 1962). Accumulating evidence suggests that restricting access to information has slowed the rate of growth of knowledge (Heller & Eisenberg, 1998; Paul, 2005; Runge & Defrancesco, 2006).

Why Price Information? The Logic of the Market

Competent economists recognize that the price mechanism only maximizes monetary value for resources that are competitive in use, also known as rival or subtractive resources. The rationing of nonrival resources creates artificial scarcity and actually reduces the economic value of the resource.

Paradoxically, the value of existing nonrival resources is maximized at a price of zero. This is readily evident from an example. If someone develops an inexpensive, safe, and carbon-free substitute for fossil fuels, the more people that adopt this technology, the better off society is. Placing a high price on the technology (that is, the information required to produce it) would reduce adoption and increase the probability and severity of climate change. In more technical terms, net benefits to society increase whenever the marginal social benefits (i.e., the benefit from one additional "unit") of an activity exceed the marginal social costs. The marginal cost to society of disseminating information is nearly zero. Individuals continue consuming resources as long as the marginal benefits they receive are greater than the price, and if forced to pay for access to information or other nonrival resources, they will stop consuming them long before their marginal benefit falls to zero. In economists' terms, this creates a dead-weight loss of economic surplus—a loss of value. The price mechanism fails to maximize value for nonrival resources.

Prices also pose problems for the creation of new knowledge. If we accept the conventional economist's notion of value, then the marginal value (for instance, the value of an additional unit) of a rival resource is determined by the greatest amount any single individual is willing to pay for it. If this exceeds the cost of producing an additional unit, profit is possible, or at least a fair return on the labour and resources used in production. However, the marginal value of a nonrival resource is given by summing the marginal benefits across all users (Samuelson, 1954). The sum of marginal benefits to all users of the clean-energy technology described above may far exceed the R&D costs at a price of zero. However, as soon as the producer charges for use, the number of users and hence total value of the technology decreases. Again, the value to society is maximized at a price of zero, but at such a price there is no market incentive to produce new information.

Patents and copyrights are an effort to solve this paradox. Intellectual property rights, in essence, give a state-protected monopoly to information for a limited time. According to article 1, section 8, of the United States Constitution, their purpose is "To promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." When the patent expires, the price of information reverts to zero, maximizing the value of the invention. The belief, albeit far from unanimous, was that positive incentives for innovation overwhelmed the negative impacts of monopoly.

Both patents and copyrights initially lasted fourteen years, and were national, not international. Fourteen years of monopoly profits were considered adequate incentive for the private sector to develop new ideas. When such patent laws were first put in place, technology moved slowly, and inventions might have had a useful life of many decades. Governments were often much smaller, with fewer resources to invest in publicly sponsored R&D. In such a context, intellectual property rights were perhaps a good idea, though even this is subject to debate (Arrow, 1962; Boyle, 2003; Jaffe, 2000).

However, under the aegis of the World Trade Organization (WTO), patents are now international, and last twenty years. Copyrights in the United States have been extended to seventy years beyond the death of the author or to ninety-five years for anonymous works or those produced for others (e.g., corporations). The cost and ease of transmitting information around the world has plunged to almost zero, making information increasingly nonrival and nonexcludable, more of a pure public good. The contribution of information to value-added has also increased. Society has responded by trying to strengthen intellectual property rights to maintain the incentives for innovation (Boyle, 2003) at considerable cost. At the same time, the rate of change of technology has increased exponentially, and new technologies frequently have a useful lifespan shorter than the patent or copyright that protects them. In essence, governments now spend considerable money protecting monopolies for the useful life of a product or idea, even as costs of dissemination approach zero.

In the presence of such dramatic changes, we must assess whether or not the market price mechanism is an effective institution for allocating resources toward the production of knowledge that is the most valuable to society, then allocating that knowledge among users in a way that maximizes its value once it has been produced.

The Production Side

There are two separate questions relevant to the production of information. First, what types of economic institutions will produce the information that provides the greatest net benefits to society? Second, for any type of information society does produce, what economic institutions will generate it at the lowest total cost?

Do Markets Produce the Most Desirable Information?

The first question asks whether or not market forces allocate scarce resources (scientists, laboratories, etc.) toward the production of knowledge that helps people satisfy basic biological needs and promote sustainability (i.e., maintain the conditions to satisfy basic biological needs for future generations). Markets systematically allocate resources toward whatever knowledge maximizes monetary value and generates the most profit. This presents three basic problems.

First, people unable to satisfy their basic biological needs are destitute by definition and, as explained above, have negligible market demand. It is far more profitable to provide luxuries for the rich than necessities for the poor, and this fact determines what type of information markets are likely to provide. The example of eflornithine provides a clear illustration. Scientists discovered in 1979 that eflornithine kills trypanosomes, the parasites responsible for African sleeping sickness. The only other treatment for second-stage sleeping sickness is arsenic-based, extremely painful to administer, not very effective, and sometimes lethal. Nonetheless, poor Africans could not afford to pay for the new drug, so very little was produced for that purpose. However, it turned out that eflornithine also removes unwanted facial hair in women, which is a very lucrative market (Gombe, 2003). In pursuit of profit, the allocative function of price apportions few resources toward developing cures for lethal diseases that afflict the poor (Trouiller et al., 2002) but billions toward cosmetics. Although most people would presumably think saving lives is a more valuable use of resources than developing cosmetics, market demand is a function of preferences weighted by wealth and income. Markets allocate resources toward those who have money and unmet wants, not toward those who have unmet needs. Markets provide few incentives to create technologies that help the poor meet basic biological needs.

Second, markets will only allocate resources toward knowledge that protects or provides goods and services that can be bought and sold on the market. A stable climate, the ozone layer, the ecological resilience provided by biodiversity, and a host of other ecosystem services are essential to human survival, yet cannot be privately owned (in economic jargon, such resources are nonexcludable). Property rights are a prerequisite for conventional markets to function. Technologies that convert ecosystem structure into economic products, inevitably generating waste in the process, are therefore likely to be far more profitable than technologies that conserve or restore ecosystems to provide critical ecosystem services. Markets provide few incentives to create technologies that promote sustainability.

Markets in information also influence academic research, as obstacles exist in gaining access to patented information, including research tools. A survey by the American Association for the Advancement of Science (AAAS) found that 35 per cent of academics in the biosciences, for example, reported difficulty in acquiring patented information necessary for their research. Among all scientists reporting such difficulties, 50 per cent had to change the focus of their research, and 28 per cent had to abandon it all together (Hanson, Brewster, & Asher, 2005). In AAAS surveys in the United States, Germany, and Japan, over 40 per cent of scientists agreed that, “Obtaining access to technologies owned by others often involves contractual restrictions on publications that cause significant constraint[s] on academic freedom” (as cited in Lei, Juneja, & Wright, 2009, p. 38).

Most people presumably believe that saving individual lives or promoting the survival of our species are more desirable ends than getting rid of unwanted facial hair. Markets are unlikely to develop the information required to solve some of the most serious problems faced by society. This would be less of a problem if scientists and other resources required to produce information were available in infinite quantities, but that is not the case. Every scientist hired to develop cosmetics for the rich is no longer available to develop life-saving cures for contagious diseases or technologies that protect the environment.

A third problem is that the cost of creating new information can be very high, while the cost of providing that new knowledge to another user has become negligible—little more than the cost of transmission over the Internet. The average cost of information therefore declines as more people use it. Figure 1 depicts an example of a hypothetical new technology for generating methane from sewage that simultaneously sterilizes it and converts it to a safe organic fertilizer. The costs of retrofitting existing sewage plants to use this technology are met by subsequent sales of methane and fertilizer, so the only cost to adopters is payment for the information underlying the technology. The technology will have important ecological benefits that are not priced in the market and have no impact on private sector decisions. A private sector firm estimates that the technology will cost $80 million to develop. Average cost per user declines as more users adopt the technology, as depicted in Figure 1. The firm has also estimated the demand curve for the product, also depicted in Figure 1. The demand curve is an estimate of how many sewage utilities will purchase the technology at a given price. Demand curves are determined by the marginal benefits of adoption, so the area under the curve provides a measure of total benefits to society. The total market benefits minus the total costs equal the net benefits to society.

However, firms are interested in profits, which are determined by total revenue (sales price x quantity sold) minus total costs, in this case $80 million. The problem is that to sell more products, the firm must lower prices. At some point, the falling prices outweigh the increasing sales, and total revenue falls. In economists' jargon, products with these characteristics are natural monopolies, as will be explained below.

Though developing clean energy sources is arguably one of the most important challenges for society today, as a result of the problems described above, the energy sector is one of the least innovative industries. The sector invests about 6 per cent as much, relative to capital intensity, as the manufacturing sector as a whole, with a minimal share of these investments dedicated to the needs of the poor. There are very high costs to developing new technologies and scaling them up, and when one firm bears the costs, other firms capture many of the benefits (Avato & Coony, 2008). Private sector investment in energy technology (research, development, and deployment) has fallen steadily since the 1980s, and accounts for only 0.3 per cent of sales in the United States (Coy, 2010).

In summary, the private sector directs research efforts toward market goods that satisfy the desires of the rich rather than public goods and benefits for the poor. The fact that most resources are currently allocated by market forces, along with the rule of diminishing marginal utility, suggests that allocating resources toward public goods and the poor would yield greater welfare benefits at the margin than markets. Even if we accept the goal of maximizing the net monetary benefits of production, there are circumstances in which market forces cannot profit from creating information for marketable products, though society as a whole would benefit.

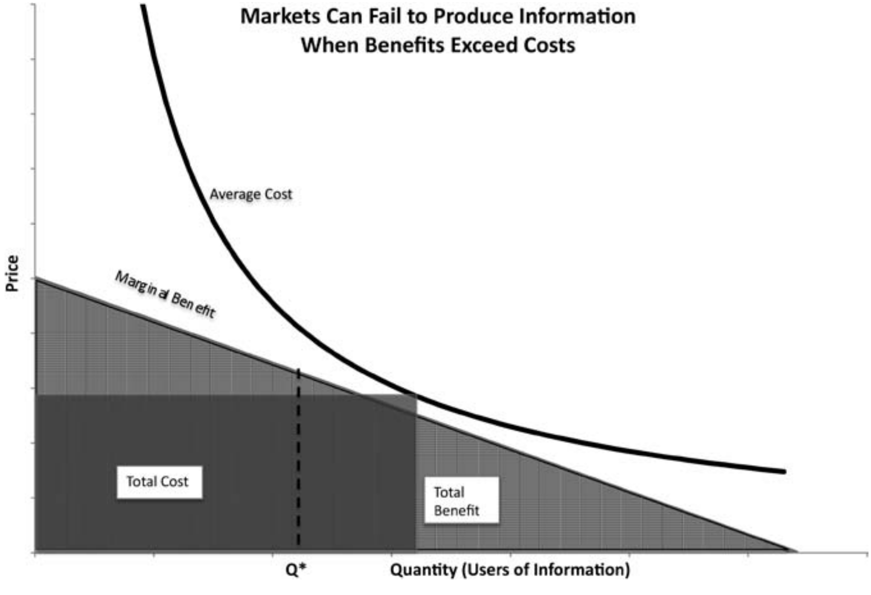

Figure 1: Information has high fixed costs and negligible marginal costs, so the average cost declines with the number of users. Total benefits, measured by the area under the demand curve, increase with number of users. However, to sell more patented information, firms have to lower the cost. As a result, there is no price at which the firm will recoup the costs of producing the information, even though for any number of users greater than Q, market benefits exceed costs. In this hypothetical illustration, the firm can never earn enough revenue (price x quantity) to cover the total costs of production (average costs x quantity), and therefore will not develop the technology. Social benefits equal total costs at Q*, and exceed them for any greater level of adoption, reaching a maximum at a price of zero. Even with patent protection, the private sector fails to create the new technology.*

Do Markets Produce Information at Lowest Cost?

Regardless of the information produced, economic efficiency demands that it be produced in the most cost-effective manner possible. The most important input into the production of information is information. Under the market paradigm, teams of scientists, typically working for corporations, compete to bring a patentable technology to market. These teams are unlikely to share information that may help competitors. This implies that considerable research is likely to be duplicated, and synergies may be lost. If several teams are taking very similar paths, when one arrives at a patentable technology first, the work of the other teams has simply been wasted. Since information improves through use, the more freely it circulates, the more likely it is to improve. For an equal level of investment, one must assume that collaborating teams of scientists freely sharing knowledge are likely to make more rapid progress than isolated competitive teams hoarding knowledge.

Considerable evidence suggests that the proliferation of patents has indeed slowed the advance of knowledge. In the medical sector, the proliferation of patents has made it much more difficult and costly to develop new drugs (Heller & Eisenberg, 1998). A survey of its members by the AAAS found that the 40 per cent of those who had acquired patented technologies for their research had difficulty doing so, and as mentioned above, many of these were forced to change or abandon their research (Hanson et al., 2005). In another recent survey of academics in the biosciences, a majority disagreed with the statement that, “Intellectual property rights on research tools provide incentives to invent more tools and/or conduct related research, and advance the research in your area,” while a majority agreed that, “Overall, the intellectual property protection of research tools is having a negative impact on research in your area” (Lei et al., 2009, p. 38). Curiously, the major research impediment was not patents per se, but rather complying with university guidelines for seeking and respecting patents.

Intellectual property rights create numerous other costs unrelated to the research itself. First are the costs of applying for patents, which can be substantial and can favour large corporations over individuals. The legal costs of enforcing patents can also be quite high for both the patent owner and the court system. Estimates suggest that over 1 per cent of patents end up in litigation (Lanjouw & Lerner, 1998), with typical cases costing $2 million or more (Margiano, 2009; Tyler, 2004). In the case of patent trolling, firms create or purchase patents they do not intend to use simply to challenge the patents of other firms, and challenged firms frequently settle out of court simply to avoid litigation costs (Magliocca, 2006). Firms also patent technologies they do not plan to use simply to keep others from using them, thus slowing innovation (Turner, 1998). All of these extraneous costs reduce the quantity of money that could otherwise be made available for research.

The Consumption Side: Do Markets Efficiently Allocate Information among Consumers?

Once information has been produced, it must be allocated among consumers in a way that maximizes its value. Patents create private property rights in information, allowing it to be bought and sold. The problem with this is that prices ration access—only those willing to pay the price are allowed to use the information. However, additional use of information imposes no additional costs. In fact, it has long been recognized that information generation has positive externalities in the form of facilitating the creation of new information, which justifies subsidies for information generation (Foxon, 2003). Furthermore, use of green technologies and cures for contagious diseases generate additional positive externalities, which means that society could increase net social benefits by subsidizing use.

The inefficiency of price rationing information is clearly illustrated through example. Under the Convention on Biological Diversity, countries essentially have property rights to their biodiversity and the genetic information it contains (United Nations Environment Program, 1992). Traditionally, countries that find new strains of contagious diseases make them available to the World Health Organization, which allows anyone to develop vaccines or cures for those diseases. Typically this means that the genetic information would be passed on to private sector corporations, which would compete to develop a vaccine. As discussed above, competition is likely to be a less effective means for developing new medicines than co-operation. Indonesia recently discovered a new strain of avian flu. In terms of allocating a successful vaccine, Indonesia realized that a private corporation would likely price the vaccine at a cost too high for most of the world's poor, including Indonesia's citizens. Indonesia therefore threatened to sell the virus to a single corporation, presumably with the requirement that any resulting vaccine be made available to Indonesia's citizens (McNeil, Jr., 2007). Rationing access to the virus would reduce the likelihood of discovering a vaccine, while rationing access to the vaccine would increase the likelihood of a pandemic.

Charging for information leads to the grossest sort of inefficiency. Returning to the example of a technology for generating methane and fertilizer from sewage, imagine that the hypothetical firm discussed above makes a breakthrough and realizes it can develop the technology for only $60 million. This shifts the average cost curve down, as shown in Figure 2 below, and makes it profitable to create, patent, and sell the technology. With the patent protecting the firm from competition, the firm can choose a profit-maximizing price and quantity. The area in the lower left shows the total costs to the firm, and the area above, its maximum possible profits. The net market benefits to society are given by the private profits plus the triangle between the profits and the demand curve. However, the triangle depicts the additional *net* market benefits to society if the technology were to be given away free of charge. In economists' terms, the failure to realize these additional benefits is a deadweight loss to society caused by patent pricing. The technology, of course, also creates methane that replaces carbon emissions from fossil fuels, organic fertilizer that replaces highly polluting chemical fertilizers, and less pollution from sewage disposal, all nonmarket benefits of immense value.

If other firms saw the large profits being made from this technology, they might decide to develop a "me-too" product. However, this would presumably cost an additional $60 million in development costs simply to replicate an existing product. In other words, the more firms that develop competing

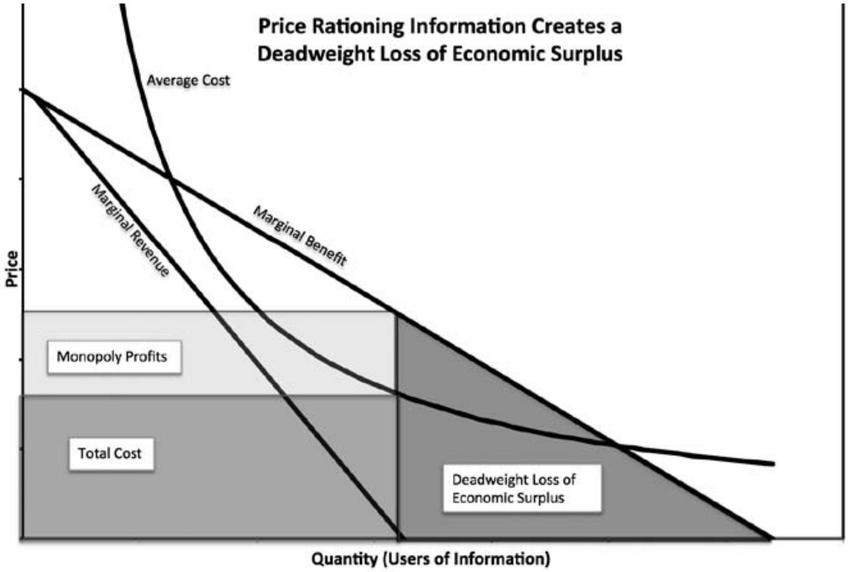

Figure 2: The private sector will develop a new technology when the monopoly profits are positive, but this generates a deadweight loss of economic surplus.

products, the greater the total costs to society, with negligible additional benefits, which is why products with high fixed costs and low marginal costs are known as natural monopolies.

Alternative Economic Institutions

Both theoretical and empirical evidence suggest that markets are unlikely to produce the most desirable types of information, fail to produce information at the lowest possible cost, and lead to suboptimal "consumption" of information. Compounding the inefficiency of these failures, both the government and private sectors waste substantial resources creating and protecting the patents essential to the market production of information. For some types of information, the benefits of market production might outweigh the costs. However, the most serious threats to today's society, ranging from global climate change to global pandemics, involve public goods. Markets inherently fail to prioritize public-good production. Rather than forcing solutions to such problems into the market model, we need a more scientific approach that adapts economic institutions to the nature of the problem. We need to foster economic institutions that reduce or eliminate these inefficiencies.

The challenge is to develop institutions that stimulate production of the technologies we need to solve our most serious societal challenges, then disseminate that information as quickly and broadly as possible. We will review a variety of existing mechanisms based on who covers research costs: the public sector, the not-for-profit sector, market forces, individual efforts, or some combination thereof.

Public-Sector Provision

As information has the characteristics of a public good, public-sector provision seems an obvious solution, especially for information required to protect and restore public goods. There is, of course, a long tradition of government-financed R&D. Organized public support for R&D in agriculture, with results freely disseminated as public goods, dates back over 150 years (Tansey, 2002), with the land grant universities in the United States as just one example. However, while the most serious problems society currently faces are increasingly public good in nature, the share of public funding for research has declined dramatically in recent decades. In the United States, federal funding for R&D has fallen from well over 60 per cent for most of the 1960s to well under 30 per cent in recent years, with the private sector making up most of the difference. Federal funding continues to account for the bulk of basic research, however, and the bulk of funding for universities (National Science Foundation, 2010).

While in theory the public sector should focus research efforts on public goods and pay less attention to potential monetary returns, it is not clear that governments are effectively allocating R&D resources toward solving society's most pressing problems. As in the private sector, government support of alternative energy R&D has fallen substantially since the 1980s. In the United States, the President's Council of Advisors on Science & Technology has recommended an increase in energy R&D funding from $6 billion to $16 billion, though an actual increase of that magnitude seems unlikely given the resistance from recently elected Republicans (Johnson, 2010). Global climate chaos could have dramatic impacts on quality of life and life expectancy, while advances in health care can at best add a few years to our lives. Nonetheless, well over half of nondefence R&D in the United States is spent on health, while investments in energy and the environment are negligible (Knezo, 2005), and in other Organisation for Economic Co-operation and Development (OECD) countries nonhealth R&D merits little more than an asterisk. Furthermore, the Bayh-Dole Act of 1980 allows private sector businesses and universities to patent publicly funded research, with the potential for seriously restricting its dissemination.

Prizes

Another possibility is prizes for innovative research, which dates at least to 1714, when the British government offered a prize for developing a method to estimate a ship's longitude. Such prizes are primarily designed to direct research toward solving specific problems. Competitors undertake much of the risk, so the prize essentially leverages private sector resources. If the winner of the prize must also place the resulting technology in the public domain, then prizes effectively turn the innovation into a public good and address the problem of dissemination (Stiglitz, 1999). However, the best-known prize is currently the XPRIZE, which allows inventors to retain full intellectual property rights to their inventions. In this case, the only advantage of the prize is to stimulate research on a specific topic.

The XPRIZE foundation has the motto, "revolution through competition," and describes itself as "an educational nonprofit organization whose mission is to create radical breakthroughs for the benefit of humanity thereby inspiring the formation of new industries, jobs and the revitalization of markets that are currently stuck" (http://www.xprize.org/). In spite of these lofty goals, it is highly questionable that the research it inspires actually addresses humanity's most pressing problems. The first prize essentially went to the development of space-based tourism. A current prize focuses on cheap and rapid sequencing of the human genome, in order to "improve help and ameliorate suffering," but such medical advances will likely be available only to the wealthy. Other prizes, such as that awarded to the 100 mpg car, may prove more beneficial, though cars are also likely to remain the privilege of the global wealthy.

Such prizes do attract considerable attention and publicity, which may be more important than the money they offer (Ledford, 2006). Prizes work "not only by identifying new levels of excellence and by encouraging specific innovations, but also by changing wider perceptions, improving the performance of communities of problem-solvers, building the skills of individuals, and mobilizing new talent or capital" (McKinsey & Co., 2009, p. 7). The America COMPETES Act, passed by Congress on December 22, 2010, authorizes all government agencies to conduct prize competitions.

In spite of some advantages of the prize approach, in particular when the resulting innovations become public goods, it still stimulates competition in research and fails to achieve the benefits of sharing information in the innovation process.

Commons-Based Peer Production

Another approach to innovation, arguably the oldest of all, is commons-based peer production, whose "central characteristic is that groups of individuals successfully collaborate on large scale projects following a diverse cluster of motivational drives and social signals" (Benkler, 2002, p. 2). By its very nature, such research is freely available to all. Commons-based peer production tends to be most successful when research equipment is quite cheap (e.g., computers), problems can be broken down into small modules of different sizes, and integration of the modules is relatively easy. The modular nature allows contributors to determine their own level of contribution and self-select for the tasks at which they excel (Benkler, 2002).

In spite of economists' assumptions about self-interested behaviour, we know empirically that individuals freely contribute enormous amounts of time to collaboratively solving problems and generating new technologies. Benkler (2004) argues that "instead of direct payment, commons-based production relies on indirect rewards: both extrinsic, enhancing reputation and developing human capital and social networks; and intrinsic, satisfying psychological needs, pleasure, and a sense of social belonging. Instead of exclusive property and contract, peer production uses legal devices like the GPL [General Public License], social norms, and technological constraints on 'antisocial' behavior" (p. 1110). Within this peer production community, monetary returns may actually have negative connotations, and can potentially decrease co-operation (Benkler, 2002). Although some computer programmers report being paid for their contributions (Todd, 2007), there is actually evidence from behavioural economics and psychology that monetary incentives can make people more selfish (Vohs, Mead, & Goode, 2006, 2008) and "crowd out" the intrinsic motivations to co-operate, which drive much of this research (Frey, 1997; Frey & Jegen, 2001). It thus appears that most contributors participate to be part of a gift economy, for the status conferred, or to make the world a better place. However, it does not really matter what the particular motivation is for an individual to participate—different individuals can participate for different reasons (Boyle, 2003).

This approach may be particularly effective for software development but should work for any problem that can be modelled on a computer. Throughout history, technological advances in stone knapping, agriculture, architecture, government, and others involved a similar approach, as did language, culture, and music. The advantage of this approach is that it does not require any changes in intellectual property rights. The problem is that some of the most important societal problems we currently face, such as alternative energy technologies, may require substantial and expensive investments in basic science, additional investments to apply the research, and a significant learning curve to achieve economies of scale.

Dissemination: Open Access and Open Source

Once information has been produced, there is still the problem of dissemination. The value of technologies that address society's most serious problems is clearly maximized when made freely available for all. When there are positive externalities to use, which is the case for any green technologies or cures for contagious disease, it may even be socially efficient to pay people to use the technology.

There are currently two dominant approaches to making information freely available: open access and open source. Open access refers to information that is freely available for all but which cannot be modified. Open source refers to information that is freely available to all and can be modified by anyone.

There are important differences between the two models. In the scientific realm, most open-access publications and the research behind them are generated by academics, and paid for with salaries or grants, which may also cover the costs of publication. Publications typically contribute to promotions and higher salaries, but nonmonetary compensation such as status and prestige provide considerable incentive. There is also a strong element of reciprocation, or "gift economies," as scientists know that they will also benefit from the contributions of others. Such payments allow researchers to devote full time to specific problems and the knowledge required to address them. However, many academics jealously guard the data underlying their research, at least until publication, which reduces the value of the data to society. Also, at the same time that open-access publications are becoming more common, so, too, are patents on research results.

Open-source information is generally produced via commons-based peer production. It can be used as is or modified, as long as it is properly cited. More importantly, it is typically protected by a General Public License (GPL) or copyleft. Though anyone can use and alter the work, all subsequent work is protected by the same licence and can never by patented or placed under conventional copyright.

One promising alternative for production and dissemination is a hybrid of the open-source and open-access approaches. One example is the Alzheimer's Disease Neuroimaging Initiative, in which a large consortium of researchers looking for biomarkers for Alzheimer's shares all its data and makes findings public immediately. No one owns the data and no one submits patent applications. Scientists on the project are paid for their research with salaries and grants, primarily from universities or the public sector, and also gain status and other nonmonetary benefits. Participants have referred to the results as "unbelievable" and "overwhelming" (Kolata, 2010, p. A1). There are other open-source initiatives in the health sciences focused on diseases of the poor, which provide little opportunity for profit in any case (Hale, Woo, & Lipton, 2005; Maurer, Rai, & Sali, 2004).

The advantage of this hybrid approach is that it allows scientists to work full-time on problems that serve the public good. We suspect that in general scientists would prefer to find cures for life-threatening diseases or improve technologies that mitigate environmental catastrophes rather than develop cosmetics for the rich.

One major obstacle with public funding, however, is pooling adequate resources. In the United States, for example, the Republicans are proposing dramatic cuts in government-supported R&D. While government-sponsored research might require an increase in taxes, it could also reduce other demands on both government and private resources. Health care provides one of the most obvious examples. Most people are not aware that even in the United States, over half of every dollar spent on health care is provided by the government (Woolhandler & Himmelstein, 2002). The skyrocketing cost of pharmaceuticals is rapidly increasing both private sector and government expenditures. If government-sponsored research on pharmaceuticals was freely shared by all, pharmaceutical costs would likely plunge, freeing up government resources to spend on research and private sector resources that could be used to pay additional taxes. The private sector can fund research through profits on patents, but those profits ultimately come from the taxpayer's pocket. Should it matter to the taxpayer whether they pay for R&D through monopoly profits or through higher taxes? Even if the government proves unwilling to dedicate as much money to R&D as the private sector, if knowledge were better directed and freely shared, presumably much less money would be required.

The big question is where such money should come from in a time of fiscal crisis? The answer is actually quite obvious—from the sectors causing the problems. On the source side, oil companies have earned record profits in recent years and, as pointed out earlier, invested very little in R&D. In economic theory, a firm deserves a fair return on labour and capital. Additional returns are from the value of the resource in the ground, which is created by nature, and are known as rent, or unearned income. Most countries enjoy sovereign rights to mineral resources and are entitled to the rent they generate. Furthermore, it is well established in theory and practice that capturing rent by charging royalties does not create any loss of economic surplus. It is also obvious that nonrenewable resources cannot be equally divided across generations. Justice and sustainability instead demand that enough of the rent generated by such resources be invested in renewable substitutes such that the resource is depleted no faster than those substitutes are developed (El Serafy, 1981). Society should also capture additional revenue on the sink side, either through carbon taxes or a cap and auction system on carbon emissions, which could be invested in other green technologies. The wealthy countries have done the most to cause the problems we face and are the most capable of contributing resources to a global, open-source, R&D program. However, any single country can begin the initiative and will still benefit by sharing results with all countries due to the public-good nature of knowledge and the benefits it provides (Beddoe et al., 2009).

Conclusion

Human society has made a dramatic transition from an environment in which ecosystem goods and services, including fossil energy, were abundant, and human-made artifacts scarce, to one where the opposite is true. Market economies proved very effective at converting energy and natural resources to human-made artifacts, but that is no longer our most pressing challenge. Economics addresses the allocation of scarce resources and must adapt to reflect these new scarcities. The challenges we face are immense and information will play a critical role in building a post-carbon economy. Although market-based allocation systems have the advantage of providing incentives for the private sector to create certain new information, they fail to correctly determine what information best promotes society's desired ends, fail to produce information at the lowest cost, and they make information artificially scarce after it has been produced.

The correct sequence for economic analysis is to decide on the desirable ends, assess the physical characteristics of the scarce resources necessary to attain them, and only then determine what economic institutions are most appropriate for allocation. If we apply this analytic sequence to the problem of developing a sustainable post-carbon economy, we see that the production of information should be based on co-operative approaches rather than competitive markets, and information once produced should be open-access, freely available to all. There are a number of economic institutions available for achieving this. Perhaps the most promising is open-source R&D, publicly funded at the global level. We should test this and various other options using a scientific approach of adaptive management in which we strive to improve upon effective institutions and discard ineffective ones. We can no longer afford to take an ideological approach in which we predetermine that markets are the most effective allocative institutions, regardless of the desirable ends and scarce resources in which we test various options.

A different allocation system is required for both the production and consumption of information. Since information is the basis of economic production, common ownership, or elimination of property rights, of information would significantly increase information transfer and produce a greater rate of innovation. It will also provide a means of allocating information toward the desirable ends of society and the common good by allowing a larger number of scientists and researchers access to the information.

References

Arrow, K. (1962). Economic welfare and the allocation of resources for invention. In R. Nelson (Ed.), *The rate and direction of inventive activity* (pp. 609–625). Princeton, NJ: Princeton University Press.

Avato, P., & Coony, J. (2008). Accelerating clean energy technology research, development, and deployment: Lessons from non-energy sectors. Washington, DC: The World Bank.

Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., … Woodward, J. (2009). Overcoming systemic roadblocks to sustainability: The evolutionary redesign of worldviews, institutions and technologies. *Proceedings of the National Academy of Sciences*, 106, 2483–2489.

Belluck, P. (2010, June 13). For forgetful, cash helps the medicine go down. *New York Times*, p. A1.

Benkler, Y. (2002). Coase's penguin, or, Linux and the nature of the firm. *Yale Law Journal*, 112(369). Retrieved from http://digitalcommons.law.yale.edu/fss_papers/3126/

Benkler, Y. (2004). Commons-based strategies and the problems of patents. *Science*, 305, 1110–1111.

Bentham, J. (1907). An introduction to the principles of morals and legislation. Oxford, UK: Clarendon Press.

Boyle, J. (2003). The second enclosure movement and the construction of the public domain. *Law and Contemporary Problems*, 66(1 & 2), 33–74.

Campbell, C. J., & Laherrere, J. H. (1998). The end of cheap oil. *Scientific American*, 278, 78.

Coy, P. (2010). The other U.S. energy crisis: Lack of R&D: R&D neglect is holding back innovative energy technologies. *Bloomberg Business Week*. Retrieved from http://www.businessweek.com/stories/2010-06-16/the-other-u-dot-s-dot-energy-crisis-lack-of-r-and-d

Daly, H. E. (1990). Towards some operational principles for sustainable development. *Ecological Economics*, 2(1), 1–6.

Diamond, J. (1997). Guns, germs and steel. New York, NY: W. W. Norton and Company, Inc.

El Serafy, S. (1981). Absorptive capacity, the demand for revenue, and the supply of petroleum. *Journal of Energy Development*, 7, 73–88.

Farley, J. (2008). The role of prices in conserving critical natural capital. *Conservation Biology*, 22, 1399–1408.

Foxon, T. J. (2003). Inducing innovation for a low-carbon future: Drivers, barriers and policies. London, UK: The Carbon Trust.

Frey, B. S. (1997). On the relationship between intrinsic and extrinsic work motivation. *International Journal of Industrial Organization*, 15, 427–439.

Frey, B. S., & Jegen, R. (2001). Motivation crowding theory. *Journal of Economic Surveys*, 15, 589–611.

Gombe, S. (2003, November). Epidemic, what epidemic? *New Internationalist*, (362). Retrieved from http://newint.org/features/2003/11/05/epidemic/

Hale, V. G., Woo, K., & Lipton, H. L. (2005). Oxymoron no more: The potential of nonprofit drug companies to deliver on the promise of medicines for the developing world. *Health Affairs*, 24, 1057–1063.

Hanson, S., Brewster, A., & Asher, J. (2005). *Intellectual property in the AAAS scientific community: A descriptive analysis of the results of a pilot survey on the effects of patenting on science*. Washington, DC: AAAS Directorate for Science and Policy Programs.

Heller, M., & Eisenberg, R. (1998). Can patents deter innovation? The anticommons in biomedical research. *Science*, 280, 698–701.

International Energy Agency. (2010). *World Energy Outlook,* 2010. Paris, France: Author.

Jaffe, A. B. (2000). The U.S. patent system in transition: Policy innovation and the innovation process. *Research Policy*, 29, 531–557.

Johnson, J. W. (2010). Panel urges jump in energy R&D. *Government and Policy Concentrates*, 88, 32.

Knezo, G. J. (2005). *Federal research and development: Budgeting and priority-setting issues,* 109*th Congress*. Washington, DC: The Library of Congress, Congressional Research Service.

Kolata, G. (2010, August 12). Sharing of data leads to progress on Alzheimer's. *New York Times*, p. A1.

Kubiszewski, I., Farley, J., & Costanza, R. (2010). The production and allocation of information as a good that is enhanced with increased use. *Ecological Economics*, 69, 1344–1354.

Lanjouw, J., & Lerner, J. (1998). The enforcement of intellectual property rights: A survey of the empirical literature. *Annales d'Economie et de Statistique*, 49, 223–246.

Ledford, H. (2006). Kudos, not cash, is the real X-factor. *Nature*, 443, 733.

Lei, Z., Juneja, R., & Wright, B. D. (2009). Patents versus patenting: Implications of intellectual property protection for biological research. *Nature Biotechnology*, 27, 36–40.

Magliocca, G. N. (2006). Blackberries and barnyards: Patent trolls and the perils of innovation. *Notre Dame Law Review*, 82, 1809–1835.

Margiano, R. (2009). *Cost and duration of patent litigation. Managing intellectual property*. New York, NY: Cohen Pontani Lieberman & Pavane LLP.

Maurer, S. M., Rai, A., & Sali, A. (2004). Finding cures for tropical diseases: Is open source an answer? *PLOS Medicine*, 1, e56.

McKinsey & Co. (2009). "And the winner is…" Capturing the promise of philanthropic prizes. Retrieved from http://www.templeton.org/who-we-are/media-room/publications/reports-by-grantees/and-the-winner-is-capturing-the-promise-of-ph

McNeil, Jr., D. G. (2007, February 7). Indonesia may sell, not give, bird flu virus to scientists. *New York Times*. Retrieved from http://www.nytimes.com/2007/02/07/world/asia/07birdflu.html

Mill, J. S. (1871). *Utilitarianism, 4th edition*. London, UK: Longmans, Green, Reader, and Dyer.

National Science Foundation. (2010, March). *National patterns of R&D resources: 2008 data update detailed statistical tables*. NSF 10-314. Retrieved from http://www.nsf.gov/statistics/natlpatterns/

Paul, A. D. (2005). Can "open science" be protected from the evolving regime of IPR protections? *Journal of Institutional and Theoretical Economics*, 160, 9–34.

Pimentel, D., & Pimentel, M. (2008). *Food, energy, and society*. Boca Raton, FL: CRC Press.

Runge, C. F., & Defrancesco, E. (2006). Exclusion, inclusion, and enclosure: Historical commons and modern intellectual property. *World Development*, 34, 1713–1727.

Samuelson, P. A. (1954). The pure theory of public expenditure. *Review of Economics and Statistics*, 36(4), 387–389.

Stiglitz, J. (1999). Knowledge as a global public good. In I. Kaul, I. Grunberg, & M. A. Stern (Eds.), *Global public goods: International cooperation in the 21st century* (pp. 308–325). New York, NY: Oxford University Press.

Tansey, G. (2002). Patenting our food future: Intellectual property rights and the global food system. *Social Policy & Administration*, 36, 575–592.

Todd, M. H. (2007). Open access and open source in chemistry. *Chemistry Central Journal*, 1(3), 1–4. Retrieved from http://www.journal.chemistrycentral.com/content/pdf/1752-153x-1-3.pdf

Trouiller, P., Olliaro, P., Torreele, E., Orbinski, J., Laing, R., & Ford, N. (2002, June 22). Drug development for neglected diseases: A deficient market and a public-health policy failure. *The Lancet*, 359(9324), 2188–2194. doi:10.1016/S0140-6736(02)09096-7)

Turner, J. S. (1998). The nonmanufacturing patent owner: Toward a theory of efficient infringement. *California Law Review*, 86, 179–210.

Tyler, C. (2004, September 24). Patent pirates search for Texas treasure. *Texas Lawyer*.

United Nations Environment Program (UNEP). (1992, June 5). *Convention on Biological Diversity*, Rio de Janiero.

Vohs, K. D., Mead, N. L., & Goode, M. R. (2006). The psychological consequences of money. *Science*, 314, 1154–1156.

Vohs, K. D., Mead, N. L., & Goode, M. R. (2008). Merely activating the concept of money changes personal and interpersonal behavior. *Current Directions in Psychological Science*, 17, 208–212.

Weatherford, J. (2004). Genghis Khan and the making of the modern world. New York, NY: Crown Publishers.

Woolhandler, S., & Himmelstein, D. U. (2002). Paying for national health insurance—and not getting it. *Health Affairs*, 21, 88–98.