Global Obstacles to Disruptive Innovation In Sustainable Agriculture and Energy

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Abstract— **The U.S. national innovation system has a dual structure: part suited to rapid innovation, and part stubbornly resistant to change. The complex established "legacy" sectors (CELS) that resist change share common features that obstruct the market launch of innovations, beyond the "valley of death" and other obstacles that have been the traditional focus of innovation policy.**

Innovations in CELS must penetrate a well-established and well-defended technological/economic/political/social paradigm that favors existing technology, characterized by (1) "perverse" subsidies and price structures that create a mismatch between the incentives of producers and broader social goals, such as environmental sustainability, public health and safety, and geopolitical security; (2) established infrastructure and institutional architecture that imposes regulatory hurdles or other disadvantages to new entrants (3) market imperfections beyond those faced by other innovations: network economies, lumpiness, economies of scale, split incentives, needs for collective action, and transaction costs (4) politically powerful vested interests, reinforced by public support, that defend the paradigm and resist innovations that threaten their business models (5) public habits and expectations attuned to existing technology and (6) an established knowledge and human resources structure adapted to its needs.

We have developed a new, integrative analytic framework for categorizing the obstacles to market launch faced by CELS, and earlier applied this method to energy, health delivery, the long-distance electric grid, building, and air transport. In energy especially, the requirement for innovation is sufficiently urgent that large-scale domestic and collaborative international research should take place even at the cost of possible competitive disadvantage and even if it is some time before the U.S. adopts carbon charges and thereby puts pressure on the prevailing paradigm of fossil fuel use. We now extend this method to sustainable agriculture.

American paradigms in agriculture and in energy are exported world-wide, delaying the development and spread of needed innovations that are not consistent with them. Foreign manufacturers wishing to enter U.S. markets must suit their products in these sectors to American paradigms, while American exports of technology may be insufficiently cost-conscious or respectful of environmental sustainability. Developing countries are technology takers and suffer from asymmetric innovative capability. They need to choose sources of technology best suited to their situation. India and China constitute new competitive threats, but also represent "innovative developing countries" that have large domestic markets in which to launch innovations aimed at the needs of poor people.

Index Terms— **Technoeconomic paradigm, Obstacles to Innovation, Legacy Sectors, Perverse Subsidies, Globalization, International Collaborative Research, Asymmetric Innovative Capacity, Market Imperfections, Collective Action, Lumpiness, Organic Agriculture**

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I. Introduction

In the most innovative society in the world, why are certain parts of the economy – like the health delivery system and the electrical distribution grid – stubbornly resistant to innovation? Why is it hard to launch sustainable innovations in energy, health delivery systems, buildings, and agriculture at a scale sufficient for substantial impact? In short, why does the U.S. have what amounts to a dual economy: breathtakingly rapid innovation, capable of disrupting long-established practice and structures in the information, medicine, industrial agriculture, and military and aerospace industries -- at the same time that other, equally important parts of its economy successfully resist disruptive innovations that would address broad environmental, security and public health goals?

These questions highlight an important gap in the American literature on innovation, which is focused largely on the "valley of death" and other problems facing radical innovations that introduce new functionality but do not face the interlocking obstacles encountered in the disparate, disruption-resistant, complex established legacy sectors (CELS) cited in the preceding paragraph. These CELS share common features that, taken together, define a technological/economic/political/social paradigm that enables them to resist fundamental change [1],[2].

These paradigms have implications beyond America's borders. First, they set limits on the ability of other countries to develop and launch desirable innovations in these sectors, since their efforts to penetrate some of their biggest potential markets for these products will be hamstrung by deeply entrenched obstacles. Second, most developing countries lack the technological and innovative capacity to strike out in fundamentally new directions, so that they largely accept the direction of innovation charted by technologically advanced countries and adapt the resulting innovations to their needs. This process occasionally produces remarkable results, as in the case of mobile finance in Africa and the application of biotechnology to problems of tropical medicine and agriculture. It has, however, delayed essential innovations in sustainable agriculture, energy conservation and other areas of great importance to developing countries.

I. Paradigms Inhibiting Innovation in Complex Established Legacy Sectors (CELS)

In our previous work, we used a new analytic framework to explain how technological/political/economic paradigms in complex established legacy sectors (CELS) in the US create major barriers to desirable technological innovations. They do so by enforcing and perpetuating a mismatch between broader social goals, such as environment and security, on the one hand, and the incentives of producers and consumers, on the other. In this paper, we expand the framework used in our previous publications to encompass international markets for technology and innovation, and to relate our framework to those used by other innovation researchers, specifically business-oriented researchers exploring disruptive technology[2] and science, technology and society (STS) researchers exploring the properties of socio-technical systems.[3]

We then explore the properties of domestic CELS paradigms in the agricultural and energy sectors, and expand the discussion to international markets in order to show how asymmetries in innovation capacity result in the export of these paradigms to developing countries and hinder the development and flow of technologies that could make important contributions to global social, environmental and security problems. In agriculture, these barriers to desirable innovation are exacerbated by tariff regimes and other imperfections in global markets that inhibit overall investment in the sector, deny tropical countries their natural comparative advantage, and in this way inhibit their overall economic and social development.

We begin by defining the common features of these paradigms, expanding the definition to take into account the social dimension of the paradigm. We add new elements of the definition to those enumerated in previous papers: knowledge and human resources, value network (industrial structure), and the habits and expectations of consumers and users. This makes our definition of a technological/ socio/economic/political paradigm [now with the addition of the prefix 'socio'] more nearly equivalent to the definition of a socio-technological system, with the difference that we drill much more deeply into the role of economics, policy and regulations, and the politics that underlie them. These common features are: [4]

(1) "Perverse" subsidies and price structures favorable to existing technologies that create a mismatch between the incentives of producers and innovators and the goals of the larger society. These include the numerous subsidies to fossil fuels, the procedure-oriented fee structure used by doctors and hospitals, sales-oriented profit structure of electric utility companies, and regulated electric power tariffs that discourage investment in the electricity distribution network.

(2) An established institutional architecture that imposes regulatory hurdles or other policy disadvantages favoring existing technology or discouraging new entrants, accompanied by government support to infrastructure adapted to the requirements of existing technology. An example is the balkanized regulatory structure that poses major obstacles to the "smart grid" and to large-scale solar and wind energy installations.

(3) Well-established and politically powerful vested interests that resist the introduction of technologies that threaten their business models. These include oil, coal and natural gas companies in energy, health insurance companies, hospitals and medical associations in health delivery, and state regulatory agencies in the utility industry.

(4) Market imperfections that reinforce the position of existing technologies. These include network economies, lumpiness (minimum required size) of investments, split incentives , and requirements for collective action. These will be explored in more detail in the next section of this paper.

(5) Public habits and expectations attuned to existing price structures, dominant products and technology that underpin popular support to the policies and public expenditures favorable to existing technology. These include public expectations of cheap and convenient energy, widespread satisfaction with existing health delivery options (for those who receive adequate care and do not have to pay for it), and public reluctance to pay higher prices for energy-efficient buildings.

(6) An established knowledge and human resources structure: educational curricula, career paths and professional standards in medicine, legal and technical fields that are adapted to the needs of existing technology.

These paradigms directly affect the speed and direction of innovation in the American industries to which they apply. Despite the very real obstacles that they face, innovations that reinforce these paradigms, or are at least compatible with them, constitute the basis for much of the United States' comparative advantage in bio-pharmaceuticals, fossil fuel, and agricultural, military and aerospace technology. Even in CELS, technologies like light emitting diodes (LEDs) and off-

[2] For disruptive innovations, see [3] The definition of "disruptive innovation," taken from the website of its originator Clayton Christensen, "describes a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentless moves up-market, eventually displacing established competitors" (http://www.claytonchristensen.com/disruptive_innovation.html). As originally conceived, this process takes place entirely in the private sector. In his later work, Christensen broadened this concept to include a product or organizational framework (as, for example, the rationalization of the hospital and indeed much of the health care system), whose introduction could lead to the rationalization of an entire industry. The latter process often exceeds the capacity of the private sector acting alone and requires substantial changes in public policy. See [4] for example.

[3] For socio-technical systems, see, for example [5].

[4] The first four of these features are taken from [1, pp.162ff] Numbers 5 and 6 are added in order to bring our definition closer to the definition of regime found in the literature on socio-technical systems, which emphasizes the link between technology and social systems, especially in firms and other organizations. See [6] for example, and [7, pp.128] Where our previous work emphasized the dimension of political economics, we now refer explicitly to the social dimension that underlies the politics that in turn often dictates the economics. In practice, all of these elements are intertwined.

grid wind and solar energy have been successfully launched into niche markets from which they can expand and perhaps challenge established competitors.

On the other hand, paradigms in these CELS inhibit the development, the market launch and the implementation at scale of technologies that do not fit neatly into them, such as those for renewable energy, energy conservation, sustainable agriculture, and the "smart" grid for the distribution of electric power in the United States. In some CELS, such as energy and developing country agriculture, innovation is further inhibited by a general under-investment in research and development, and in some cases, as in electric power distribution, by under-investment in or under-capitalization of the sector as a whole. As we shall see later in this paper, these paradigms also impose obstacles for the development of technologies for many of the needs of developing countries that must depend on advanced countries for technologies that can be applied or adapted to their own particular needs.

II. Imperfections in Technology Markets

Of particular importance in our previous work was the identification of imperfections in the market for technology that apply to specific industries, over and above those affecting the innovative process as a whole [1, pp.165ff]. We found that the need to achieve *network economies* was a particular barrier to the introduction of innovations based on information technology into the health care delivery system, whereas minimum investment size (known to economists as "*lumpiness*") was important to innovation in the pharmaceutical industry (whose business model depends on highly profitable "blockbuster" drugs) and in the development of engineering-intensive technologies like carbon capture and sequestration and enhanced geothermal in the energy sector.

The imperfection of "*split incentives*," in which the benefits of innovation go to someone other than the inventor, is an obstacle to innovation in the application of information technology to both the "smart" electric power distribution grid, in which the cost of investments in increased reliability cannot be passed on to consumers, and in the delivery of health services, in which the cost of investments in increased efficiency cannot be passed on to patients and insurance companies. This imperfection also applies to energy conservation technologies for buildings, where landlords are reluctant to make efficiency investments the benefits of which they cannot recapture.

The need for *collective action* is a particularly important obstacle to innovation in the building industry, which is composed of undercapitalized firms. It is also a factor in the commercial airline industry, which is also undercapitalized and which has benefited from innovation historically funded by the military budget, a pattern that has been undermined by the reduction in the procurement budget for military aircraft and the divergence between civilian and military performance requirements. As we shall see below, the need for collective action is also an important factor in innovation in agriculture.

Innovation can also be severely impacted by the pattern of *government regulation* or *institutional structure*. Balkanized regulatory structures inhibit innovation in the electric grid, and also affect the installation of large-scale solar and wind power installations, all of which require multiple approvals from separate jurisdictions for the installation of high-voltage power lines to connect them to the main electric power distribution grid.

III. Exporting Inappropriate Paradigms

We now turn to the international dimension of our analytic framework, and to the concept that implicitly underlies the regime defined and enforced by the World Trade Organization (WTO) and by the Trade Related Aspects of Intellectual Property Rights (TRIPS) regime in areas other than agriculture. This regime constitutes the international analog to the domestic quasi-free market defined in our previous publication[1, pp.160ff]. This system is universally accepted among advanced industrial countries as the basis of the globalized knowledge economy and is enshrined in WTO and TRIPS.

Within the constraints of the WTO system, each sovereign country is entitled to evolve its own national innovation system and its own domestic paradigm. Any country may make investments in innovative capacity – defined broadly to include business climate, capital markets, connectivity and physical infrastructure, as well as support to research and development, scientific and technological services, and human resources – and consequent dynamic comparative advantage. Once a new product is developed, WTO rules make it difficult for other countries to restrict it from being imported, with largely theoretical exceptions for products deemed to have detrimental environmental or public health effects. The system of intellectual property rewards innovation by protecting the resulting monopoly and the consequent economic rents of the innovator.

The quasi-free[5] international market in technology leads to an inherent conflict between intellectual property rights, which are essential to encourage vital private investment in innovative technology, and needed global environmental, public health or other benefits associated with widespread implementation of many innovations in complex established legacy sectors. This conflict admits of no clean universal solution but must be addressed case by case. In agriculture, development assistance agencies, private foundations, non-governmental organizations, and even some multinational corporations have undertaken to make available innovative technology to farmers who otherwise could not afford them. In infectious disease, major programs of research and technical assistance have long been underway[8]. In energy, some programs of international collaboration on technology implementation and to some extent on pre-competitive research are gradually taking shape [9],[10].

[5] We refer to the market in which many innovations operate as "quasi-free;" it is not completely free, not only because it is designed to provide economic rents to the innovator and is affected by market imperfections at the stage of market launch, but also because such innovation benefits from extensive government funding of early-stage research (which greatly exceeds private-sector expenditures at this stage), and major support to science and technical education. See [9],[10].

The impact of the quasi-free market on developing countries is mixed. The "Gang of Four" (Korea, Singapore, Taiwan, and Hong Kong) made the necessary investments in dynamic comparative advantage during the 1970s and 1980s and are competitive in the new knowledge economy. Likewise, China, India and perhaps Brazil and Mexico are on their way to becoming "innovative developing countries."[6] Gulf States could, if they so chose, use their oil money to finance and benefit from innovation, especially given the current financial crisis in Europe and the US. A few other developing countries – Thailand, Malaysia, Turkey and Chile, perhaps, are also within range. The "Arab spring" may revitalize science and technology in some North African countries. But the challenges for smaller and least developed countries are much more serious because markets and technology are moving so fast, and because some of the methods used by the Gang of Four are now forbidden by the WTO (although China evades WTO restrictions because of the allure of its huge market for foreign investors).

The result is *asymmetric innovative capacity*, in the sense that most developing countries are technology takers and have no choice but to accept technology from advanced countries and hence to import paradigms that evolved in advanced countries under quite different circumstances.[7] This works well if the needs of a developing country are the same as those of advanced countries, directly or with minor modifications, as for example in the case of middle class banking services. Occasionally, as in the specific case of cell phones, developing countries have not only leapfrogged legacy land-line technology but also built on imported technology to make world-class innovations in mobile finance to suit their own needs and situation. Even so, the export of paradigms from developed countries can also result in the importation of ill-suited technological patterns that inhibit innovation that might otherwise have been directed toward social objectives – high-tech hospitals rather than well-designed rural clinics, for example.

With important exceptions, developing countries have historically lacked sufficient technical and innovative capacity to strike out on their own to develop technologies not based on or adapted from models from advanced countries, or even to choose to import technologies from smaller exporters whose situation is closer to their own (a choice that may require resistance to political pressures and to temptations to corruption). The international technology market in LDCs involves important additional market imperfections. Capital goods specifically suited to conditions in developing countries require economies of scale in manufacture, which may be difficult to achieve if their market is scattered across many countries and if innovative firms in developing countries lack the expertise and infrastructure for world-wide marketing. Moreover, the combination of lack of market power and lack of technical and innovative capacity results in important areas of "orphan technology" – technologies like malaria vaccine that would answer a critical social need, but that have no commercial market and are therefore dependent on public sector intervention by governments, private foundations, non-governmental organizations or development assistance agencies based in advanced countries.

The situation is brightened by a number of promising developments. The research arms of bilateral and multilateral assistance agencies, including the specialized agencies of the United Nations, have long sought to overcome these obstacles. More recently, their efforts have been complemented by new technologies and new actors. The revolution in information and communications technology has provided disruptive technologies in finance, education, health services delivery, small business creation and all aspects of logistics and coordination. The rise of India and China (which have large markets comparable to those of other developing countries and the innovative capacity to develop sizable products to satisfy them) has helped to create markets for efficient, low-cost products suited to the needs of poor people. The revolution in information and communications technology has provided a new vehicle for global marketing of products of all kinds. A growing number of public-private partnerships are now aimed at orphan technologies at the "bottom of the pyramid," especially in public health and education but also in raising the productivity of scattered small-scale producers[11].

Despite these positive developments, the obstacles to innovation in developing countries remain important. The combination of entrenched paradigms in CELS in advanced countries, asymmetric innovative capacity, lack of market power and assorted imperfections in domestic and international markets inhibits the development and spread of innovations that could make important contributions to global humanitarian, development and environmental problems. We explore these considerations as they apply to agriculture and energy, using our expanded analytic framework.

IV. Industrial Agriculture as a Disruption-Resistant CELS

The US has a strong techno/economic/political/social paradigm for large-scale, mechanized, input-intensive industrial agriculture -- big subsidies, strong vested interests, a well established value network, strong public expectations and habits, and a well-established knowledge structure -- all of which reinforce the effects of the vast land and water resources and continent-sized market in favoring industrial, input-intensive agriculture [12]. The US Department of Agriculture at the federal level, with its subsidies and price supports, R&D and extension programs, and the educational and research functions of the land grant colleges it helps support at the state level, overcomes the problem of *collective action* facing the fragmented US agricultural sector, at least as it applies to industrial agriculture.

"Sustainable," small-scale, low-input agriculture, however, does not benefit from this paradigm. In addition to the weight of historical development favoring industrial agriculture, sustainable agriculture suffers from a number of intrinsic

[6] The phrase is due to R. A. Mushalkar.

[7] This statement is a variant of the commonplace that technology embodies the economic factors and social values of the place where it was invented or commercialized, so that the importation of technology may either require an importation of these values or, alternatively, may be inappropriate to local conditions or factor proportions.

problems. First, sustainable agriculture is subject to many alternative definitions [13]. The various standards for the definition of "organic" agriculture disagree on whether any use of chemical pesticides, inorganic fertilizer, bovine growth hormone, or genetically modified crops is to be allowed. Other possible definitions would require free range livestock, much more efficient water irrigation, minimum energy use, minimum environmental footprint, or local production that minimizes transport between the sites of production and consumption. Second, sustainable agriculture in the US does not benefit from many of the services of the US Department of Agriculture and the land grant system that supply a scale of support that largely overcomes the collective action problem for American industrial farmers. On the contrary, most organic producers of whatever stripe are small and ill-equipped to carry out research.[8]

The result is that organic and sustainable farmers have been forced to establish themselves as an upscale, high-cost niche market. It is expanding rapidly from a low base but despite the high hopes of its devotees, does not show signs of becoming a truly disruptive technology that can reach a scale to challenge the strongly entrenched, prevailing paradigm of high-input, large-scale industrial agriculture.[9] Indeed, the most promising sign that organic agriculture may be "mainstreamed" into the prevailing paradigm is its adoption by large-scale farmers – who in some cases achieve compliance with official organic standards by use of environmentally dubious, energy-intensive technology.

Fortunately, there are potential forcing mechanisms for a different kind of agriculture in the U.S. and other advanced countries lurking in the wings. Water availability is a growing world problem including in the US; climate change may accelerate this problem and disrupt current world food supply patterns over time. The rise in energy costs provides another threat to the industrial scale of capital equipment pervasive in US agriculture. There is thus hope that a more sustainable agriculture may in time disrupt the CELS in U.S. agriculture and provide a source of technology better suited to the needs of developing countries as well.

V. The International Market in Agricultural Technology

Turning now to the international picture, industrialized countries have their own systems of agricultural education, research and extension, and their own set of agricultural policies that define their domestic paradigm, reflecting societies accustomed to cheap food and a well-established market system of processing and distribution of agricultural products. All advanced countries subsidize their agriculture in one way or another, in order to assure their populations cheap food and stimulate exports. These subsidies are heavily defended by farmers and agribusiness, which are overrepresented politically in most advanced countries. These subsidies are complemented by research, extension and other institutions that provide necessary innovative capacity and technical services.

Farmers in developing countries, like farmers everywhere, suffer from *collective action* problems, but the institutions serving them are much weaker than those in advanced countries. Research and extension institutions are much less effective – an aspect of the asymmetric innovative capacity we discussed earlier -- and when they do exist are typically patterned on those of the advanced countries. Besides, technology for sustainable agriculture tends to be much more locality specific than industrialized agriculture, and hence would put much heavier requirements on these researchers and extension workers for response to local conditions and hence for collaboration with farmers.

This means that developing countries have little chance of developing innovative, sustainable technologies that protect their environment, which by and large is more sensitive to unsustainable practices than that of temperate zones.[10] This situation is exacerbated by an overall under-investment in developing country agriculture and agricultural research [16], and by the imperfections in the global market for agricultural products -- most especially by the subsidies to and protective tariffs around developed country agriculture that encourage dumping of surplus production into export markets. The well-known result of these subsidies is to reverse the classical comparative advantage in agriculture that should be enjoyed by tropical countries, and hence to depress investment in agriculture in these countries [17].

The upshot of this situation is that the input-intensive system of agriculture that characterizes advanced country agriculture has been exported to the developing countries in modified form. The first stage of this paradigm export was the Green Revolution,[11] in which internationally-supported research laboratories (that helped to overcome the problems of both *asymmetric innovative capacity* and the need for *collective action*) transferred and adapted technology for high-yielding varieties of cereal grains, including wheat and rice, based on selection and hybridization techniques that were already in use in Japan and the United States [18],[19],[20]. These crop development efforts to suit local production conditions were coupled with modern management efforts, large-scale production of hybridized seed, irrigation techniques, synthetic fertilizers and pesticides.

As with other forms of advanced country technology, this has resulted in major tangible benefits: greatly increased yields and much lower food prices initially in Mexico, Pakistan and India, then more broadly in Asia and Latin America than would otherwise have been the case. This arguably avoided the widespread starvation in India that had been authoritatively predicted [21], and some argue may have saved a billion lives

[8] For materials on sustainable agriculture, see Rodale Institute website, http://rodaleinstitute.org/new_farm

[9] For a more optimistic assessment of this process in the United Kingdom, see A. Smith [14].

[10] For a comprehensive assessment of the state of agricultural technology in developing countries, see [15].

[11] The term was first used in a speech by W. S. Gaud, Director of U.S. Agency for International Development, to the Society for International Development, 1968, available at http://www.agbioworld.org/biotech-infotopics/borlaug-green.html

worldwide from starvation.[12] At the same time, it put stresses on tropical environments in the form of erosion, chemical pollution and water stress that might have been avoided had there been more understanding of and attention to sustainability from the beginning [13].

The point here is not to offer criticisms of the Green Revolution, a subject on which there is an ample literature, but to point out that it was based on an advanced country paradigm, because the need to raise developing country yields in the light of increasing population was urgent and because no alternative less input-intensive technology was available for transfer. Indeed, the use of fertilizer and pesticides in developing countries was so low in the 1950s that it was thought urgent at the time to increase them. The research and extension capabilities in Mexico, India, Philippines and many other developing countries increased dramatically, but the model was from the US, Great Britain and France, reflecting their national agricultural paradigms.

The export of this paradigm has been further complicated by the recent impact on developing countries of two issues of foreign origin: the rise in food prices caused by competition for land use induced by subsidies to food crops, especially corn,[13] and the export to developing countries of the largely European controversy over genetically modified (GM) crops. In the latter case, European risk/benefit calculus -- one perhaps appropriate to a region with ample food supplies – has been exported to countries where GM crops could make a major contribution to agricultural productivity [24]. Critics point out quite correctly that existing GM crops benefit mostly large industrial farmers in advanced countries – but this is a matter of the choice of research objectives, itself a reflection of an entrenched paradigm. If researchers were tasked with, and given adequate resources for applying GM techniques to sustainable agriculture, the resulting technology could be quite different. Here the lumpiness of research on GM crops poses major obstacles to agricultural researchers in LDCs,[14] as the cost of a single commercial GM crop exceeds the entire budget of the Consultative Group on International Agricultural Research (CGIAR), the major network of international laboratories devoted to agricultural research for developing countries.[15]

The impact of intellectual property (IP) protection on the availability of GM crops suited to the needs of developing country agriculture is more complicated. The Green Revolution, as noted above, was based on food crop varieties adapted by publicly funded international research laboratories from varieties developed by government and university laboratories in Japan, the U.S. and Europe, and placed by them in the public domain. The large commercial seed companies raised no objection to this system. Nor did governments raise objections to the international exchange of genetic material, which was correctly perceived to be of universal benefit. GM crops, in contrast, are developed by private companies and are subject to IP protection. Private foundations exist to facilitate the donation of these IP rights to developing country laboratories.[16]

There are, to be sure, possibilities for increased sustainability through a major shift within the prevailing paradigm of high-tech industrial agriculture, driven by disruption of traditional growing patterns due to climate change and by increasing global water shortages. Networks of low cost sensors and RFIDs in plants and soil could enable far more efficient delivery of dosages of nutrients and water appropriate to particular plants and field areas.[17] Coupling drip irrigation techniques with a sensor system that delivers water based on the needs of different parts of fields could add significant conservation efficiency. Small-scale, semi-autonomous robotics responsive to field sensor networks could replace some of the current energy-intensive, large-scale mechanized equipment. Harvesting could occur when the network indicates particular plants are ready, not on a fixed preset calendar date.

As with energy, there is no single technological silver bullet; different geographic and climatic regions as well as nations will require differing agricultural conservation and technology approaches. Any such new agricultural technologies must still go through the cycle of research, development, prototyping, and testbeds to demonstrate efficiencies and costs, and enable enough early deployment to drive down a cost curve so as to be competitive with industrial agriculture. The problems of *collective action*, *split incentives*, and *lumpiness* in the legacy agricultural sectors of both the developed and developing world remain; until they can be overcome, such a transformation will remain elusive.

VI. The International Fossil Fuel Economy

Our previous publications [25],[2] set forth the characteristics of the technological/social/economic/political paradigm that underlies the fossil-fuel-based energy economy in the United States and by extension on all advanced countries. In this paradigm, producer incentives are misaligned with the broader environmental need to conserve energy and minimize carbon dioxide emissions, as well as the geopolitical and economic need to minimize the importation of petroleum. Both of these social needs apply world-wide, in the sense that it is in everyone's interest that everyone else apply carbon-minimizing and energy-conserving technology, no matter where on earth they live.

The quasi-free international market in energy technology thus leads to the tension, previously discussed, between the desire of innovators and innovating nations to realize the gains of IP rights, on the one hand, and global environmental and

[12] The failure of the Green Revolution to benefit many African farmers is a separate story, see [13].

[13] This may well have been further exacerbated by the use of corn for ethanol fuels. See, for example, C. F. Runge and B. Senauer [22]. and compare, R. Zubrin [23]

[14] A similar lumpiness makes it uneconomic to develop commercial pesticides specific to "minor" crops whose markets total "only" a few billion dollars, forcing growers to use less effective and more environmentally harmful chemicals developed for other crops.

[15] See www.cgiar.org

[16] See, for example, work of the International Service for the Acquisition of Agri-biotech Applications (ISAAA), www.isaaa.org

[17] This approach reflects ongoing conceptual work by Prof. Sanjay E. Sarma, MIT.

security externalities, on the other. Intellectual property rights are essential to encourage private investment in innovative energy and energy-using technology. On the other hand, the existence of global externalities implies that a free exchange of innovative technology would be desirable to encourage the implementation of technologies that minimize carbon dioxide emissions and petroleum imports.[18]

At a minimum, these global externalities justify a substantial program of international collaboration on pre-competitive research as well as in technology implementation, and in fact some efforts at such programs are underway. Innovative crossover efforts are underway in countries that do not share the impediments of American paradigms, as for example the production financing by provincial Chinese governments for US-developed advances in energy technology that the US is not prepared to implement at scale itself.[19] While the US may reasonably wish to benefit from its own innovations rather than shifting their market-creation gains to China, in effect these constitute pilot projects for technologies that could be potentially disruptive back in the US should market imperfections and other obstacles somehow be removed.[20] Either way, the implementation of these technologies would greatly benefit American consumers -- although at the potential cost of competitive disadvantage of American producers. On the other hand, we cannot count on China or any other country to take up the slack in developing and launching technologies for which there is unlikely to be a near-term commercial market because of deeply entrenched obstacles in a global CELS paradigm.

The absence of carbon charges or other incentives for carbon-saving technology poses obstacles even at the stage of research collaboration, especially when large sums of money are involved, as is the case for demonstration projects of lumpy, engineering-intensive technologies like carbon capture and sequestration and enhanced ("hot rocks") geothermal. Firms and countries will likely slow the investment of billions of dollars and the time commitment of its best technical people in a risky technology that will be economic only if carbon charges come into widespread global use.

The situation is further complicated by the rise of China as a major manufacturer of hardware for renewable energy [26],[27],[28],[29] and increasingly as a major investor in research and development in this area[30],[31],[32]. Efforts to launch collaborative research at the pre-competitive level have been hindered by the recession in advanced countries, and by the political complications associated with the rise of China as an economic and possible geopolitical competitor[33]. It remains to be seen how these issues will play out in the context of specific individual collaboration projects.

VII. Global Implications of Domestic Paradigms

It is a standard observation in the study of the transfer of technology to developing countries that imported technology embodies cultural values essential to industrial modernization: workforce discipline, acceptance and support of productivity gains, and understanding of the economic value of time. The older literature on "appropriate technology" also frequently noted that such imported technology was typically developed to correspond to the factor endowments of developed countries, which it was frequently argued were inappropriate to developing countries [34],[35].

Neither literature, however, took explicit note of the fact that in some sectors at least, technology in advanced countries embodies less desirable characteristics: lack of cost consciousness, for example, and profligacy in the use of natural resources stemming from their having been treated economically as free goods . Technology in these sectors can result from paradigms that are resistant to change even though they do not take into account important social and environmental objectives in the exporting country, and, in effect, are "inappropriate" to both the exporter and the recipient . Indeed, it is common to acknowledge this fact indirectly in the form of a wistful hope that the developing countries might avoid repeating the mistakes of the developed countries, and instead "leapfrog" over legacy technologies and follow a more sustainable path. Continuing resource exploitation and the rapid growth of automobile markets in emerging nations are examples that suggest, however, that this may remain a hope rather than a reality.

With occasional exceptions – cellphones are the most prominent example -- this hope by and large has not been fulfilled . As we have seen earlier, agricultural research in developing countries has historically focused on technologies requiring the increased application of fertilizer and pesticides (although to be sure, starting from a very low base), on the assumption that attention to environmental issues could be postponed. Energy policies in emerging nations have focused on increasing the supply of fossil-fueled electricity, rather than on supplying energy in forms best suited to conservation and specific end-uses [36].Builders in tropical countries have constructed "modern," glass-walled, air-conditioned skyscrapers, even in desert countries with distinguished traditions of attractive, energy-conserving architecture.

The reasons are not hard to find. First is the familiar problem of "orphan technology" – technologies for which there is a need but no market. Poor countries and poor people do not offer large enough markets for products like malaria vaccines, which therefore depend on the benevolence of rich countries and private foundations. This is not a market failure. It is, after all, the way markets are supposed to work. They need enough customers with money to pay in order to allow products to be made at sufficient scale to be profitable.

But important imperfections in the international market for technology are also involved here. Developing countries have lacked the technical and corresponding innovative capacity – and perhaps more importantly, the institutional and political strength – to strike out in new directions, although some emerging economies have shown that it is possible to break out

[18] See discussion of this balance in [25, ch. 7].

[19] See, for example, Clean Air Task Force, http://www.catf.us/coal/where/asia/; Asian Clean Energy Innovation Initiative (AECII), http://www.aceii.org/

[20] See, generally, U.S. Dept. of Energy, "U.S.-China Clean Energy Cooperation, A Progress Report," Washington, DC, Jan., 2011, available at http://www.pi.energy.gov/documents/USChinaCleanEnergy.PDF.

of this box. Importation of high-tech equipment makes for attractive photo-ops, and in addition is popular with exporting countries and their development assistance agencies -- and not incidentally offers superior opportunities for corruption. "Advanced," imported technologies have the prestige of the foreign, and have the extra advantage of having been shown to work in their countries of origin – a version of the *first mover advantage*.. More generally, these nations point out, why should we take the chance of trying out a new approach, when we can follow a well-worn path blazed by the countries that have already developed? Why have we the responsibility to conserve resources for the benefit of humankind, they ask, when our predecessors have not done so?

The technological/economic/political/social paradigms in innovative countries thus have global as well as domestic implications. Technology trajectories in legacy sectors whose origins lie in market imperfections peculiar to their country of origin may affect the choice of technology all over the world. This technological lock-in may be problematic not only because it limits access to new, more appropriate technology paradigms in developed nations but may be even less appropriate to the differing needs of the developing world. The dramatic rise of China and India raises both problems and opportunities. These countries combine growing investments in research, development and innovation with large domestic markets that offer attractive commercial possibilities for products suited to the needs of the poor as well as a growing middle class. For these countries, and especially for China as the world's leading manufacturing center, "orphan technology" is at least as much a commercial opportunity as a social problem. China especially is emerging as a formidable competitor, vigorously seeking markets for low-cost products in both advanced and developing countries, as well as for potentially disruptive products like equipment for generation of renewable energy. From the developing country point of view, this may be a big advantage, as these new actors are likely to be major sources of technology aimed at poor people – technologies that have hitherto been "orphaned" by the lack of a commercial market of paying customers [37].On the other hand, the world is in great need of innovative technology in complex, established legacy sectors like agriculture and energy, where both the development and large-scale implementation of innovation is often stymied by entrenched paradigms that have been exported world-wide. Here developing countries need to build the capacity to identify technology that has been developed in countries unaffected by these strictures.

There are sustainability reasons for the U.S. and other advanced countries to engage in cooperative, pre-competitive research and technology implementation, in efforts to overcome established technology paradigms in areas like sustainable agriculture, renewable energy or infectious disease, where continued innovation serves everyone's interest. However, it is overly optimistic to expect that such international collaboration will overcome the many obstacles to widespread implementation of sustainable technologies in these and other complex, established legacy sectors in the absence of substantial change in one or another underlying technological/economic/political/social paradigm. The question for the future is whether the U.S. paradigm in these and other complex established legacy sectors will be entrenched as a global paradigm and hence as a permanent obstacle to badly needed innovation, or whether disruptive innovations begun and tested in places free of these strictures will come to flourish.

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