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Understanding carbon lock-in

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Abstract

This paper narrative argues that industrial economies have been locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale. It is asserted that this condition, termed *carbon lock-in*, creates persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages. The notion of a *Techno-Institutional Complex* is introduced to capture the idea that lock-in occurs through combined interactions among technological systems and governing institutions. While carbon lock-in provides a conceptual basis for understanding macro-level barriers to the diffusion of carbon-saving technologies, it also generates questions for standard economic modeling approaches that abstract away technological and institutional evolution in their elaboration. The question of escaping carbon lock-in is left for a future paper. © 2000 Elsevier Science Ltd. All rights reserved.

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> "You cannot solve a problem using the same thought process that created it."
>
> Albert Einstein

1. Introduction

This paper presents an initial exploration of interlocking technological, institutional and social forces that can create policy inertia towards the mitigation of global climate change. It is the contention of this paper that industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale. This condition, termed *carbon lock-in*, arises through a combination of systematic forces that perpetuate fossil fuel-based infrastructures in spite of their known environmental externalities and the apparent existence of cost-neutral, or even cost-effective, remedies. Rational corrective policy actions in the face of climate change would include removal of perverse subsidies and the internalization of environmental externalities arising from fossil fuel use. While the actual costs of environmental damage from fossil fuel use, such as acid rain and climate change, are not fully known, they are clearly greater than zero. Yet, instead of systematically correcting market and policy failures, governments frequently exacerbate them through subsidy and institutional policy (Ksomo, 1987).

While scientific uncertainty could provide a reason for delaying policy action, in the case of climate change much of the uncertainty has been overcome. The Intergovernmental Panel on Climate Change (IPCC), an international body of over 2000 researchers empowered by governments to assemble and peer review all relevant climate-related research, announced in 1995 that "the balance of evidence of suggests a discernible human influence on the global climate". (IPCC, 1996a, p. 10). Since 1995, the evidence has compounded to the point that numerous scientific bodies, from ecologists to economists, have indicated that it is time for action (Economist Statement on Climate Change, 1997; World Scientists Call for Action, 1997; Ecologist's Declaration on Climate Change, 1997). While uncertainty about climate change does still exist, it is focused mostly on the scientific details, such as timing and impacts, and not the question of if climate change will occur.[1] Thus, given that current

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[1] It has been asserted that "scientific uncertainty" is currently being used in the self-interest of groups likely to be disadvantaged by climate change policies (Gelbspan, 1997).

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scientific consensus is towards action, the inability of governments, and society in general, to take even precautionary action to date is explained here as a result of carbon lock-in.

An essential insight is that carbon lock-in arises from systemic interactions among technologies and institutions. To encompass these ideas in a simple conceptual framework, the notion of a *Techno-Institutional Complex* (TIC) will then be introduced. TIC arise because large technological systems, like electricity generation, distribution and end use, cannot be fully understood as a set of discrete technological artifacts but have to be seen as complex systems of technologies embedded in a powerful conditioning social context of public and private institutions. TIC develop through a path-dependent, co-evolutionary process involving positive feedbacks among technological infrastructures and the organizations and institutions that create, diffuse and employ them. Once locked-in, TIC are difficult to displace and can *lock-out* alternative technologies for extended periods, even when the alternatives demonstrate improvements upon the established TIC.

This paper will first present a selective overview of the climate change mitigation cost debate and the barriers to adoption arguments used to explain the apparently slow diffusion of carbon-saving technologies. Then the issues of lock-in will be explored in three different areas. First, the concept of *technological systems* will then be introduced to emphasize the role of positive feedback economics in creating lock-in among large systems of interrelated technologies. Here, firm-level *technological lock-in* will be highlighted, building on a diverse literature that includes resource-based strategy theory, innovation studies and technological change economics. Then the idea of *institutional lock-in* will be introduced and explored at two levels. First, the role of private institutions in enhancing technological lock-in will be developed followed by an examination of the impact created by formal governmental institutions. These sections will build on established industrial organization and neo-institutional economic literature. Finally, a simple conceptual framework will illustrate the interactions among technologies, organizations and institutions that create carbon lock-in. The examples of automobile-based transportation and electricity generation technologies will be used throughout the paper to illustrate presented concepts. It should be emphasized that carbon lock-in is not conceptualized as a permanent condition, but instead a persistent state that creates systemic market and policy barriers to alternatives.

No formal modeling is attempted here, largely because formalizing the co-evolution of technological and institutional systems is quite problematic and is in a very nascent stage of development. Instead, a narrative exploration is presented that integrates several different lines of research. The role of technological lock-in in environmental problems has been alluded to elsewhere, but has been given only cursory treatment (Ayers, 1991; Freeman and Soete, 1997) and, to my knowledge, no one has explored the systematic impacts of *combined* technological and institutional lock-in in the case of climate change. It is therefore hoped that this exploration will illustrate a set of issues that has been underappreciated in climate change policy debates.

2. Barriers to the diffusion of carbon-saving technologies

The problem of human-induced climate change is rooted in the production and consumption patterns of the diverse human societies of the earth. In industrialized countries, climate change results dominantly from meeting consumer's demands for goods and services through the application of carbon-based energy technologies and systems. The industrial world's primary sources of the key energy-related greenhouse gas, carbon dioxide, are the transportation, electricity, industrial and commercial building sectors (IPCC, 1996a). These sectors meet society's desires for locomotion, heat, light, shelter, etc., through complex systems based on of fossil fuel energy extraction, combustion and end-use technologies. Viable approaches for mitigating climate impacts from these demands include a switch to more efficient, carbon-saving technologies or toward non-fossil fuel energy sources like renewables (IPCC, 1996b).[2] The feasibility of a transition to these new technologies, the costs associated with it and the distribution of those costs are areas of active debate among climate change policy analysts.

The cost debate is usually framed between *top-down* economic modeling methods and *bottom-up* engineering approaches, which tend to come to different conclusions about the availability and costs of opportunities to switch to carbon-saving technologies. The engineering-based bottom-up studies frequently identify numerous "off-the-shelf" technologies and management practices that either do not require fossil fuels as an energy source or use fossil fuels more efficiently (Goldemberg *et al.*, 1988; Johansson *et al.*, 1993). Examples of non-carbon technological approaches include hydrogen fuel cells and renewable energy sources like wind and solar. Efficiency technologies include variable speed motors, lighting, fuel-efficient auto designs, combined heat and power, etc. Most bottom-up studies find that applying these technologies not only reduces carbon emissions, but also lowers costs, generating combined economic and environmental gains (Brown and Levine, 1997; Alliance to Save Energy *et al.*, 1997; Krause, 1996; Lovins, 1991; Sant, 1979). If this is so, the question arises "why don't

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[2] The option of reducing the demand for these services is also possible, but will not be discussed.

carbon-saving technologies and practices diffuse faster if they exist, save money and reduce climate impacts?"

One response is that if we assume that the economy is functioning efficiently, as top-down models tend to assume, these technologies cannot be saving money when the total, economy-wide costs of their adoption are considered. In a utility-maximizing quasi-static Walrasian equilibrium, any decrease in the production of carbon dioxide by-products would have to come from a decrease in the production of other goods or services. This has tended to be the reported findings of the major economic models used to assess the costs of climate change mitigation (Nordhaus, 1994; Cline, 1992; Manne and Richels, 1992). Thus, while carbon-saving technologies may reduce fuel costs, they must have other overlooked costs that make their adoption economically untenable. While systematic study has not yet resolved this question, anecdotal studies have found that in many cases there are indeed possibilities to reduce both carbon emissions and costs simultaneously (Romm, 1999; Von Weizsäcker and Lovins, 1997). Indeed, some firms are acting as if there are systematic "win-win" possibilities. DOW Chemical Corporation's Waste Reduction Always Pays (WRAP), for example, has annually produced combined cost- and energy-saving projects by the dozens for over a decade. Likewise, governments have found such opportunities on a national scale (Krause, 1996; Brown and Levine, 1997). A 1980 study by the UK Department of Energy, for example, found cost-effective ways to reduce national energy intensity by 20%. Yet a subsequent study in 1990 found that, after the 1980 reductions had been exploited, another 20% reduction could be further identified (Grubb *et al*., 1995). Several voluntary programs sponsored by the US Environmental Protection Agency, such as Green Lights, have found similar opportunities (USEPA, 1997).

There are also technological reasons why the possibilities for combined cost- and carbon-saving improvements like these should not be surprising. While most energy technology appears advanced, actual efficiencies of energy use are quite poor. Electricity generation efficiencies for steam turbines plateaued near 36% decades ago (Martin, 1996). The average internal combustion engine converts only 25% of input energy to the drive train, and of this less than 1% is actually needed to propel the passengers (Lovins, 1991). Similarly, end-use technologies, such as lighting and air conditioning, are frequently less than 10% efficient (Ayers, 1990). While the laws of thermodynamics guarantee we cannot capture and use 100% of energy released, at these levels even incremental improvements can lead to large relative gains in efficiency. In fact, technologies have been identified that can double auto and appliance efficiencies, increase electricity generation efficiencies to 50 or 60% and capture up to 90% of usable heat through cogeneration applications (Flavin and Lessen, 1994).

Given the compounding evidence that profitable energy-saving opportunities exist, alternative explanations for their failure to diffuse have focused on the idea of *barriers to adoption* (Lohani and Azimi, 1992; DeCanio, 1993, 1994a, b, 1998). These explanations generally focus at firm- and consumer-level decision-making and emphasize *bounded rationality*, *informational asymmetries, moral hazard* and *principal–agent conflicts* (Sanstad and Howarth, 1994; Krause, 1996). While the "barriers to technology adoption" explanations are insightful, they focus mostly on failures that arise from myopic, microeconomic decision-making. These microeconomic effects are not the only possible sources of barriers, however. The following sections explore larger, macro-level forces that can create systematic barriers to the adoption of carbon-saving technologies at the level of technological systems and social institutions.

3. Technological systems

Technology is commonly thought of in terms of individual artifacts like the personal computer or the microwave oven. However, most fossil fuel energy technologies can be better understood as part of larger technological systems that provide wanted energy services to consumers (Martin, 1996). Technology can be defined as method or knowledge imbedded in artifacts, such as industrial machinery or consumer electronics, but this narrow view of technology ignores the important systemic interrelations among individual technologies (Arthur, 1991). Technology is better understood in terms of know-how imbedded in architecturally linked systems and subsystems. The concept of a "system" as a subject of analysis has been explored in detail elsewhere (Von Bertalanffy, 1968; Forrester, 1971), but here we can consider a *technological system* as inter-related components connected in a network or infrastructure that includes physical, social and informational elements.

The automobile transportation system, for example, is composed of numerous interconnected technological systems including cars, roadways, traffic lights, service stations, etc., managed by a series of public and private social institutions. However, the automobile itself can be seen as a complex technological system composed, in turn, of numerous subsystems such as the engine, drive train, brake systems, etc. The larger subsystems, like the engine, can be further broken down into architecturally linked technological components. For example, the ignition subsystem is composed of spark plugs, wires, timing and distribution mechanisms, etc. This multilevel nature of technological systems can create a "levels of analysis" issue as a unit of observation can be defined at nearly any system or subsystem level. Many technology studies tend to focus on the artifact/component level, like the automobile or personal computer. However, as is usually the case in complex systems, the whole is frequently greater than the sum of individual parts and, as discussed below, the properties of large technological systems are often different from those of the individual components.

4. The evolution of technological systems

Changes in technological systems occur at all scales and are often conceptualized in an evolutionary framework with the "dominant design" as basic theory for the establishment of a technological system (Nelson, 1995). *Dominant design* models begin when invention and innovation create several technological variants designed to meet some expected consumer demand (Abernathy and Utterback, 1978).[3] A period of uncertainty, termed the "era of ferment", ensues as variants compete for performance improvements (including cost reductions) and market share. The era of competition ends when one of the variants captures a critical mass of the market and becomes the de facto standard (Anderson and Tushman, 1990). Following the establishment of a dominant design a shift occurs from product (Schumpeterian) innovation to incremental process (Usherian) improvement (Ayers, 1991).

Dominant design models have been applied to numerous industries but appear to best fit sectors characterized by systemic, technological relationships (Gort and Klepper, 1982; Utterback and Suarez, 1993). In contrast to purely economic arguments, in which perfect markets and fully informed, optimizing agents select the optimal technology, a superior technological variant does not necessarily win out in dominant design frameworks. Apparently inferior designs can become locked-in through a path-dependent process in which timing, strategy and historic circumstance, as much as optimality, determine the winner (Arthur, 1989). This results largely because technologies can exhibit *increasing returns to scale* during their development and commercialization that can accelerate improvements relative to competing variants.

In the last decade the importance of path dependency (hyperselection, self-organization) and increasing returns (positive feedback) economics in the outcome of technological competition has gained growing recognition (Arthur, 1988). A useful way to conceptualize the increasing returns process is in terms of an S-curve model where the x-axis is some measure of scale, such as production volume, market share or installed base, and the y-axis is some measure of performance or utility (Fig. 1). The S-curve model implies that returns to scale are not constant as adoption increases, but change from a period of increasing returns at the lower half of the S-curve, to decreasing returns at the upper half.

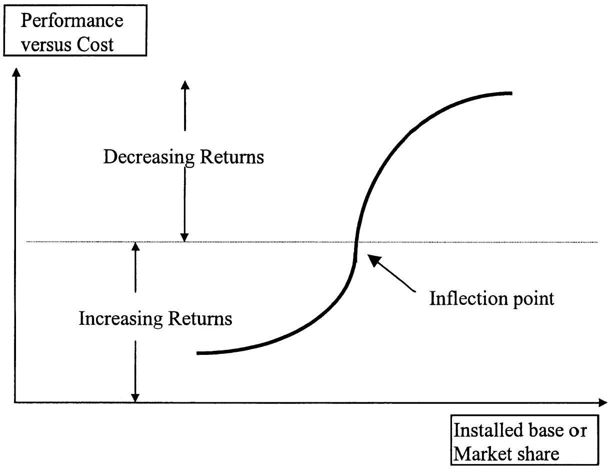

Fig. 1. A simple representation of the evolution of a performance/cost relation for a given technology with increasing scale of adoption. Various mechanisms, including adaptive expectations, scale, learning and network economies create increasing returns early in the technological evolution. Once established and markets near saturation, decreasing returns emerge as in standard economic theory.

Traditional economic analysis has tended to focus on the upper, decreasing returns half of the curve, arguing that what is important are the long-run equilibrium returns. However, in a condition of path-dependent technological competition, timing and the exploitation of increasing returns in the lower half of the S-curve can create indeterminacy in the competitive outcome. Increasing returns are most influential during the early period of competition where positive feedback can give a technology with the right timing, or favorable historic conditions, advantages that can lead to market domination (Arthur, 1994). Examples in the literature have focused on apparently inferior technologies becoming locked-in as dominant designs, such as the QWERTY keyboard, VHS video tape technology and light-water nuclear reactors (David, 1985; Cowan, 1990).

Four major classes of increasing returns tend to be identified in the literature: *scale economies, learning economies, adaptive expectations* and *network economies* (Arthur, 1994). The best known of these mechanisms are *scale economies* in which unit production costs decline as fixed costs are spread over increasing production volume (Mansfield, 1988). Also well explored are *learning economies* which tend to reduce costs and improve performance as specialized skills and knowledge accumulate through production and market experience (Arrow, 1962). These economies accrue to firms pursuing the development and commercialization of a new technology (Argote and Epple, 1990). *Adaptive expectations* in the market arise as increasing adoption reduces uncertainty and both users and producers become increasingly confident about quality, performance and permanence

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[3] Dominant design models tend to ignore pre-commercial research and development phases, focusing instead on competition among commercially viable technologies.

(Arthur, 1991). *Network economies* emerge due to the interrelations among technological systems and users that will be discussed in more detail below.

An example of the lock-in of a dominant design can be seen in the competition that resulted in the establishment of the gas-powered internal combustion engine (ICE) as the source of automobile propulsion. At the beginning of the 20th century, competition existed among steam-, electric- and gas-powered ICE vehicles as potential mechanized substitutes for the horse and carriage (Mowery and Rosenberg, 1998). There is no single reason for the establishment of the ICE as the dominant design. Indeed, in 1885, it was considered the least promising option, being the most noxious, noisy, complicated and dangerous alternative. However, the very cheap cost of gasoline, which at the time was a hazardous by-product from the production of kerosene, clearly played a role (Ayers and Ezekoye, 1991). Several chance events, like the closing of horse troughs used to supply steam vehicles and a 1895 victory in a horse-less carriage race that led Olds to shift to the ICE, also provide a relative lead over alternatives (Arthur, 1988). Once established, the ICE-powered car, and its associated Fordist system of mass production, entered a period of increasing returns to scale, driving prices down, improving performance and locking-in the ICE as the dominant propulsion design.

Similar competition, called "the battle of the currents", occurred in the early establishment of electricity infrastructures (Hughes, 1983). In 1882, Edison introduced the first electric system at Pearl Street in New York City and based it on direct-current (DC) technology. However, DC was challenged by alternating-current (AC) technology, backed by Westinghouse, and the two systems competed intensely between 1887 and 1892 to become the dominant design. Both systems had benefits and draw backs. DC tended to be more efficient but had a transmission limit of less than 2 km. On the other hand AC, when combined with transformer technology, allowed long-distance transmission permitting centralized generation close to sources of fossil fuels. Competition between the systems showed little resemblance to neoclassical ideals and included extra-market battles in the courtroom, political arena, public relations and academia (David and Bunn, 1988). Edison, for instance, attacked AC on safety grounds by patenting the electric chair and convincing the State of New York to use it for executions of condemned criminals, calling electrocution "being Westinghoused". Despite these efforts however, the AC system captured the market and became the dominant design, ultimately absorbing the DC network. The adoption of AC technology allowed the emergence of large centralized power stations and massive distribution grids run by regional or national monopolies. Alternatively, DC technology would have required a more decentralized system of competing local generation and distribution, a model some analysts currently see as the future of energy systems (Goldemberg *et al*., 1988; Johanasson *et al*., 1993).

Empirical studies have demonstrated that the lock-in of a dominant design, like the ICE or AC, results in an industry shake out where producers of alternative designs, like steam or electric propulsion, are forced out of business (Abernathy and Utterback, 1978). Indeed, in the case of automobiles, such a shake out occurred among ICE producers themselves and led to a huge reduction in the number of manufacturers and massive industry concentration. In the 1890s, for example, there were 1900 different firms producing over 3200 different variants of the ICE-powered vehicle in the USA (Rae, 1984). However, by the 1920s this number was reduced to a few dozen with familiar "big three" of General Motors, Ford and Chrysler in oligopolistic domination. By 1955 the "big three" held 90% of the domestic and 80% of the global automobile market (Nester, 1997).

Following such a shakeout, dominant design models and empirical studies show that the surviving oligopolistic firms generally shift their focus from product to processes innovation and the development of specialized knowledge about market demands and complementary assets. This design-specific know-how ultimately becomes a firm's *core competencies* and forms the basis of a company's competitive advantage (Prahalad and Hamel, 1990). The logic of the dominant design can be so pervasive that it becomes imprinted in the producing firms' organizational structure (Christensen, 1999). For example, General Motors recognizes the dominant design logic of the ICE organizationally by dividing engine development projects into 22 subsystem design teams that include ignition, electrical and fuel systems, lubrication, etc. This organizational structure has lasting impacts as specialized labor and knowledge develop in these focused departments (Christensen, 1999). Within these organizational silos "rules of thumb" or standard operating procedures emerge which routinize management (Nelson and Winter, 1982). Lovins has identified such "rules of thumb" as the source of many barriers to the adoption of carbon-saving technologies (Lovins, 1998).

The logic of this specialized, continued refinement of the dominant design can define a *technological trajectory* along which firms incrementally develop their know-how (Dosi, 1982). However, while pursuing the development trajectory improves the dominant design, it can also limit the knowledge-base and investment choices of successful firms (Christensen, 1997). Research indicates that firms tend to focus preferentially on existing competencies and away from alternatives that could make their present products obsolete. Management efforts, instead, emphasize technologically incremental programs like *total quality management* (TQM), *kaizen* (constant incremental improvement), standardization of procedures, etc.

Similarly, capital investment goes preferentially towards projects that reduce production costs and incrementally perfect existing products. The overall impact of this increasing specialization is the constraint of knowledge acquisition and continued re-investment in dominant design competencies. These investments have lasting impact because they are frequently irreversible or sticky investments in specialized, durable and untradable assets (Ghemawat, 1991).

Such repeat investments, which Lovins (1998) comically terms "infectious repititus", commit a firm to the dominant design trajectory and create lock-in at the firm level. This phenomenon helps to explain the well-known stylized fact that incumbent firms are rarely the source of radical innovations (Foster, 1986). In general, it is entrepreneurial entrants that challenge and overthrow an existing dominant design with a new technological solution. When faced with change that destroys the value of their technological competencies, incumbent dominant design producers are frequently unable to adjust (Henderson and Clark, 1990). Bower and Christensen (1995) has even documented firms whose competencies were destroyed by apparently minor architectural changes in existing technology. Thus, when challenged by a superior technological alternative, the core competencies that were once so vital to a firm's competitiveness become *core rigidities*, impeding effective responses to the challenge (Leonard-Barton, 1992). Consequently, instead of adopting the emerging technologies, incumbents frequently intensify efforts to improve the existing dominant design (Cooper and Schendel, 1976). While these efforts can lead to substantial improvements, they have historically only postponed eventual obsolescence and substitution (Grubler, 1996).

5. Lock-in of interdependent technological systems

While technological lock-in at the firm level is important, the condition is further intensified by *network externalities* arising from systemic relations among technologies, infrastructures, interdependent industries and users. Positive externalities arise because physical and informational networks can become more valuable to users as they grow in size (Rohlfs, 1974; Katz and Shapiro, 1985). For example, a road network increases in value as it expands and drivers can reach more destinations, while a telephone network increases in value with the number of subscribers that can be contacted (Noam, 1994). In interdependent technological systems, these externalities are multiplied among the many subsystems that co-evolve or grow in tandem with the primary network (Frankel, 1955). Grubler (1990) has demonstrated this co-evolutionary growth among technology clusters and systemic infrastructures in several industries. Importantly, as the primary network grows and increases in value, the subsystems increase in value along with it.

Three major types of network effects will be recognized here. The first are industry and inter-industry forces of coordination, such as the creation of standards and design-specific supply relationships. The second are reinforcing effects that can arise from private mechanisms available for financing the development and diffusion of technological systems. Finally, the forces created by networks of private associations and educational institutions, which develop in response to social and market needs created by the expanding system, will be considered. These cohesive forces are important in creating, coordinating and perpetuating the knowledge, skills and resources needed to maintain a technological system.

The development of the automobile as the dominant personal mobility technology provides an example of inter-industry network dependencies. The viability of the automobile depended upon the co-temporal development of multiple supporting technologies and industries in order to create a fully functional system (Fink, 1988). To build cars, for example, whole supply industries including petroleum, glass, rubber, etc. were required, each with their own distinctive core competencies. Similarly, in order to construct the needed roadways, large quantities of asphalt, concrete, metals, aggregate and machinery were required. The daily use and operation of the road network depended upon the existence of service stations, motels, drive-in movie theaters, etc. The co-temporal growth of these industries created complex networks of co-specialized, interdependent and complimentary assets (Teece, 1987) whose value depended upon, and rose with, the scale of the automobile-based transport system. Such technological inter-relatedness can create lasting barriers to competing technologies (Frankel, 1955; Arthur, 1988).

This growth of interconnected industry networks and subsystems often requires significant coordination that can be supplied through codified standards and conventions. Examples include 110 or 220 V current, hypertext markup language (HTML), octane standards, etc. The introduction of such standards reduces or eliminates uncertainties that can hinder investment and tend to institutionally lock-in key aspects of the dominant design. Standards can be generated by private organizations, such as the American Society for Testing and Materials (ASTM, founded in1898), or the International Standards Organization (ISO, founded in 1947), or they can be established by government fiat. For example, North American, European and Asian governments have been heavily involved in setting cellular phone and high-definition television (HDTV) standards (Farrell and Shapiro, 1992). Once established, standards can become powerful sources of lock-in on their own. Most sectors of the US economy, for example, are still locked-into the British system of standard weights and measures despite the obvious benefits of the metric system and numerous official efforts to transition.

The constellation of interdependent industries and standards can create strategic sources of lock-in as the establishment of a new dominant design can often require coordinated inter-industry changes or elimination of existing standards. Given these dependencies, risk adverse firms may not gamble on a new technology when they are uncertain about the preferences and potential responses of other firms and supporting industries (Farrell and Saloner, 1986). Unless innovators are confident that a technology will become the new dominant design and bring along supporting networks, it may be judged too risky to make the required irreversible investments to market the new technology. Even if a single firm creates and markets a challenger to the existing dominant design, it is possible the same uncertainties will prevent other needed supporting industries from following the lead. Thus, a firm hoping to introduce an innovative technology can face huge barriers, or "excess inertia", if the technology is based on a new standard (Katz and Shapiro, 1985; Katz, 1986). This condition is clearly seen in the computer industry where Microsoft DOS and Windows have functioned as the dominant design standard for over a decade. Hardware manufacturers and software firms create applications based on the Windows platform and anyone wishing to introduce a new platform needs to convert customers and applications firms to their new standard. This creates substantial barriers as Windows operating system challengers OS/2, GEOS and others have found (Shapiro and Varian, 1999).

The way in which large technological systems are financed can further exacerbate lock-in conditions. The majority of investment capital in the USA, for example, nearly 90% between 1952 and 1995, was funded by companies' internal cash flow or retained earnings (Henwood, 1998). Thus profitable firms generate most of their own capital financing which logically goes towards strengthening their dominant design-based core competencies. This continued re-investment of returns creates a self-reinforcing positive feedback that can lock-in existing technological solutions. Likewise, when capital is sought from outside, financial institutions can further reinforce lock-in through risk-averse lending practices. In general, financial institutions prefer making loans to companies with collateral and a proven ability to service debt. However, companies with these prerequisites tend to be dominant design producers, and therefore funds are most readily available to successful firms within the existing network. On the other hand, when funding is sought for technological innovation that diverges from the existing dominant design, it frequently comes from venture capital or government research programs with much stricter conditions or higher costs. Thus, these financing tendencies create incentives that can further enhance lock-in conditions.

6. Coevolution of technological systems with private institutions

Up to this point, forces of lock-in have been at the firm and industry levels. However, formal and informal societal institutions can emerge alongside technological systems and impact their evolution in important ways. Private, often non-commercial, institutions tend to emerge because users and professionals operating within a growing technological system can, over time, come to recognize collective interests and needs that can be fulfilled through the establishment of technical, aficionado and professional associations (Granovetter, 1973). These institutions can create non-market forces of lock-in through coalition building, voluntary association and the emergence of societal norms and customs. Beyond their influence on expectations and confidence, they can further create powerful political forces to lobby on behalf of a given technological system.

An example of these influences is seen in the early history of the automobile where numerous societal institutions co-developed along with the automobile infrastructure. As the technological system grew, corps of specialized labor were needed to support the physical assets and solve the arising problems. To meet this demand, knowledge-based institutions emerged in a coevolutionary manner. For example, existing institutions like the YMCA, working with automobile clubs, set up technical schools to train labor to service the growing auto network (Fink, 1970). However, beyond this basic technical training, the emergence of new technologies can create whole new academic disciplines (Nelson and Winter, 1982). Automobile technology, for example, led to the establishment of disciplinary departments like *highway* and *automobile engineering*, staffed by highly trained individuals whose purpose was to educate professionals and refine the body of knowledge underlying the dominant design. These disciplines are often the source of "rules of thumb" that are ultimately applied routinely practicing engineers. Furthermore, the establishment of such "disciplines" can create a large, self-sustaining network of like-minded professionals and institutions that are invaluable to the growth of the system. However, as Kuhn (1970) has demonstrated, these disciplinary professionals tend to be quite conservative and can actively resist challenges to orthodox methods. Thus, standard approaches developed within a disciplinary context can become locked-in as "curriculum" for long periods of time.

Similarly, institutions such as *unions* and *industry associations* emerge to provide representation for the various professionals that service the technological system. For example, the Society of Automotive Engineers (SAE) was organized in 1905 to assist practitioners in improving the state of the technology through the publication of articles and information dissemination (Fink, 1970). Likewise, skilled auto labor organized the United Autoworkers Union (UAW) in 1936 to gain representation, improve working conditions and appropriate more of the value created by the growing technological system. Even users organize associations to meet their diverse needs. Examples include automobile owner's clubs, which were founded in many countries to exchange information and generally encourage the continued development of the motor car. Galbraith (1967) has argued that the interests of unions and other social institutions eventually merge with the interests of the oligopolistic dominant design producers as their common reliance on the continued expansion of the technological system becomes mutually obvious.

Other societal institutions can impact the formation expectations, preferences and attitudes of the public towards an emerging dominant design. The views of the journalistic institutions towards new automobile technologies have historically had a large impact on popular expectations. By the turn of the century, for example, periodicals such as *Automobile, Motor World* and *Motor Age* published dominantly enthusiastic articles about the continued growth and improvement of auto-based transportation (Fink, 1970). Media such as these assisted in the creation of adapted expectations about the persistence and quality of cars, and helped to acculturate citizens to the auto-based society.

Finally, as the acceptance of a technological system increases it can become an increasingly integral part of daily life, which can lead to the emergence of behavioral institutions that socialize public use. These institutions can range from simple social norms about technology etiquette to more complex customs and rituals. A whimsical example is the lock-in of "hello" (invented by Edison) over "ahoy" (favored by Bell) in answering the telephone (Shapiro and Varian, 1999). However, more pervasive impacts arose in the case of the automobile which reshaped courtship, residence, education, work habits and leisure time (Fink, 1970). The establishment of electricity distribution networks and the co-evolution of end-use technologies had enormous impacts on home making, leisure, women's roles, etc. (Nye, 1990). This social co-evolution with technology can have pervasive and lasting influence on individual preferences. From this perspective, expectations and preferences co-evolve with, and become adapted to, the dominant technological system in an endogenous path-dependent manner.

7. Lock-in of public institutions

The institutions of association and industry coordination discussed to this point cannot be seen as inconsequential. They interact to create a self-referential system that tends to increase in value with the growth of the technological system, a condition that technology historian Thomas Hughes calls "momentum". Hughes (1983) concisely describes this positive feedback in the turn-of-the-century emergence of electric power networks:

> "The momentum initially came mostly from an aggregate of manufactures who invested heavily in resources, labor, and manufacturing plants in order to produce the machinery, devices, and apparatus required by the new system; later, educational institutions taught the science and practice of the new technology; then research institutions were founded to solve its crucial problems; and all the while a growing number of engineers, skilled laborers, appliers of science, managers, and other persons invested their experience and competence in the new … system."

While the momentum created by this mass of interdependent technological systems, institutions and individuals creates its own condition of lock-in, these forces can be further intensified by the involvement of formal governmental institutions. The involvement of government is important for two principal reasons. The first is the ability of institutional policy to override market forces. Governmental intervention can create alternative incentive structures, or "rules of the game", to which firms have to adapt their strategies (North, 1981, 1990; Williamson, 1975, 1985). In general, most markets need some government intervention to create transaction enabling institutions, such as enforceable contracts. When intervention is limited, firms can respond dominantly to the neo-classical market forces of competition. However, when there is intense government intervention, standard market forces can be circumvented. In the evolution of a technological system, government intervention can remove market uncertainty about the direction of technological development through policy, and thus favor a specific design. For example, government policy has made generally low-return investments in electric power plants (5–10% before adjusting for inflation) risk free and therefore quite attractive (Ayers, 1991).

The second reason governmental institutions are important is that once they are established they tend to persist in their initial form for extended periods. Interestingly, this pattern of institutional evolution parallels that previously discussed in dominant design models for technological evolution. Once established, institutions tend to become locked-in and undergo only incremental change for long periods. Williamson (1997) has found that formal institutions, such as governmental and legal structures, change over timescales of decades, while informal institutions, such as culture, norms and values, change over centuries. The well-known problem of removing unproductive institutions, such as subsidies or antiquated governmental agencies, demonstrates the persistency that path dependency, increasing returns and incumbency can create in institutional settings. According to North (1990):

> "the interdependent web of an institutional matrix produces massive increasing returns"

and

> "once a development path is set on a particular course, the network externalities, the learning process of organizations, and the historically derived subjective modeling of the issues reinforce the course."

Thus, the involvement of formal government institutions in the development or management of a technological system can have long-term impacts. Governments can become involved in the evolution of technological systems in many ways. In market democracies, for example, constituencies can draw law makers in by lobbying officials for support and preferential treatment of an existing technological system. Here governmental institutions interface with the professional and social networks discussed in the previous section. In the early history of automobiles, for instance, US government officials were lobbied for road building projects by a large network of institutions that included the Portland Cement Association, the American Automobile Association, the American Road Builders Association, the Association of Highway Officials, the Rubber Association of America, the National Paving Brick Association, the National Automobile Chamber of Commerce and scores of others (Lewis, 1997). This network was successful in inducing government to undertake massive road building projects that extended the technological system. The "highway lobby" is still recognized today as one of the most powerful interest groups in US fiscal policy.

While this interface between governmental institutions and social networks can intensify lock-in conditions, truly major impacts occur when government uses formal justifications for overriding market forces and extending a technological system through public policy. Governments use numerous reasons for their interference in the competition and evolution of technological systems. *National security* has been the basis for government involvement in the construction of many technological systems including highways, the Internet and nuclear power (Cowan, 1990). During World War II, for example, security issues led the US government to invest over $30 billion in the domestic automobile industry and then, after the war, to even assist in rebuilding the defeated powers' auto industries as part of the post-war reconstruction effort (Nester, 1997). Alternatively, *natural monopoly* arguments have been used to justify government involvement or outright ownership in telephony and electricity networks. Governments can also become involved when a technology becomes so pervasive that it is perceived as a social need. For example, *universal service* policies have provided social welfare arguments for the extension of telephone and electricity networks to ensure access for all citizens (Mueller, 1993). *Public safety* is another frequent justification that has resulted in policies such as licensing and the creation of safety standards in many technological networks (Rae, 1984).

Once founded, governmental and legal institutions can greatly exacerbate lock-in conditions. Beyond the state-sponsored lock-in of standards and technology, government franchised monopolies or direct government ownership can stifle innovation by redirecting incentives towards rent seeking and the development of political and regulatory management competencies (Casten, 1998). In regulated monopolies, for example, managing public service commission politics is as important a core competency as the physical management of electricity generating stations. The situation can be further exacerbated by the fact that regulatory officials tend to be risk averse because the failure of a technological system, such as brown or black-out, could mean an end to their tenure. Thus, the incentives are to invest in established dominant design technology over perceived risky alternatives. Ultimately government agencies can, over time, become captured by the interests they are empowered to regulate (Lowi, 1979). Repeated exchanges can create precedents and standard practices that are rarely questioned, as well as a culture and jargon shared only by the regulators and regulated. This can be further reinforced by "revolving door" employment practices whereby former regulators join the regulated firms at the end of their term of office.

It needs to be clarified, however, that government support is usually focused, not on supporting a specific firm, but on supporting the technological system. In the USA, for example, the government frequently attacks individual firms on anti-trust basis, even while supporting the continued expansion of the technological system. The US government, for instance, sued General Motors for anti-trust violations while at the same time continued the expansion of the road network, the protection of oil supplies and other supports for the auto-based technological system. In fact, natural monopoly regulation exists in theory to prevent abuses by individual companies. The obvious exception, of course, is in the case of state owned utilities, etc.

8. The techno-institutional complex

The previous sections have illustrated numerous individual sources of inertia that can create localized conditions of lock-in. However, at the macroeconomic scale, technological systems and institutions can become intimately inter-linked, feeding off one another in a self-referential system that I term the *Techno-Institutional Complex* (TIC). These complexes are composed of large technological systems and the public and private institutions that govern their diffusion and use. TIC emerge through synergistic coevolution initiated by technological increasing returns and perpetuated by the emergence of dominant technological, organizational and institutional designs. These techno-insititutional infrastructures create persistent incentive structures that strongly influence system evolution and stability. Early in their history, TIC played an important role in facilitating the expansion of useful technological systems like telephone and electricity networks. However, in advanced stages, TIC can become the locus of techno-institutional lock-in, which can slow the emergence of alternative technological solutions. Beyond the already discussed symptoms of technological lock-in, this inertia exhibits itself as market and policy failures that go systematically uncorrected or even exacerbated by institutional forces.

An extreme example of a TIC is the industrial production system developed in Soviet-era Russia and associated communist states (USSR). In the USSR command economy, the institutions of government were intimately tied with the technologies and systems of production (Campbell, 1992). This arrangement created some successes, including the rapid industrialization of a previously feudal country and massive increases in industrial output. However, while intense government intervention can aid an economy in catching up from a position of technological backwardness, it is usually unable to generate the innovations that create future growth (Freeman, 1997). In the command economy, government monopoly status removes much of the dynamism created by competition. Moreover, since most innovations arise from entrepreneurial entrants and not incumbent producers, technological change is inhibited by these systematic policy failures. These factors surely played a role in the general slowdown in Soviet technological and economic dynamism that began in 1950 (Amann and Cooper, 1986) and led to the ultimate institutional collapse.

While it might be expected that these problems would not develop in a free market economy, TIC can still be identified in many OECD countries. The air traffic control system in the US, for example, is managed by the Federal Aviation Administration (FAA) to provide a reliable and safe travel (Rochester, 1976). However, the present guidance systems use dominant design technologies installed by the FAA in the 1950s and 1960s that are two to three generations old. These systems are in need of upgrading to superior, proven technologies and for nearly two decades the FAA has been working on the modernization effort, spending upwards of $41 billion (State Journal Register, 1999). Despite this effort, the FAA has been unable to bring the required new technologies online and continues to rely on the outdated designs. While the FAA was successful in establishing an air traffic control system in the 1950s, this TIC has been locked into its earlier decisions despite great effort to change.

While it could be argued that the USSR and the FAA are extreme cases, elements of TIC can be identified throughout energy systems that utilize carbon-based technologies. Take, for example, electricity generation. Despite recent efforts at privatization and deregulation, electricity generation in most countries has been seen as a natural monopoly requiring government ownership or regulation for social welfare reasons (Hughes, 1983). This situation of government institutional control over the growth of power systems has created TIC in some energy sectors. In many countries, the historic path of development has been through state ownership of the technological system. In the United States, welfare is ensured through a system of private ownership and close regulatory over sight.

To illustrate the electricity generation TIC in a simple framework, a highly abstracted representation of the interrelations among technological and institutional elements is presented in Fig. 2. This rudimentary influence diagram represents electricity generation in the US and illustrates some of the positive feedbacks that foster the growth and incumbency of the TIC. The framework abstracts three basic elements: the physical capital of the technological system itself, the private organizations and/or public institutions that build and operate the system, and the larger societal institutions in which the system is embedded. These groups operate within an environment that includes market and non-market forms of coordination. The purpose of the diagram is simply to illustrate the macro-level systemic feedback that creates and maintains the condition of lock-in. The increasing returns mechanisms at the subsystem levels, such as scale and learning economies and adaptive expectations are presented in a suggestive manner. While detailed cause–effect relations have not been elaborated, the reader should keep in mind the multi-scale nature of the positive feedback mechanisms discussed in the previous sections.

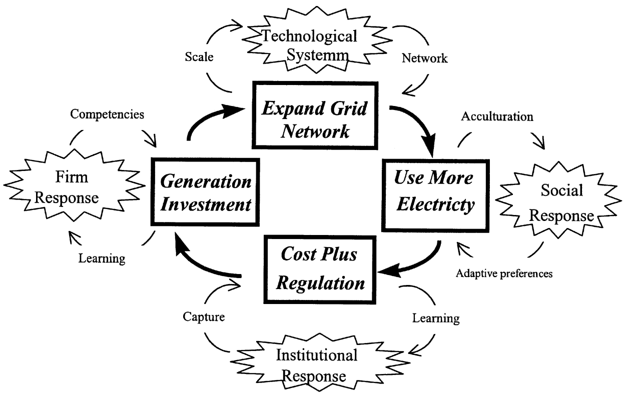

Fig. 2. A simple illustration of the techno-institutional complex that fosters lock-in in electric power networks. See text for elaboration.

The figure represents the TIC after a dominant design has become established and networks of industries and institutions have emerged to support the system growth. The figure has no real starting point, but we can begin where government incentive or approval allows investment in new generation capacity, which expands the scale of the technological system. As the system expands, increasing returns mechanisms drive down costs and increase the reliability and accessibility of the system. The increased availability of cheap electricity tends to encourage increased consumption as more customers become connected and acculturated to the system, and innovators in secondary industries invent new applications and end-use technologies. In response to this induced demand, the government regulators build or approve the construction of more capacity to meet expanding needs, feeding a new growth cycle. As this feedback cycle continues, and the scale of the system increases, the technological and institutional forces of lock-in solidify.

A second example, shown in Fig. 3, is an abstraction of the TIC underlying the automobile-based transportation system. As in the previous diagram, the figure represents a point after the emergence of the ICE automobile/highway system as the dominant transportation design. Again, the diagram has no real starting point, but we can begin where government commissions or builds new roadways. This expansion of the road network simultaneously draws in new drivers and/or encourages more intensive use by existing drivers who can now reach new destinations. While governments frequently subsidize road building directly, it is often additionally funded by the taxation of driving in the form of fuel taxes and registration fees. These funds, derived from increased driving, are then used to expand the network and continue the positive feedback cycle (Lewis, 1997).

Obviously, these simple diagrams are extremely rudimentary and informal, but they do concisely illustrate the positive feedback mechanisms conceptualized in the above sections. It would obviously be more satisfactory to create formal representations that would allow testing of "causal" arguments and logical completeness, but modeling the co-evolution of technological systems and institutions is complicated and not yet well developed. Importantly though, the goal here is not to present a fully elaborated model, but instead provide a framework for policy discussion. Despite the obvious short comings, it is asserted that policy analysts can benefit from this appreciative assessment of carbon lock-in.

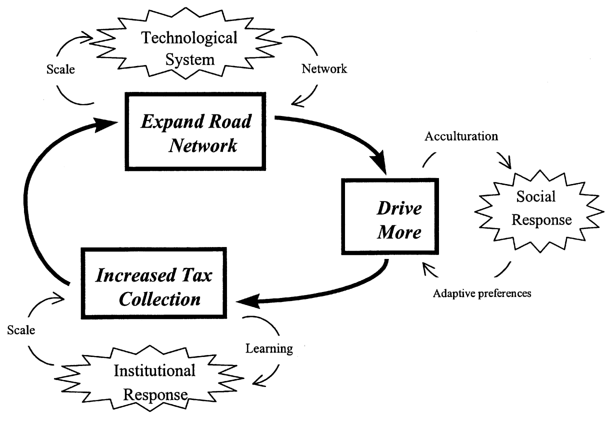

Fig. 3. A simple illustration of the techno-institutional complex that fosters lock-in in automobile-based transportation networks. See text for elaboration.

9. Carbon lock-in

As the examples have illustrated, the idea of techno-institutional lock-in can be considered relevant to the climate change debate. Technological, organizational and institutional forces of lock-in have been crudely illustrated in both the transportation and electricity generation sectors. These two sectors each account for approximately one-third of global carbon emissions and, combined, can reach from one-half to three-quarters of total emissions in many industrialized countries (IPCC, 1996c). Clearly, the issue the of TIC-sustained lock-in in these sectors is a policy question that deserves more discussion.

If the argument is accepted that TIC exist and can create carbon lock-in, then additional, higher level explanations for the policy difficulties and failures of carbon-saving technology diffusion can be found. Techno-institutional lock-in implies that there are systematic forces that make it difficult to change the development path of existing techno-institutional systems. Even with the growing of evidence of substantial environmental risk, these forces can create pervasive market, policy and organizational failures toward the adoption of mitigating policies and technologies. Many existing laws and ministries relevant to the climate issue were created to facilitate the expansion of carbon-based TIC and, in some cases, inhibit entrepreneurs and adopters of carbon-saving technological approaches. For example, in response to government policy makers who could not understand why energy- and cost-saving technologies were not diffusing more quickly, the CEO of Trigen Energy Corporation published a practitioners account of the numerous institutional barriers he encounters in marketing cogeneration technology (Casten, 1998). The fact that government policy makers do not recognize the importance of these barriers illustrates the difficulties that members operating within the TIC have in seeing its pervasive influence.

However, legal structures that inhibit technology adoption are not the only manifestation of techno-institutional lock-in. The difficulties governments have in removing outdated, even counterproductive, subsidy programs can equally be seen as a symptom of carbon lock-in. Despite increasing evidence of climate change and other environmental externalities associated with fossil fuels, governments continue to subsidize fossil fuel industries at an estimated $200 billion annually worldwide (Flavin and Dunn, 1997). In many cases governments have direct control over carbon-intense sectors and, while the rational behavior would be to correct the externality of environmental degradation, governments instead exacerbate the problem through continued subsidization (Goldemberg *et al*., 1988). By some estimates, policies such as "depletion allowance" and the failure to internalize environmental damage distorts fossil fuel prices by a factor of three or more (Hohmeyer, 1988)

As discussed above, the effects of lock-in extend to social institutions and customs as well. In many industrial countries, citizens have adapted their lives completely to the automobile transportation system and actively resist efforts to rationalize it with the environmental and social externalities it can create. In Germany, frequently considered an environmentally progressive nation, attempts to put speed limits on the autobahn, which could reduce emissions, are strongly resisted (Flavin and Lessen, 1994). In the US, the 55 mile per hour speed limit, established during the oil crises to reduce fossil fuel consumption, was overturned in 1995. Labor unions and academic departments, being generally conservative institutions, face the same difficulties as other institutions that co-evolved with the TIC. Even new entrants to the job market find incentives to conform to the existing TIC. Rather than subjecting themselves to the risk of an uncertain career with a new technological alternative, trainees may prefer to prepare for positions in which demonstrated opportunities exist. These "preferences" are not autonomous but evolve in a path-dependent manner with TIC expansion.

The concept of the TIC can also be seen as congruent with *collective action* arguments used in the climate change debate. The collective action problem arises from the fact that, in order to resolve the climate issue, large numbers of dispersed individuals have to take coordinated actions (Sandler, 1992). These groups are handicapped, however, by the fact that the damages from climate change will be spread globally among all members of the planet while costs are concentrated among fossil fuel intensive sectors. In collective action jargon, the fossil fuel industries are considered "preferred groups" as they are in the advantageous position of being smaller in number and able to coordinate their substantial resources to resist any change that threatens their interests, such as limits on the combustion of fossil fuels. On the other hand, the diverse beneficiaries of climate protection policies have much greater difficulty in coordinating their responses. The idea of a TIC is useful in this framework because it serves as a locus for the emergence of preferred groups.

10. Conclusion

This paper has attempted to expand the debate over the "barriers to diffusion" of carbon-saving technologies and an effort has been made to illustrate that path-dependent evolution can create technological cul-de-sacs.[4] It has been argued that the lock-in of carbon-based TIC has had the effect of locking-out alternative carbon-saving technologies through a variety of systemic processes. While it is hoped that this will broaden the barriers to diffusion debate, the ideas presented here also pose questions for more traditional top-down economic modeling approaches. It has been asserted that the combined interactions among evolving technological systems and societal institutions can create important and persistent market and policy failures. However, most economic models tend to abstract away both technological evolution and institutions in their elaboration. If the arguments presented here are accepted, then the failure to treat technological evolution and institutions explicitly may be biasing model results.

The carbon-based TIC discussed here are possibly the largest techno-institutional systems in history and therefore have no real precedent. However, the reader should not be left with the impression that TIC are invulnerable. Incremental change in challenging technologies is always diminishing a dominant design's technological advantage and discontinuous technological transitions have occurred repeatedly in history (Grubler, 1996). Examples include the transitions from whale oil, to gas, to electric lighting; from the vacuum tube, to the transistor, to the integrated circuit, etc. Examples in larger systems include a shift from canals, to trains to trucking transportation and, perhaps, from fixed line to wireless phones. While the carbon-based TIC can create barriers to new technologies, history shows that they can only delay the time when these technologies will be replaced by new dominant designs that resolve the existing environmental contradictions. How such transitions may occur is the subject of another paper currently in preparation.

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[4] There is evidence that entire nations become locked into specific technological trajectories that prevent the adoption of innovations. Cardwell (1972) has identified the succession of technological and international leadership from Spain and Portugal in the Age of Discoveries, to the Dutch in the Age of the Reformation, to Britain during the Industrial Revolution and most recently to Germany and the US. The explanation for this succession is that it is exceedingly difficult to alter technological and institutional systems that have been successful in the past, even in the face of change that makes the current system obsolete.

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