policy

Capital cycles and the timing of climate change policy

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Pew Center on Global Climate Change

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Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Patterns of capital investment by businesses can have a major impact on the success and cost-effectiveness of climate change policies. Due to the high cost of new capital, firms often are reluctant to retire old facilities and equipment. Thus, capital investment decisions made today are likely to have long-term implications for greenhouse gas (GHG) emissions. Because businesses consider a range of factors when making capital stock decisions, policy-makers need to understand and focus on these factors in order to craft effective climate change policies.

The Pew Center commissioned this report to gain an understanding of the actual patterns of capital investment and retirement, or "capital cycles." Authors Robert Lempert, Steven Popper, and Susan Resetar of RAND, with Stuart Hart of the Kenan-Flagler Business School at UNC-Chapel Hill combine analysis of the literature on investment patterns with in-depth interviews of top decision-makers in leading U.S. firms. Their work provides important insights into the differing patterns of capital investment across firms and sectors, and what factors spur those investments.

The authors found that capital has no fixed cycle. In reality, external market conditions often drive a firm's decision whether to invest or disinvest in large pieces of physical capital stock, and a firm often invests in new capital only to capture new markets. In the absence of policy or market incentives, expected equipment lifetimes and the availability of more efficient technologies are not significant drivers of capital stock decisions. With regular maintenance, capital stock often lasts decades longer than its rated lifetime, and the availability of new technology rarely influences the rate at which firms retire older, more polluting plants.

The authors suggest certain policies that can stimulate more rapid turnover of existing capital stock. These include putting in place early and consistent incentives that would assist in the retirement of old, inefficient capital stock; making certain that policies do not discourage capital retirement; and pursuing policies that shape long-term patterns of capital investment. For example, piecemeal regulatory treatment of pollutants rather than a comprehensive approach could lead to stranded investments in equipment (e.g., if new conventional air pollutant standards are put in place in advance of carbon dioxide controls at power plants). The authors also note that even a modest carbon price could stimulate investment in new capital equipment. Ultimately, any well-crafted policy to address climate change must consider and harness market factors and policies that drive capital investment patterns.

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Executive Summary

One important source of climate-altering greenhouse gas (GHG) emissions is the capital equipment that supports the world's economic activity. Capital stock, such as electricity generation plants, factories, and transportation infrastructure, is expensive and once built can last for decades. Such capital also presents important and conflicting constraints on policy-makers attempting to reduce society's GHG emissions. On the one hand, attempts to reduce emissions too quickly may create a drag on the economy if they force the premature retirement of capital. On the other hand, delaying reductions may raise the cost of future actions because the facilities built today can still be polluting decades from now.

This report aims to help policy-makers navigate between these conflicting tensions by providing an understanding of the actual patterns of capital investment and capital retirement and the key factors that affect these patterns. "Capital cycles" have been studied extensively in the empirical and theoretical literature. Nonetheless, the topic remains poorly understood in the debates over climate change policy. In part, there are few good summaries available of the voluminous and complex literature. In addition, the differing patterns of capital investment across firms and sectors can have important implications for climate change policy. Such heterogeneity is not well-captured by the existing theoretical and empirical literature.

This report begins with a brief overview of the existing theoretical and empirical literature on capital cycles. It then turns to its main focus—the results of a small number of in-depth interviews with key decision-makers in some leading U.S. firms. In the course of the study, nine interviews, designed to illuminate the key factors that influence firms' capital investment decisions, were conducted with firms in five economic sectors. The firms interviewed are mostly members of the Pew Center's Business Environmental Leadership Council (BELC). Based on the information gathered during the interviews, this report closes with some observations regarding the implications for the timing of climate change policy.

This is a small study with limited scope. Nonetheless, several consistent and clear findings emerged from the firm interviews:

Capital has no fixed cycle. Despite the name, there is no fixed capital cycle. Rather, external market conditions are the most significant influence on a firm's decision to invest in or decommission large pieces of physical capital stock. In particular, firms strive to invest in new capital only when necessary to capture new markets. Firms most commonly retire capital when there is no longer a market for the products they produce and when maintenance costs of older plants become too large.

Capital investments may have long-term implications. Today's capital investment decisions can have implications that extend for decades. Capital stock is expensive, and firms often have little economic incentive to retire existing plants. The environmental performance of capital stock is not fixed over time and can improve as a firm makes minor and major upgrades. Nonetheless, there are limits to such upgrades, so that investment decisions made today may shape U.S. GHG emissions well into the 21st century.

Equipment lifetime and more efficient technology are not significant drivers in the absence of policy or market incentives. It is often assumed that the engineering and nominal service lifetimes of physical equipment are important determinants of the timing of capital investment. The phrase "capital cycle" derives at least in part from the notion that capital equipment in each sector has some fixed lifetime, which drives the industry's capital investment decisions. This study finds that the physical lifetime of equipment does drive patterns of routine maintenance in different economic sectors, but it appears to be a less significant driver of plant retirement or for investment in new facilities. With regular maintenance, capital stock can often last decades longer than its rated lifetime.

In addition, discussions of climate change policy often highlight the potential of new technology to enable low-cost reductions in GHG emissions. This study finds that however beneficial such technology may be, it will likely have little influence on the rate at which firms retire older, more polluting plants in the absence of policies promoting technology or requiring emissions reductions. New process technology, that is, technology that improves the efficiency and cost-effectiveness of a factory or power plant, requires performance improvements of an exceptional magnitude to induce a firm to retire existing equipment whose capital costs have already been paid. Firms do adopt new process technology, but only when other factors, particularly changes in demand for their products or regulatory requirements and other government policies, drive them to invest in new capital stock.

Firms focus investment towards key corporate goals. Although manifested differently across firms and economic sectors, all the firms we interviewed followed the same basic decision-making process for capital investment. Each year a firm's leadership allocates the funds available for capital investment—first to *must-do investments*, then to *discretionary investments*. The former are required to maintain equipment and to meet required health, safety, and environmental standards. The latter are prioritized according to their ability to address key corporate goals. In particular, firms' capital investment is often driven by the desire to capture new markets. Uncertainty was a recurring theme in all our interviews. Capital investment decision processes are shaped by the desire to reduce the potential regret due to adverse or unforeseen events over the long lifetime of capital stock.

These results are based on interviews with a small number of firms and are by no means definitive. Nonetheless, they suggest that climate policy should combine modest, near-term efforts to reduce emissions and more aggressive efforts to shape capital investment decisions over the long term. In particular:

The long lifetime of much capital stock may slow the rate at which the United States can obtain significant GHG emission reductions. Firms are often reluctant to retire capital and attempts to force them to do so on a short-term timetable can be costly. Sporadic and unpredictable waves of capital investment make it more difficult for climate policy to guarantee low-cost achievement of fixed targets and timetables for GHG emissions reductions. Reductions may be more rapid during periods of significant capital turnover and less rapid otherwise.

Policy-makers should consider early and consistent incentives for firms to reduce GHGs. Incentives ranging from early action credits to emissions trading can take advantage of those rare times when firms make major investments in new capital. Relatively low-cost opportunities for GHG emissions reductions are often available during such periods of investment. This analysis suggests that introducing a relatively low carbon price could serve as a consistent incentive to reduce GHG emissions.

Policy-makers should avoid regulations and other rules that discourage capital retirement. The retirement of older facilities often provides the opportunity for low-cost deployment of new, emissions-reducing technologies. The grandfathering provisions of the Clean Air Act and other environmental regulations may delay the retirement of older plants by exempting them from the environmental regulations governing new plants. At the same time, regulations governing some pollutants may provide an opportunity to address GHGs simultaneously while these investments are being made.

Policy-makers should pursue policies that shape long-term patterns of capital investment. While policy may only make small perturbations in near-term decisions regarding the composition of U.S. capital stock, over the long term, policy may significantly shape the market forces and opportunities perceived by firms. Government-sponsored research and development on new, emissions-reducing technologies and policies such as a cap-and-trade program may have a profound effect on the direction of long-term investments in new capital stock. Overall, the dynamics of capital investment and retirement suggest that policy-makers can set ambitious long-term climate goals, but should allow firms a great deal of flexibility in the timing with which they will respond to them.

I. Introduction

Imagine you are driving your car at night on an unfamiliar road in a sudden, intense rain. Prudence suggests that you should slow down to better avoid potential hazards. But braking too quickly also has its dangers. You might skid, potentially causing as much damage as that threatened by any obstructions on the road. As important as knowing what may lie ahead, a good decision requires reliable information about how well your car handles.

Policy-makers concerned with climate change face a similar problem. Atmospheric concentrations of climate-altering GHGs have been increasing for over two centuries, driven primarily by the increasing energy use and changing land use of the world's economy. While the precise impacts of future increasing concentrations of carbon dioxide (CO_2), methane (CH_4), and other gases remain uncertain, there is now overwhelming scientific evidence that the human-induced atmospheric changes to date have already made a discernable impact on the Earth's climate.[1] Accordingly, the United States and other nations of the world have committed themselves in the United Nations Framework Convention on Climate Change to the long-term stabilization of atmospheric concentrations of GHGs at environmentally and economically safe levels.

This commitment has raised complex and contentious issues about policies aimed at reducing GHG emissions and the timing of such reductions. A significant source of GHGs is the capital equipment—such as electric generation plants, factories, and transportation infrastructure—that supports the world's economic activity. This capital equipment is usually very expensive and can be very long-lived. As an extreme example, most U.S. power plants are at least twenty years old, over a third are older than fifty years, and only a small fraction of all those plants built since the end of the 19th century have been retired.[2] Capital stock may be significantly modified and upgraded over the years. Nonetheless, the environmental performance of an older plant will often lag behind that of a state-of-the-art plant built today. Thus, the United States' ability to reduce emissions of GHGs is constrained by the large stock of emissions-producing capital built up over many decades. On the other hand, plants built today may still be emitting GHGs well into the 21st century, so any delay in reducing emissions could have very long-term consequences.

These patterns of capital investment, driven by the decisions of numerous individual firms throughout the economy to retire and invest in new plants and equipment, are a key influence shaping the success of any GHG reduction policies. Colloquially, the net observed outcome from this ebb and flow of capital investment is often referred to as the "capital cycle." While concise and evocative, this phrase masks at least one important characteristic of the patterns of capital investment—they have no fixed or predictable period. Plants and other large pieces of capital equipment regularly last longer in some economic sectors than in others. But the patterns of capital investment important to climate change policy move in irregular fits and starts. In this study we will use the term "capital cycle" to refer to the timing of firms' retirement of old and investment in new plants and other large pieces of equipment aggregated across sectors and the economy as a whole.

These capital cycles have been extensively studied in the empirical and theoretical literature. Significant data exist to describe the average patterns of capital investment across the economy. Microeconomic theory provides a detailed understanding of how firms ought to make the individual decisions that shape these patterns of capital investment. Nonetheless, the topic remains poorly understood in debates over climate change policy. In part, few good summaries of the literature and its implications for climate change exist.[3] In addition, the differing patterns of capital investment across individual firms and economic sectors are not well-captured by the aggregate data nor easily predicted from microeconomic theory. Perhaps most importantly, theory and data do not provide a complete picture of the key factors that influence the timing of capital investment decisions as they vary among firms and sectors. This heterogeneity in the patterns of capital investment may be crucial to the choice and timing of effective GHG reduction policies.

This brief study provides an overview of the patterns of capital investment and the key factors that influence them as they pertain to climate change policy. The aim of the study is to provide decision-makers with a better understanding of the factors that affect firms' decisions about capital investment and retirement and to highlight policy implications. Because the heterogeneity of capital investment patterns across the economy is relatively under-explored and yet important for climate change policy, the study is designed with a particular focus on the differences between capital investment patterns among firms and among economic sectors and the factors causing the variations. The study begins with a brief overview of both the empirical and theoretical literature on patterns of capital investment. This section provides the basic context for the assessment of the average lifetime of capital equipment in different economic sectors and the key drivers of firms' decision-making that affect capital lifetime. The study then turns to the results of a small number of in-depth interviews with leading U.S. firms in the electric generation and manufacturing sectors, designed to illuminate the key factors that influence firms' capital investment decisions in practice. The study concludes with some observations on the implications for the timing of climate change policy.

Overall, we find that the patterns of capital investment, and the factors that drive this investment, present key opportunities for and constraints on policy-makers attempting to address the threat of climate change. This study aims to help policy-makers pursue a portfolio of climate change policies that avoid costly disruptions in near-term patterns of capital investment, successfully capture near-term opportunities created by these patterns of investment, and positively shape long-term trends in markets and technologies that will affect capital investment and GHG emissions over the coming century.

II. The Literature on Capital Investment Patterns

The empirical and theoretical literature provides much information on patterns of capital investment and the factors that influence them. This section gives a brief overview of that literature to provide some background and context for climate change policy-makers and to help frame the firm interviews to follow. The discussion here reviews the main findings of the empirical data and touches briefly on the microeconomic theory of investment decisions. This section also reviews the quite pertinent but relatively poorly known practitioners' literature found in the industry press.

A. What is a Capital Cycle?

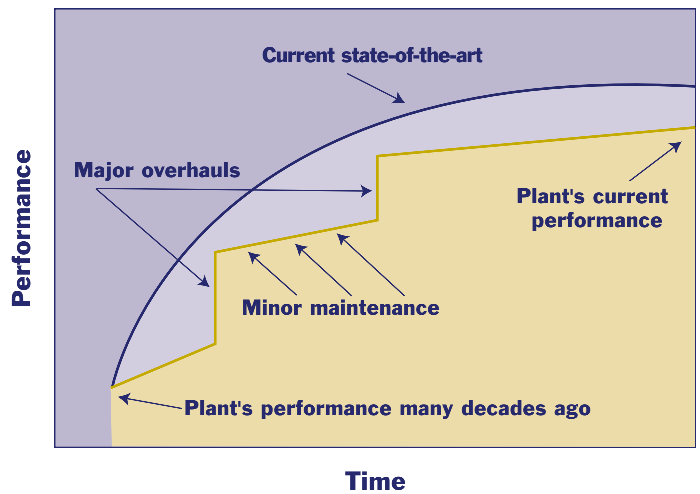
In this study the term "capital" refers to capital goods, or those produced commodities that in turn are required to produce other goods or services. We clearly distinguish between physical and financial assets, only examining the former. In addition, we focus on capital owned and operated by firms as opposed to individuals. Thus, a factory or power plant is the capital of interest in this study. Given the focus of this study, the discussion deals almost entirely with real capital of the fixed-asset character: buildings, installations, and major machinery. These are usually characterized as durable goods. Such goods, by their nature, attract the attention of those interested in climate change policies because they tend to be in place for long periods before their retirement or renewal.

The term "capital cycle" is used in this study to mean the timing of investments in and retirements of large-scale capital stock. While there is no universally accepted definition, the term "capital cycle" is often used to characterize the empirical observation that, in the aggregate, private sector investment decisions often exhibit a cyclical character. This behavior is closely connected to the larger business cycle, but, as we will argue in this study, it is best understood as being fundamentally driven by technological, regulatory, and market factors.

Physical capital can undergo a variety of modifications during the course of its life that affect its performance. This generic life history is captured in Figure 1.[4] The solid curve represents the state-of-the-art performance as it improves over time for some type of technology, such as a coal-fired power plant. The curve could reflect the performance improvement in any one of a variety of characteristics. For our purposes here let us imagine that it refers to one of particular relevance to climate change, such as increased energy efficiency. Typically, this performance continues to improve over time, eventually leveling off.[5] When an individual plant is built, its performance is generally at or close to the state-of-the-art. Subsequently, its performance then trails the state-of-the-art, which continues to improve. Each minor maintenance improves the plant's performance slightly. Major overhauls provide the opportunity to make major jumps in performance. For some technologies and some plants, these major overhauls will return a plant's performance to near state-of-the-art levels. In other cases, the particulars of a plant's situation and/or limitations in the original design will perpetually keep the plant's performance less than that of a new plant. Figure 2 provides a snapshot of the results of such a process, conducted in many power

Figure 1

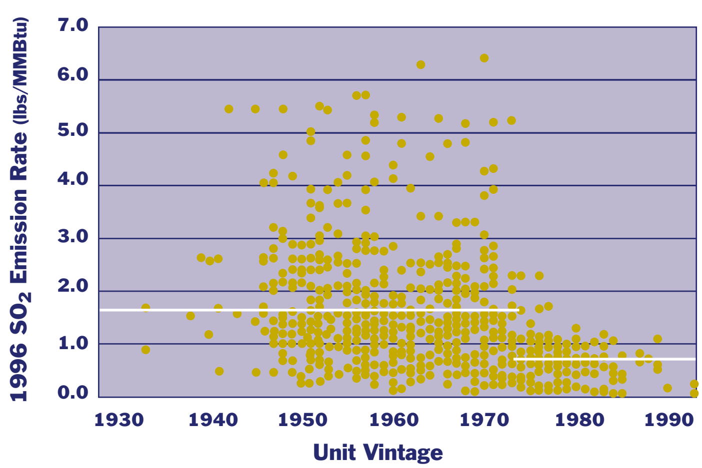
Performance Improvements Due to Major and Minor Overhauls of a Plant Over Time Compared to the Performance of a New, State-of-the-Art Plant



Source: S&T Policy Institute, RAND.

Figure 2

1996 SO_2 Emissions from U.S. Electric Generation Plants, by Vintage



Note: White horizontal lines indicate new source performance standards under the Clean Air Act.

Source: Biewald 1998.

plants for many years, on sulfur dioxide (SO_2) emissions from the electric generation sector. The figure shows the emissions for 886 U.S. coal power plants in 1996 as a function of the year they were built.[6] All plants built in the last 25 years have the low, state-of-the-art emissions levels required by the new source performance standards under the Clean Air Act. Older plants, which are not required to meet those regulations, show a wide range of emissions performance.

In this study, we focus on the timing of major maintenance events and the original decision to build a plant of a certain type. Taken in aggregate across the economy, such decisions help determine the nation's long-term GHG performance and the timescales over which near-term investment decisions affecting emissions are difficult to reverse.

B. Empirical Studies

Often, discussions of the economics of climate change claim that there are lifetimes for various types of capital. Some capital is long-lived, lasting several decades. Other types turn over every few years. The Bureau of Economic Analysis in the U.S. Department of Commerce provides estimates on mean service lifetimes for fixed assets across different sectors of the economy based on census data and other information sources such as prices observed in used-asset markets. The data suggest that the mean service lifetime of capital extends from seven to thirty years, in sectors ranging from office and computing machinery to electric transmissions and distribution equipment (See Table 1). These estimates provide a suggestion of the differential rates of aggregate turnover of capital across the economy.[7]

These numbers do not, however, mean that there is any fixed lifetime to individual pieces of capital. There is a wide range of actual lifetimes within these

Table 1

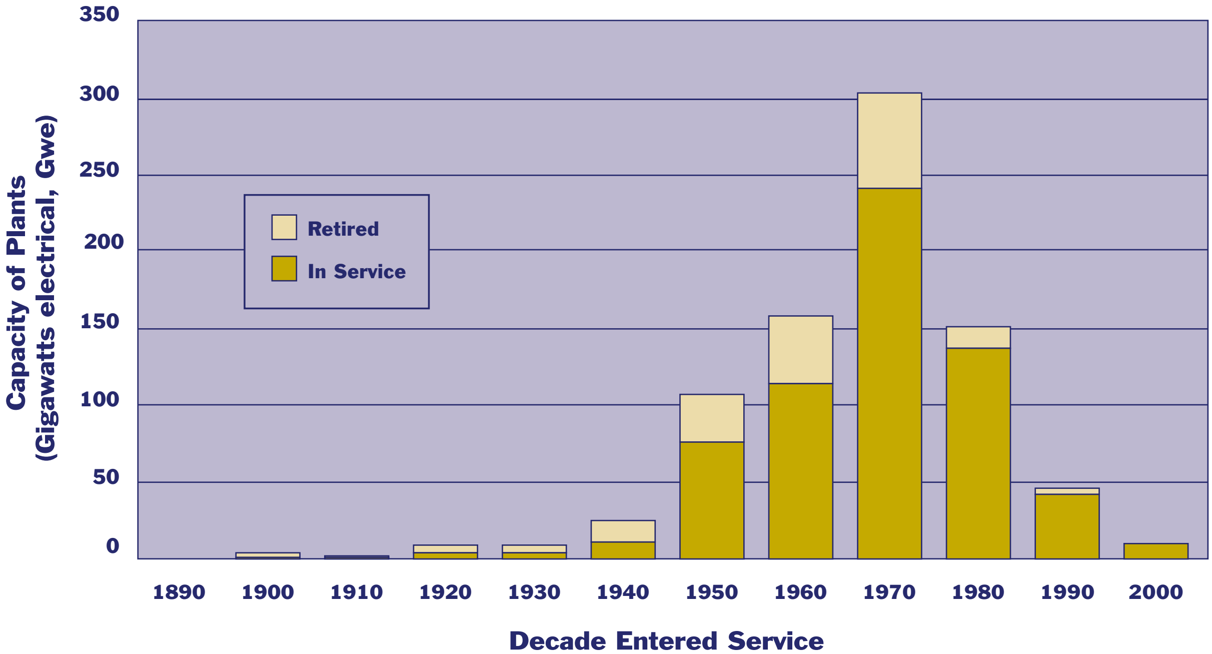
Mean Service Lifetime of Various Types of Capital Equipment

Type of Equipment	Mean Service Lifetime (years)
Office and computing machinery	7
Communications equipment	13
Steam engines and turbines	32
Internal combustion engines	8
Metalworking machines	16
General industrial, including materials handling	16
Electricity distribution, transmission, and industrial apparatus	33
Trucks, buses, and truck trailers	11

Source: Fraumeni 1997.

Figure 3

U.S. Power Plants Still in Operation by Capacity

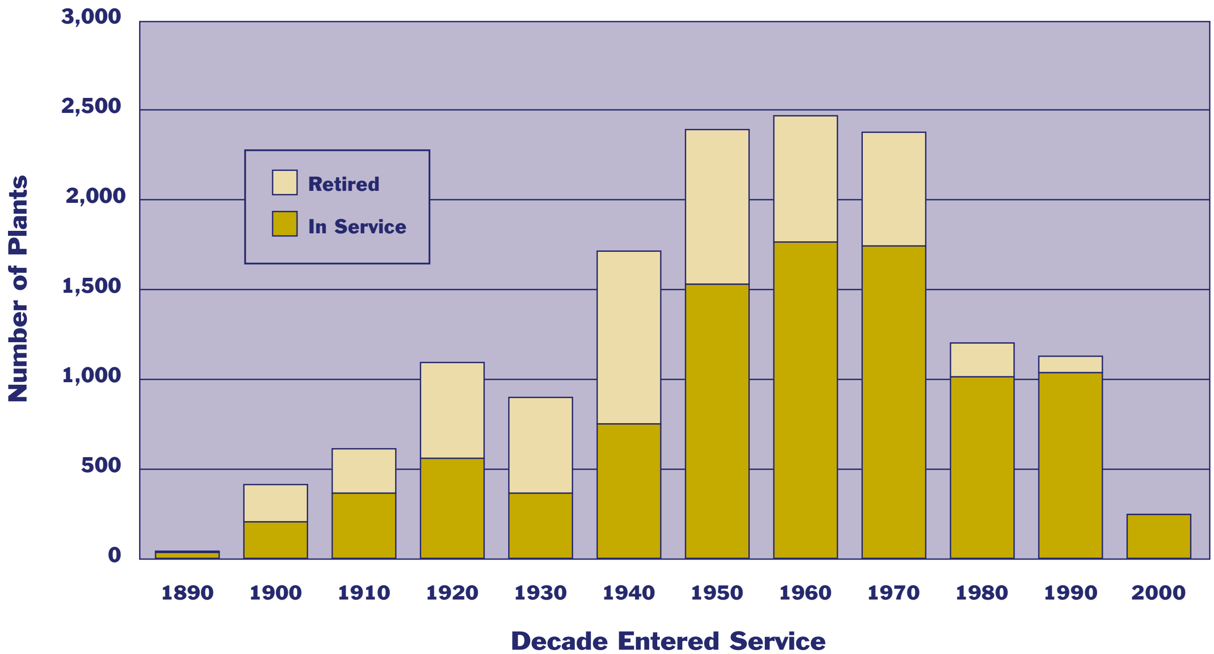


Source: Energy Information Agency 2002.

averages.[8] Figure 3 shows the *capacity* of U.S. power plants built by utilities each decade since the 1890s.[9] While the average age of the plants is only about 30 years, a significant fraction of U.S. generating capacity was originally built over 40 years ago. Surprisingly few plants have been retired. Because U.S. electric generation grew exponentially over most of the 20th century, about 80 percent of the capacity built over the last century is still in operation. This number is skewed by the huge increase in capacity over the last few decades. In addition, these data reflect capacity of plants currently in operation, not the actual amount of power generated by these plants. In practice, older plants are likely to operate less frequently than newer ones. For example, the former may be used solely for peaking load purposes and may generate only a fraction of the power and the emissions that come from newer baseload plants. Nonetheless, Figure 4 shows the *number* of U.S. power plants built since the 1890s that are still in service. Roughly two-thirds of the electric power plants ever built in the United States, and half of those built in the first half of the 20th century, are still in operation.

Figure 4

U.S. Power Plants Still in Operation by Number



Source: Energy Information Agency 2002.

In addition to these macro-level data, the U.S. Census Bureau and others gather data on capital investment patterns at the firm level. These data are surprisingly unexamined by academics, perhaps due to the great difficulty of working with them. The work that has been done provides valuable insights on the timing and nature of capital investment decisions. In particular, recent work with U.S. Census Bureau data on firms at the plant level suggests that the apparently cyclical patterns in the macro-level data are comprised of individual investments by which firms alter their capital stock in a "lumpy" or episodic manner rather than in a continuous fashion over time.[10] The aggregate investment patterns are considerably influenced by large investment projects in a relatively small number of plants. The data also suggest that these large investments result from "threshold" behavior; that is, they are triggered when the differences between the actual and desired capital stocks grow quite large. Smaller plants, plants managed by organizations undergoing administrative restructuring, and plants that switch industries exhibit the lumpiest investment behaviors. The more disaggregated the data, that is, the more one focuses on individual subsectors or firms, the lumpier the investment behavior becomes.

In a theme that will recur throughout this study, the "lumpiness" of the capital cycle suggests that affecting the aggregate pattern of capital investment may depend on understanding and influencing a relatively small number of key decisions at a relatively small number of firms.

C. Economic Theory

Empirical data paint a picture of capital cycles. Economic theory can help us understand the factors and behaviors that influence these cycles, and understanding the factors influencing decisions about capital stock turnover and how they vary across firms and sectors of the economy is of central importance to policy-makers.

There is a long history in the economic literature of examining and explaining phenomena related to capital cycles. In the earliest days, the study of capital cycles was an offshoot of the main preoccupation with what was then called political economy and is now the province of modern macroeconomics, namely determining the factors driving the business cycles in market economies and so discovering the source of the wealth of nations. Economic thought underwent a change in focus beginning at the turn of the 20th century. This refocusing of economic theory came into full force after World War II and led to the rise of microeconomic theory. In microeconomic theory, the primary goal of economic analysis shifted from empirical examination of large-scale phenomena for insights into the macro structure of the economy to a focus on the nature and influence of micro-level decision-making. The investment decision-making behavior of individual firms became viewed as the root source of that larger structure.

The theoretical literature on investment decision-making at the firm level is by now voluminous.[11] The principal finding from this work is that, given certain assumptions about the structure of capital markets and the nature of information, firms are best advised to select the specific investments, from the set of alternatives, that maximize the discounted cash flow (DCF)[12] in the form of the future income stream expected as a consequence of the given investments. As a practical matter, this means that calculating the net present value (NPV)[13] of future income streams is the most authoritative indicator determining which investment option to select. Thus, a business manager deciding whether or not to invest in a new piece of capital equipment would calculate the annual revenues resulting from that investment and the annual costs of making and maintaining that investment. Then, given assumptions about the time value of money into the future, the manager would calculate the present value of the investment by discounting the future revenue and cost streams. Finally, the manager would compare the resulting NPV with that estimated from competing investments, and choose the investment with the highest present value.

This theory also suggests the methods that decision-makers ought not to use in making capital investment decisions. In particular, methods not primarily based on DCF calculations, such as calculating the payback period,[14] are viewed more skeptically in the economics literature on theoretical grounds.[15] In a payback period calculation, a decision-maker would estimate the number of years it would take for the income from a particular investment to pay back the costs of the investment. This approach is theoretically flawed because it puts a fixed time horizon on considering the consequences of the investment. Such a measure may be biased against investments whose most significant benefits come after their payback period. Further, a payback period calculation does not take into account the timing of returns to investment (i.e., the time cost of money).

As the theorists themselves would be the first to point out, this core microeconomic result—that firms should invest to maximize DCF—rests on a series of simplifying assumptions. Yet, the soundness of this principle often holds true even under more sophisticated treatments. In particular, the theory suggests that in the presence of certain types of uncertainty about the future costs and benefits of capital investments, firms ought to maximize their *expected* DCF. That is, the firm ought to estimate the likelihood of various future scenarios, calculate the DCF in each of these futures, and sum to find the average (expected) DCF across the possible futures. As an example, if a firm envisions a two-thirds chance of a DCF of $100 and a one-third chance of a DCF of $40, their expected DCF is $80. Under uncertainty, a firm ought to choose the investments with the highest expected DCF.

It is often difficult, however, to reconcile this theoretical approach with the observed aggregate behavior of capital investment decision-makers across the economy. The problem of aggregating from micro theory to macro observation is one of long standing. It is not as simple as it first may appear to derive rules on the expected behavior of economic agents and then merely aggregate to come up with credible predictions of macro behavior. In addition, the textbook arguments about the behavior of firms under uncertainty are predicated upon a series of assumptions about the information available to the firm and their responses to risk that often do not correspond to the information that is available in practice.

Clearly, firms whose capital stocks are more easily adjusted or whose managers feel less strongly about the consistency of year-to-year earnings may have an entirely different investment response to uncertainty than firms exhibiting the opposite characteristics. The circumstances in which the firms find themselves also matter. In the presence of uncertainty over future prices for a firm's output, the core microeconomic result suggests that the risk-neutral (neither risk-loving nor risk-averting) firm in a competitive market will tend to increase its investment in capital stock relative to the uncertainty-free case.[16] However, if the conditions of perfect competition do not hold, the investment behavior of a firm facing uncertainty in demand is less clear. Empirical evidence would suggest that the response is most likely to be a reduction of the firm's capital stock and a risk averse pre-disposition on the part of the firm would reinforce this inclination.[17] This may stem from the fact that the uncertainties faced by actual firms are greater in number and less well characterized than those appearing in theory.

In part, firms in practice are often risk-averse. In addition, as uncertainty grows, firms are left with trade-off decisions (invest in capital stock and run the risk of over-capacity, or under-invest and face the prospect of demand that cannot be met) that are difficult to resolve in the abstract. Finally, managers generally lack the time and other resources to fully assess all the options theoretically available to them. In practice, they will employ heuristic rules and procedures for decision-making and will often attempt to choose a familiar option they believe will satisfy their objectives.[18] To actually implement decisions, firms will need to compensate for a lack of reliable information on the likelihood of alternative future scenarios. At this point, a great number of factors not included in the textbook DCF calculations may come into play. In other words, the simple theory does not always provide a reliable guide to the key factors that in practice influence firms' decisions about capital investments.

D. Practitioners' Literature

There is also an extensive literature in the industry press in which practitioners share experience and advice on how to make capital investment decisions. This practitioners' literature provides an interesting complement to the theoretical and empirical literature. In particular, it suggests that in practice, firms often use methods regarded as theoretically unsound, such as payback period, for making their investment decisions. Moreover, when firms do use the proper DCF methods, they are often substantially modified to reflect the deep uncertainties and institutional constraints faced by firms.

A recent review of 38 different surveys of investment assessment over a 22-year period found, for example, that payback methods of evaluation remain "important, popular, primary, and traditional" methods for assessing investment.[19] They are often used in conjunction with other measures despite the academic literature having "almost unanimously condemned the use of payback period as misleading and worthless in reaching investment decisions."[20]

There are several reasons why theoretically less-satisfactory methods for decision-making might be used in practice. First, firms may face a principal-agent problem.[21] That is, while the payback method is less beneficial from the point of view of the firm, it may benefit the managers within the firm who use it because the method helps ensure that the investment will prove its worth within a time span that reflects favorably on the manager's career. Empirical studies provide evidence for this type of behavior.[22]

In addition, setting an artificial threshold for a maximum acceptable payback period may reflect a practical attempt to compensate for management's limited forecasting abilities. DCF methods depend on estimates of future cash flows that can extend indefinitely into the future. Such forecasts become increasingly inaccurate the further into the future they extend. The risk that long-term forecasts of returns on investments may be significantly overestimated may be reduced by use of a truncated payback period. This, of course, is something of a shortsighted approach since long-term returns may, in principle, also be underestimated. Nonetheless, payback methods may provide an imperfect rule-of-thumb approach to risk reduction that is easy to compute, transmit, and understand.

There is some evidence to suggest that payback and other such methods do serve this risk-reduction role. For example, the use of payback does not appear to decrease with an increase in firm size or in the resources presumably available to conduct investment decision analyses.[23] To put it differently, "it may be the case that the problem which managers are seeking to solve by the use of payback is not, in fact, handled by the tools many textbook writers espouse."[24] Some authors even argue that, in practice, the payback method will outperform more sophisticated DCF models in deeply uncertain environments.[25]

In addition to the principal-agent challenges and those of deep uncertainty, a variety of practical concerns related to gathering information often affect capital investment decisions. Some firms focus their capital investment decisions on comparisons of initial cost because this information is more certain than costs that occur in the future.[26] However, initial costs are often a relatively small fraction of the equipment's total lifetime costs. In order to adopt a new process technology, firms need to understand the new process. Firms often use comparisons with other firms to gather such information. However, the literature warns that such comparisons can sometimes be misleading, because benchmarked data from another company's project can be skewed to that company's needs.[27]

The practitioners' literature also suggests that cost-justification decisions for capital purchases are often based on inaccurate information, such as misallocated manufacturing costs, "shaky" cash-flow projections, or data massaged to meet hurdle rates. Traditional analyses to support capital expenditures are often predicated on too narrow a base.[28] Another common problem is investment tunnel vision—focusing on piece-meal replacements of conventional technology rather than rethinking the entire flow of work through the shop. Finally, difficulties in allocating costs along traditional channels may affect investment decisions. For example, an investment may show on the books of one department or cost center but actually affect the whole internal value chain. This problem is especially prevalent in multi-step manufacturing where jobs flow from shop to shop or plant to plant, so the particular method for allocating overhead may significantly affect judgments about the cost of alternative investments.

In recent years, the practioners' literature has increasingly addressed the challenge of investment decision-making under deep uncertainty. As described in more detail in Section III C, uncertainty regarding investment projects can take many forms, including lack of available information about important factors and the impossibility of determining an estimate for a particular parameter. DCF methods do not accurately incorporate the interdependence of investment proposals with ongoing capital projects and are less accurate when valuing businesses with substantial growth potential or intangible assets. Furthermore, DCF does not incorporate the value of keeping opportunities open, or the ability of managers to segment investment into distinct stages. A number of methods have been devised to aid in capital investment decisions under such conditions.[29]

One of the most popular investment decision-making methods is the "real options" approach.[30] Real options theory applies concepts and mathematical formalism developed to value financial instruments known as "options" to the valuation of production facilities, research projects, and other types of non-financial investments. The basic idea is to view any investment activity as providing an option for a firm later to undertake further actions. If an investment is multi-staged, going forward with the first stage gives firms the opportunity to update information at a later time and recalculate the value of proceeding with subsequent stages. The real options approach is most useful when a near-term investment is necessary to enable some future action. For example, investing in a research project does not commit a firm to launching some future project, but may be necessary to make that product possible. The real options approach allows managers to value investments with the assumption that in the future they may be able to: abandon or halt investment; defer further investment until additional information becomes available; or make large investments in stages. Thus, the real options approach provides a more accurate valuation, in theory, than traditional valuation approaches, given uncertainty and managerial flexibility. Yet, even this technique commonly requires decision-makers to assign specific probabilities and payoffs to various outcomes and thus does not consistently address the problem of deep uncertainty.

Other methods also exist to deal with the issues surrounding DCF performance under uncertain conditions. These include the use of decision trees, sensitivity analysis, probability theory, simulations, and scenario analysis.[31] Using different principles and approaches, these methods present different DCF values under various assumptions, assess the most likely outcomes under different conditions, or incorporate multiple decision criteria. In principle, these so-called "management science" techniques allow managers to incorporate uncertainly while using DCF models. However, they are complicated and often more commonly employed by academics and consultants than by actual managers, who often resort to more direct approaches to making capital investment decisions.

III. Firm Interviews

The empirical and theoretical literature provides an overview of the timing of capital investments and the factors that influence them. To gain a deeper understanding of these factors, we conducted a series of in-depth interviews with some leading U.S. firms. By examining specific case studies of investment decision-making, this section illustrates how specific factors influencing investment decisions differ across sectors of the economy and among individual firms and describes the variety of circumstances that business decision-makers face. While largely consistent with data and theory, the results of these interviews highlight important differences in emphasis, nuance, and practical application that may be important in shaping climate change policy.

A. Description of Interviews

During the course of this study, we interviewed managers from nine firms representing economic sectors with different characteristics shaping their investment behavior. Our goal was to sample a breadth of firms to gain insights into the key factors that affect firm decisions on capital investments. In particular, we chose sectors that differ in the length of the nominal service life of their capital equipment, the degree to which they are experiencing rapid technological change in their sector, and the level of competition present in the industry. We also emphasized sectors that are important contributors to U.S. GHG emissions. Overall, our interviews focus on the economy's industrial sector, which accounts for approximately one-third of U.S. GHG emissions. We chose to focus the small sample principally on chemical firms and electric utilities, which are quite different in the dimensions we wished to investigate. We did not focus on capital stock and infrastructure in the building and transportation sectors. We also excluded the consumer products sector where individual consumers' decision-making plays a significant role. The influences on capital cycles in the sectors not considered here may be quite different than in those focused on the purchase and sale of large industrial capital equipment for corporations. The firms included in our sample are shown in Table 2 (see page 16).

Most of the firms whose managers we interviewed are members of the Business Environmental Leadership Council (BELC)[32] of the Pew Center on Global Climate Change. BELC members agree that the weight of scientific evidence indicates that global climate change is occurring and that there is enough information available to take action. They also believe firms must act now to assess opportunities for emissions reductions, investments in new efficient technologies, products, and practice; and emphasize market-based mechanisms to achieve emissions reductions and global involvement.[33] In addition, these firms are generally market leaders and may be more sophisticated than others in making capital investment decisions. Therefore, the possibility of systematic bias in our sample of firms must be acknowledged. All, as a matter of corporate policy, believe that climate change is of concern and are interested in exploring response options. However, we found no reason to expect that their view of capital investment requirements and the associated decision-making processes were significantly different from other firms in their respective industry sectors. Note also that while the sample does include a variety of economic sectors, a majority of the sectors covered are capital-intensive and involve either energy-intensive processes or energy production.

Table 2

Firms Included in the Interview Sample

Firms	Sector	Nominal Capital Service Life	Technology Innovation Rates
ABB Honeywell	Electrical Equipment	Medium to Long	High
AEP PG&E (East)	Power Generation	Long	Low
DuPont Rohm and Haas	Chemicals	Short to Medium	High
Georgia Pacific Westvaco	Pulp/Paper	Long	Low
Intel	Electronics	Short	High

The limited scale of this study allowed us to interview only nine firms in five economic sectors. Such a sample is insufficiently large and insufficiently random to provide a statistically valid survey. Thus, the conclusions from our interviews, particularly regarding inter- and intra-sectoral differences, are more suggestive than definitive. Nevertheless, the interviews do provide insights that help explain and clarify the empirical and theoretical literature and can be used to generate hypotheses for future research.

During the interview process, we spoke with up to five managers at each firm. Some interviews were conducted in person, others over the phone. On several occasions we conducted follow-up phone discussions. The interviewees were typically managers associated with the functions of planning, financial analysis, marketing/government affairs, engineering, or technology development. They were largely, but not exclusively, from the corporate offices. However, in several instances we also spoke with plant managers.

Each interview followed a structured protocol (shown in the Appendix) that included questions in the following categories:

- Budgeting practices, decision-making processes, and criteria used to make capital investment decisions;
- Key external factors affecting capital investment decisions;
- The role of technology and how information on new technology is acquired;
- The existence of windows of opportunity and drivers for investing in and deploying new technology;
- Examples of decisions to deploy or not to deploy new capital stock that highlight the range of factors that can affect capital cycles;
- The treatment of uncertainty;
- Any special considerations for capital investment related to GHG emissions or other environmental issues; and
- Investment case histories exemplifying an older plant that has been closed, an older plant that is still operating, or a new plant that has been closed.

B. Findings From Interviews

Capital is a scarce and valuable resource. Though the details and circumstances vary significantly, every firm we interviewed follows the same fundamental procedure for allocating capital among various competing needs. The investment outcomes from these procedures are varied, shaped by the market forces affecting each firm, the technical characteristics of their capital stock, and the inescapable uncertainty each firm faces. In this section, we describe the common capital allocation practices among firms, how these practices differ, and how these practices shape the lifetime of each firm's capital stock.

Common Capital Allocation Practices Among Firms

In each of the firms whose managers we interviewed, the highest-level corporate management determines the total capital available to spend on physical facilities each year and is the final judge of how that capital is allocated across the firm. Each firm decides annually how much capital it can allocate to its physical facilities based on its financial condition, market strategy, and market conditions including the growth rate of key markets and the cost of capital. Individual business units submit proposals for capital projects to the corporate management. The firm then divides its capital allocation decisions into two categories: *must-do* and *discretionary* investments. This procedure helps ensure consistency and fidelity to corporate strategy and fosters competition among the business units.

Must-do investments are those that are necessary to repair, replace, or upgrade equipment on the verge of physically wearing out, that has become a safety risk, or that cannot meet environmental or other regulatory standards. Each business unit in the firm submits a list of such *must-do* investments to the central business management. The management investment committee then allocates funds to the capital investment required to implement these projects. The share of total available investment funding that gets allocated to *must-do* investments varies across firms and business conditions. Among the firms we interviewed, the share can range in a given year from a low of 30 percent of total available funding, leaving the bulk for discretionary investment, to almost all available capital investment funds.

Discretionary investments aim at increasing the business unit's profits, growth, and/or market share. For the firms we interviewed, the key consideration in the allocation of discretionary capital is how a particular investment will advance the key strategic goals of the firm. For instance, a firm may be eager to expand into new markets or, alternatively, to enhance its competitive position in a current market niche. In the former case, a firm will often favor investing in production capacity for a new, expanding market rather than in a project with a nominally higher rate of return in a more stable market. Key corporate strategies served by capital allocation might include cutting costs, building core capabilities, or expanding into new markets. It is important to note that capital investment projects are constantly compared to alternative investments across the firm. Projects that successfully receive capital must not only have a favorable financial analysis, they must also do more to advance the firm's strategic goals than other potential capital investment options for the business:

> *"Theoretically, the rule is that you would do every project that exceeds the cost of capital. But that's just in the textbooks."* (Interview 7)[34]

In the firms whose managers we interviewed, formal financial analysis as described in the theoretical literature—measures such as return on investment, internal rate of return, and net present value—is a crucial though not completely sovereign component of discretionary capital investment decisions:

> *"The appropriate level of capital investment depends on the external and internal business environments. There are some accounting-based rules of thumb on depreciation, etc., but there is much less 'science' involved in the actual decision-making."* (Interview 5)

Often firms will set some minimum threshold for financial performance, such as a minimum rate of return, that a capital project must meet to go forward. The specific threshold (usually referred to as a "hurdle rate") will vary across projects, depending on their connection to the firm's strategic goals. Some firms suggested that their use of such financial measures has evolved considerably in recent years, replacing previous and less theoretically sound measures such as estimates of payback time. In general, firms use a time horizon of five to fifteen years when estimating the future financial performance of potential capital investments. During our interviews, some individuals seemed to worry about sunk costs and suggest these should factor into capital investment decisions,[35] but when pressed on the issue, no one admitted to taking them into consideration as part of their formal capital decision processes.[36]

Differences Between Sectors

While the general procedures outlined show great similarities across firms, the actual criteria and decision processes play out differently for individual firms and between different sectors of industry. These differences are largely driven by the strategies firms choose to follow in the particular market environments in which they find themselves. Actual technical characteristics of the equipment that is the subject of these decisions appear to play a lesser role than market considerations in explaining the differences between firms.

One of the electric utilities whose executives we interviewed has a relatively simple capital allocation process. The first priority is to allocate capital to maintain the firm's generation plants, focusing on those systems that seem most likely to break first. Over the past decade, this firm has then also chosen to make significant upgrades to its existing plants. These latter, more discretionary investments supported a corporate strategy of becoming a low-cost producer to serve the nation's newly deregulated electricity markets. The firm followed a simple decision process for scheduling the capital investment projects across its plants. When the firm began this strategy in the early 1990s, it estimated that it had eight years before deregulation went into full effect. The firm scheduled its capital investment so all its plants were upgraded by the end of the eight-year period.

Electric utilities supply a commodity product. In general, electricity looks the same to a consumer whether it is produced by a 40-year-old coal plant or a modern gas turbine. Firms we interviewed in other sectors, however, have much more differentiated product lines and plants that make products noticeably distinguishable by their potential customers. Under such conditions, firms often conduct a more sophisticated capital allocation process because they continuously need to determine which of many promising new markets to enter and which current product lines to de-emphasize.

One chemical firm in this sample has a corporate strategy focused on producing new chemical products. It explicitly avoids commodity markets, which emphasize cost-cutting. The firm divides its business into three categories—those with good growth opportunities, those managed for cash, and those managed for return—and uses capital investment criteria that vary across these categories. In particular, most of the firm's discretionary capital investment goes to the first category, and the firm requires proposed projects in this category to meet lower rate-of-return thresholds for potential investments than in the other two categories. The firm sees risk in not entering potential high-growth new markets. Thus, it tries to compensate for the uncertain long-term forecasts associated with new markets with a lower ex ante requirement for demonstrating a desired rate of return:

> *"A project in a high-growth business, even with a lower IRR [internal rate of return], will be viewed more favorably than one in a low-growth area. In a low-growth business it takes a long time to recover from mistakes. But in a high-growth area, a wrong decision is more easily recoverable."* (Interview 7)

Another firm has a similar corporate strategy to develop new products for potential high-growth new markets. This firm directs its discretionary capital investments to implement this strategy, relying heavily on creating internal capital markets in which projects proposed by the business units compete for funds based on their estimated financial performance. The firm uses such competition based on financial measures to pursue a variety of key corporate goals. For instance, the firm aims to reduce the amount of capital it needs to generate revenues. In addition, the firm has goals for improved environmental performance. To meet corporate emissions reduction targets, senior managers ask all plants to submit "bids" on emissions reduction improvements. Senior management invests in that portfolio of projects that reaches corporate goals for least cost.

Another firm, which manufactures electronic devices, has a capital investment pattern driven primarily by the pace of technology change in its industry. Its corporate strategy requires that every two years it must replace its primary product, which requires new capital equipment to produce. The timing and scale of capital investment in this firm is largely driven by this fundamental strategy. The firm's capital allocation decision revolves around the particular design tradeoffs needed to implement the desired combination of new features in the new product line. Environmental performance of the new plants is one of many such features considered in these investment decisions.

Even in the small sample surveyed during the course of this project, it became clear that while formal mechanisms for allocating investments within firms may have great similarities across firms, these processes are driven by strategic decision-making based on corporate goals that are themselves largely determined by market considerations and the particular characteristics of the industry. The actual decisions on capital investment made by firms are not what the management science literature would call a simple "knapsack" problem. In a knapsack problem, one maximizes value, subject to some constraint, by selecting in order the highest ranking items until the knapsack is full. One might initially imagine that capital is best allocated by such a process, that is, firms should rank the alternative investments available to them and then select those with the highest NPV until their capital budget is completely allocated. Reality is more complex. Individual investments may have interdependencies. Moreover, uncertainties regarding information quality, future income streams, and to a lesser extent costs and performance may not be predictable or well-characterized. Business units and projects are competing for limited resources given different market dynamics, uncertainties, and sunk costs. Thus the investment decision is much more complicated than a knapsack problem and leads firms to combine corporate strategy with a variety of financial measures (e.g., NPV, payback) and internal competition to make decisions.

Key Factors Affecting Capital Cycles

The decision processes used within firms to allocate capital manifest themselves in a variety of ways that have important consequences for the timing of capital investments and thus for climate change policy. This section weighs the relative influence of several factors on the timing of firms' investment decisions, and finds that the nominal design lifetime of capital equipment and process technology improvements have a small influence on capital cycles. Rather, changes in the markets for a firm's products, caused by economic growth, product technology changes, and/or regulations, have the most significant effect on the timing of firms' capital investments.

Design Lifetime Has Little Influence on the Timing of Plant Investment and Retirement

Large pieces of capital equipment generally have rated engineering lifetimes. For instance, electric power plants are often given a lifetime of 30 to 40 years. Chemical plants are often given lifetimes of roughly a decade. Yet, based upon discussions held in the firms we interviewed, such engineering lifetimes have little influence on the timing of actual, large-scale capital investment decisions.

Large capital often lasts for many decades, if not indefinitely. As mentioned at the beginning of this report, approximately 90 percent of U.S. electric generating capacity built since the 1890s is still in use. The U.S. utility industry built large numbers of coal plants in the 1950s and 1960s during the post-war decades of rapid economic expansion. Virtually all of these plants are still running and they have not revealed any terminal aging processes that will cause them to fail at some fixed point in the future. The firms we interviewed said the lifetimes of such plants could be virtually unlimited.

Plants last far longer than their nominal lifetimes for a variety of reasons. First, rated lifetimes are often an accounting convenience. For instance, regulated electric utilities were allowed to pay back the capital costs of a plant over some pre-determined lifetime, which regulators generally set at 30 to 40 years. But a plant at the end of the payback period is not necessarily any more ready for retirement than a house with a paid-off mortgage would be.

Second, firms have strong economic incentives to keep plants running. As will be discussed in more detail below, it is very expensive to replace the capacity of an older, paid-off plant with a new plant. Many firms stressed that it is rare for them to decommission a plant. Firms will reconfigure plants and, especially in the case of utilities, may run older plants less often. But there are often few economic incentives to tear them down. In fact, utilities with paid-off plants, like homeowners with paid-off mortgages, have a substantial economic incentive to keep old plants running. One utility's managers estimated that the cost of electricity in the United States would be double that of today if the nation had to reinvest the paid-off capital currently embodied in its power generation plants.

Finally, large-scale capital equipment is generally built to last:

> *"Once you design for 15 years or more of service life, effectively as an engineer you have the apparatus for infinite life. We are finding out that a plant built for 15 years' base load capacity can still play a new role in a comprehensive power generation system for 50 years or even more. So technology lifetime is pure guesswork at this point; it is the market price that dictates."*
> (Interview 1)

This view was echoed by several firms. A piece of equipment designed to last more than a decade often will, with proper maintenance, essentially last forever.[37] In addition, any given facility may be part of an extensive, long-lived industrial infrastructure, which may make the specific facility costly or difficult to replace. For example, an existing coal-fired electricity generation plant is connected to railroad lines, the transportation infrastructure, and electric lines, the distribution network. Replacing such a plant with multiple gas-fired generation plants could also require the construction of new and expensive gas and electric transmission infrastructure.

As plants age, the cost of maintaining them and engaging in overhauls to maintain performance increases. At some point, enough things may simultaneously go wrong with a plant that a firm would have to make a large-scale investment to prevent some catastrophic failure or to maintain compliance with safety or environmental standards. This increasing likelihood of multiple failures is one of the few key physical drivers of capital investment decisions. In general, the firm will only retire an existing plant if a random confluence of failures generates abnormally expensive repairs over some short time period.

This behavior was described as a decision analogous to that made by a person with an old, favorite automobile. The owner will repair the car if its systems break one at a time. But if the car ever generates a single, huge repair bill, the owner will junk it.

There were different opinions among the managers of the firms we interviewed as to whether new plants would last even longer than those built many decades ago. Some claimed that today's better scientific understanding of materials is allowing engineers to build new systems that will last longer than those of the past. Others held that new design capabilities allow finer tolerances and reduced redundancy which, in turn, will permit engineers to more easily achieve shorter equipment lifetimes—desirable in a plant designed to emphasize flexibility in response to fast-changing market conditions and uncertainty. In addition, some firms are increasingly designing long-lived investments in a modular fashion so that parts can be more easily replaced if future conditions change.

Market Conditions Have a Large Influence on the Timing of Plant Investment and Retirement

The managers at the firms we interviewed all stressed that external market conditions (i.e., demand for their products) are the most significant factors affecting their capital investment decisions and, in particular, any investment in new capital stock. In each case, the most compelling reason for firms to invest in new capital stock is to meet market demand for their products that they cannot serve with their existing facilities. On occasion, the forced retirement of existing capital requires new investment to meet demand even in a stable market. However, among the firms we interviewed, the more frequent practice is to invest in new capital to meet new demand.

New demand can come from two sources. Firms with commodity products, such as electric utilities, can see the demand for their existing products grow. For instance, during much of the 1950s and 1960s demand for electricity grew vigorously, and utilities built many new plants. In the 1990s, electric demand and utility investment also grew. Responses received during our interviews suggested that the practice is often to forestall the need to invest in new plants for as long as possible by investing in upgrades of existing facilities. But eventually demand cannot be met in any other way than by building new plants.

Markets can also grow for firms with highly differentiated products when customer tastes or new technology create demand for new types of products. If these new products cannot be easily produced by existing capital stock, firms will often respond with new capital investment. Within our interview sample, the most extreme instance is that of the technology pressures causing an electronics firm to introduce an entirely new type of product every two years along with the new capital necessary for its production. The chemical companies we interviewed also must build new facilities to produce new types of products. Nonetheless, firms will still often use existing capital to the extent possible even when technology is rapidly changing their potential markets. For example, one of the electric generation equipment supply firms we interviewed has, to date, run its micro-turbine program with virtually no capital stock investment to support it. At present, its turbines are all manufactured on pre-existing lines for other products.

Growing or changing markets do not, however, necessarily translate into strong pressures to retire existing capital stock. Firms with commodity products, like utilities, often lack an incentive to decommission old plants when building new plants to meet demand.

> *"It is very difficult to justify shutting down old facilities and replacing equipment. If you are going to take production off line…you can't justify the cost of capital for the new project unless it is required to come into regulatory compliance, or if demand is shrinking, or there is a need for new technology to produce a desired product and you don't want to build new technology in an old plant."* (Interview 5)

A study of the electric utility industry estimated that even in the changing electricity marketplace anticipated for the coming decade, only 20 of 886 coal generation plants have costs sufficiently high to force their retirement.[38] Actual retirements could be even fewer, because utilities could lower the costs of these plants by upgrading them, renegotiating fuel contracts, and running them less frequently. Market forces in other industries can make managers more aggressive regarding plant retirement. The economies of scale of new cement plants, for example, provide strong incentives for cement firms to respond to growing markets by building new, larger plants and decommissioning older ones.[39] However, the reluctance to decommission plants in the electric utility industry is by no means unique: even electronics firms can keep their older products on the market for a number of years after the newer versions are released. The plants originally making these older products either stay in operation, or firms shift production lines and consolidate production at older plants. Often a market must begin to disappear entirely before a plant is retired.

Process Technology Usually Has a Small Influence on the Timing of Plant Investment and Retirement

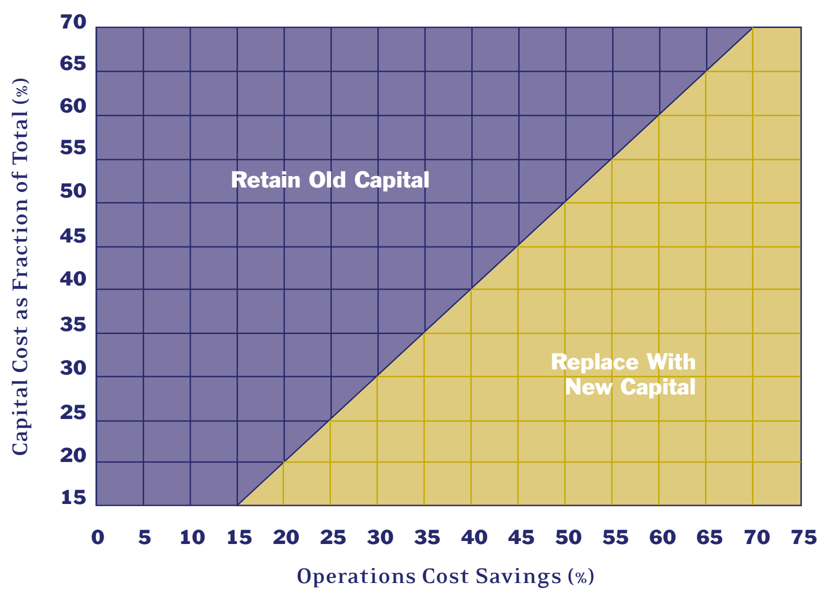
The literature on the impact of innovation on environmental quality often promotes new technologies that could lower costs and increase efficiency compared to currently deployed equipment. We found that efficiency-enhancing technology improvements, while important, have a minor effect on the timing of capital investment decisions.

Students of technology innovation distinguish between two general types of technologies: product and process technologies.[40] Product innovation changes the types of products a firm can offer and their basic design. Jet airplanes and radial automobile tires represent important product innovations. Generally, an industry's customers perceive the results of product innovations directly. In particular, the development of so-called disruptive technologies,[41] such as the Internet, can create the potential for new products and services, the demand for which causes rapid capital turnover through vast sectors of the economy.

Figure 5

Improvements in Operations Costs

Required for New Technology to Prove Economically Superior to Existing Capital Stock



Source: S&T Policy Institute, RAND.

In contrast, process innovations change the ways firms produce their products. Continuous casting of glass, just-in-time production on automobile assembly lines, and dry kilns in the cement industry all represent process innovations. Generally, process innovations affect the cost and efficiency of a firm's operations. An industry's customers only perceive such innovation to the extent it affects the price of products.

Box 1

Why Does Old, Inefficient Capital Persist?

The most modern plants and equipment often have lower costs than older systems that have been in operation for many years. If this is true, why does old, inefficient capital persist? Here is a very simple example, which captures the arguments made in many interviews, showing how economics often favors the retention of older plants.

Imagine an older plant that produces some volume of a product that it can sell at some price. The plant makes a profit of

$$\mathbf{Profit}^{old} = \mathbf{Volume}^{old}\,(\mathbf{Price} - \mathbf{Cost}^{old}_{op})$$

The annual operating costs, $\mathbf{Cost}^{old}_{op}$, may be high compared to newer systems. But because the plant is decades old, the capital costs have been paid off long ago.

Compare this plant to a modern system selling the same product. The price will be the same, because the product is identical. The new plant may have a larger capacity, while the operating costs may be much lower. The profit from the plant will be

$$\mathbf{Profit}^{new} = \mathbf{Volume}^{new}\,(\mathbf{Price} - \mathbf{Cost}^{new}_{op} - \mathbf{Cost}^{new}_{cap})$$

In contrast to the older plant, the firm must pay capital costs $\mathbf{Cost}^{new}_{op}$ for the new plant.

Figure 5 suggests how these basic economic forces can play out differently across sectors and technologies. For instance, the capital costs of a gas-fired electric generation unit is typically a third of the plant's overall costs, so that new process technology needs to produce about a 30% cost savings to justify the replacement of an older plant. The capital costs of a coal-fired electric generation unit are typically two-thirds of the plant's overall costs. Thus, new process technology for coal must produce over 60% cost savings in operating costs to justify the replacement of an older plant. This is rarely achieved in practice, so electric utilities have little incentive to retire older coal plants. In contrast, in the cement industry, new process technology can significantly increase the volume of production, which increases the incentives for retiring older plants.

There are circumstances, not addressed in Figure 5, where the economics of a new plant can justify the retirement of an older plant. First, if the older plant begins to fail, its maintenance costs can skyrocket. Second, if the types of products produced by the old and new plants are different, the prices charged can also be different. In particular, if the older plant can no longer produce products demanded in the market, it will be more profitable to replace it with one that can. Finally, if the old plant does not have the production capacity to meet the demand of a growing market, it may be more profitable to build a new plant.

The discussion above suggests that new product technology can have a significant effect on the timing of capital investments. Our interviews suggest that in practice new process technology does not, unless accompanied by changes in market demand or government policies. The availability of new process technology has little impact because it is very expensive to replace older plants. Even if a plant is inefficient compared to what modern technology can offer, this inefficiency must be very large in order to outweigh the costs of building a new, more efficient plant while also sustaining the loss of production from the one it replaced. (See Box 1.) Thus advances in process technology have a very high barrier to overcome before they drive changes in capital stock.

The availability of new process technology, however, can affect the capital investment decisions of firms faced with changing markets or regulations. Rather than being a driver of the process, new process technology is adopted by firms when it comes time to invest in capital for other reasons. Such technology enters older plants incrementally during their lifetimes as part of the continuing cycle of maintenance and upgrades.

> *"If a new technology comes along that is vastly superior, we will scrap an existing line, but that is a low-probability event. The promise of return is not the equivalent of having a known, functioning facility. It is hard to justify new technology on the basis of efficiency. Dramatically improved yield [from chemical processes] is another matter…This is why we take on energy projects only when times are good and hurdle rates are lower."* (Interview 7)

One utility firm reported that its coal plants, many of which are fifty years old or more, all now have the same emissions as newer plants built in the early 1990s. Many firms in our sample use incremental improvements to enable plants to serve new functions. For instance, old chemical plants shift to new products and old electric generation plants shift from nearly continuous baseload generation to less frequent operations to augment capacity at the times it is most needed. One of the paper products firms likened its century-old plants to the story of the woodsman who still used his grandfather's original axe, although both the handle and blade had been replaced over the years.

But there are limits to the influence such incremental improvements of older plants can have on capacity, cost, efficiency, and environmental performance. One utility we interviewed explained that over the years incremental improvements had improved the flexibility, much more than the efficiency, of operations. Both utilities reported that their existing plants were all approaching the maximum environmental performance theoretically possible from their intrinsic design. It is true that large changes in plant performance can come with major maintenance events in a plant's history. But in some cases the decision to invest in such major maintenance faces the same criteria, such as hurdle rates, as the decision to build a new plant.

Major investments in new process technology generally occur when other factors, such as the need to meet new demand or the failure of an existing plant, force a firm to buy new capital. Many of the firms we interviewed said that when they do build a new plant, they try to use as advanced technology as is reasonable because they expect the plant to operate for a long time. Thus, an opportunity for new process technologies arises during periods of rapid expansion in an industry trying to meet growing and/or shifting markets. These opportunities are important. All the firms we interviewed confirmed that their most significant improvements in plant performance, in environmental and other factors, come when they invest in new capital stock.

Regulations Can Be an Important Influence on the Timing of Plant Investment and Retirement

Government environmental and safety regulations can also significantly influence the timing of a firm's capital investments. Similar to changes in a firm's markets, regulations, such as emission standards, provide an external force changing the requirements of a plant's performance. In contrast to the opportunities presented by market changes, regulations, from the firm's perspective, often divert funds from *discretionary* investments that advance key corporate goals to *must-do* investments required for continued operations. A firm may be forced either to make capital investments that upgrade a plant's performance or to retire the plant if the required modifications are deemed too expensive.

Depending on an industry's particular circumstances and the particular requirements of the government's rules, regulations can either speed or slow capital investment and plant retirements. Some regulations, such as the Clean Water Act or the Resource Conservation and Recovery Act, require universal compliance by particular dates. Although extensions are often allowed on a case-by-case basis, such rules can force firms to make *must-do* investments that replace or significantly upgrade older plants. Thus, such regulations can often accelerate the pace of firms' capital retirement and replacement of capital stock.

Some of our interviews suggested that uncertainty about future regulations sometimes slows the pace of capital investments. Firms were concerned both about what future regulations and regulatory standards would be and how these regulations would be applied. One firm's decision-makers specified that they wanted to know for sure whether CO_2 emissions would be regulated in the future so that they could use this information to make efficient investments today. Some firms suggested that uncertainty, and some skepticism, about the science that would be used to inform future regulations made it more difficult to factor such concerns into their investment decisions. Firms in our interviews often expressed a desire for long warning times for changes in regulations.

Box 2

Grandfather's Axe

DuPont has a production plant in Virginia that first came on line in 1929 to manufacture acetate fiber. It is still running today, 72 years later, producing a different line of products. The life history of this plant provides a concrete example of the story of the "grandfather's axe"—the extent to which a plant can be entirely transformed by modifications over the years, and yet still be limited by the constraints of its original, decades-old design.

Over the last seven decades, DuPont has made significant investments for new production capacity that have maintained the plant's profitability through shifting market conditions. Investments also provided the firm with an opportunity to install equipment that, over the years, has increased the operating efficiency and environmental performance of the facility.

For its first 30 years, the plant produced only acetate fiber for use in lingerie and similar products, as shown in Figure 6. In its fourth decade, the plant went through significant changes. In 1958, facilities were installed to produce Orlon fiber and in the 1960s, initial Lycra® fiber production began. In 1974, a large Nylon production facility was installed, significantly increasing total site production capacity. At about this time, production of the site's original product, acetate, was terminated. In 1990, Orlon production facilities were also shut down due to low profitability. In 1996-97, seventy years after the plant was first built, a totally new Lycra® production facility was installed.

The original production plant included extensive equipment for on-site power generation to provide reliable power at a time when consistent power supply was not available from electric utilities. Reliable power can be critical at chemical facilities, since power interruptions can cause safety incidents and long periods of downtime for repair and system clean-out. The 1929 plant included three pulverized-coal-fired steam boilers and two 3-MW steam turbine generators. Coal was the only viable fuel when the facility was constructed and it was readily available in the region.

Over the decades, the plant site was incrementally expanded to increase production capacity, including the addition of steam and electrical generation capacity. Electric utility reliability increased, so only incremental on-site electrical generation capacity was installed in order to maximize operating efficiency. This was done through steam turbine generator cogeneration and alternative steam turbine or motor-driven refrigeration equipment.

During the mid-1960s, the three original steam boilers were replaced with new field-erected pulverized coal boilers to improve reliability and efficiency. The original boilers, equipped with riveted drums, had limited lifetimes due to metal fatigue and cracking. The boilers installed in the 1960s are still in service. With normal maintenance practices these boilers, with their all-welded construction of drums and membrane walls, are considered to have an unlimited lifetime.

In the mid 1990s a new high-efficiency fired process heater (Dowtherm® vaporizer) was installed to allow incremental increased Nylon production capacity. This allows preferential firing of a higher-efficiency unit as opposed to the original vaporizers. The new Lycra® production facility built in the late 1990s is a highly efficient facility that uses incremental steam demand for heating and solvent recovery, and purchased electricity as its primary energy source.

Since about 1970, incremental investments have been made to provide the increased capacities needed and to meet environmental requirements, e.g., installation of a baghouse for boiler particulate matter control in the 1970s. Low-NO_X burners are currently being installed to achieve boiler furnace slagging improvement, not to meet NO_X emissions reduction requirements. The site is also currently using lower-sulfur coal to meet SO_2 emissions requirements.

While DuPont has successfully adapted this plant to new conditions over the decades, its seventy-year-old vintage does limit some options. Due to its original construction design and a desire for low costs, the plant's power facilities are fairly complex, utilizing features that provide high efficiency by utilizing cogeneration, flexibility in steam as opposed to electric-driven equipment, alternative fuel capability for high uptime and reliability, and an ability to control levels of purchased power to minimize costs. However, that complexity also requires more operators and maintenance than simple facilities, resulting in higher fixed costs. This results in a constant trade-off and struggle between fixed and variable cost pressures.

Box 2 (continued)

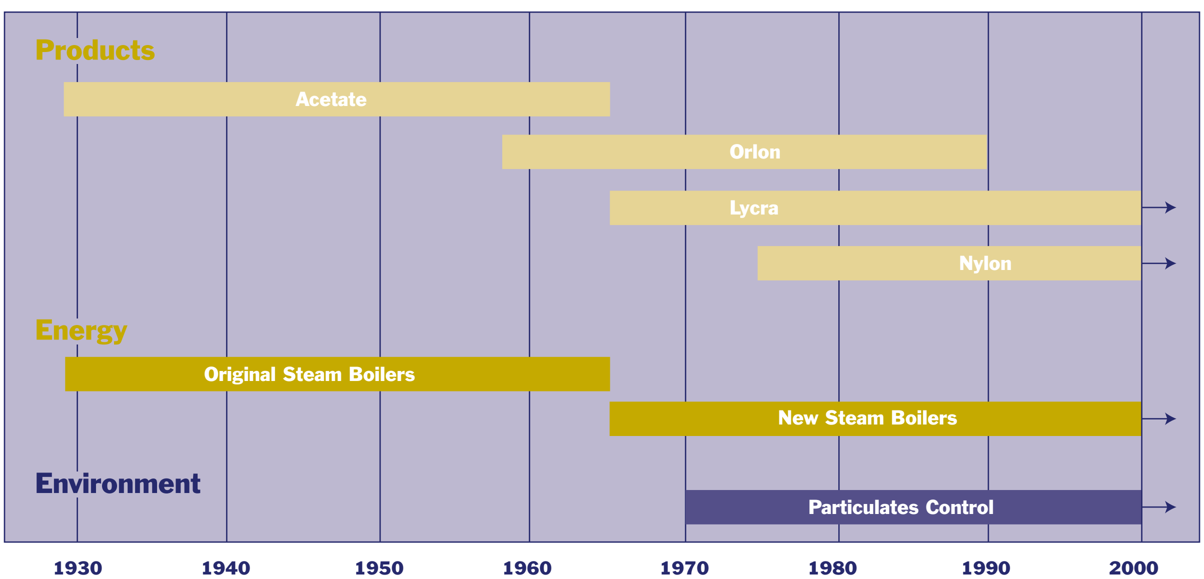
As product mix changes have decreased energy demands, the operating rate of the on-site energy conversion facilities has dropped, in some cases reducing levels of operation efficiency. Equipment also deteriorates over time (e.g., steam turbine internal erosion that lowers efficiency) and energy losses can increase. These effects can slowly put a facility such as this at a disadvantage, but targeted monitoring and corrective action have minimized this problem thus far. While the baseline efficiency of equipment of 1920–40 vintage is somewhat lower than new technology of today, investment to replace or significantly upgrade performance can be very difficult to justify economically.

Environmental pressures are also increasing on this plant. Hazardous Air Pollutant emissions controls, required under the Clean Air Act, could demand further capital expenditures and/or fuel switching to natural gas and oil. Such a change could significantly reduce overall site profitability. Future standards, such as NO_X limits, could also require additional capital expenditures for the site.

When capital stock has not reached the end of its useful life, outside influences can affect the ability to continue its operation. Capital spent on facility improvement, renewal, or replacement in many cases does not allow increased production, unless it is tied together with increased or new production projects, as has been the case over past years for this site. DuPont is exploring the possibility of third-party construction of cogeneration (or combined heat and power) facilities from which DuPont would purchase steam and possibly electricity where state electricity deregulation exists. This arrangement would allow the third party to install an optimal size facility that can efficiently provide steam to DuPont while selling a large quantity of electricity to the grid. In essence, the firm is investigating collaboration with a third party to provide capital for energy efficiency improvement projects and share in the savings as an alternative means of project implementation.

Figure 6

Timeline of Key Events in the History of a 72-Year-Old Chemical Plant



Source: S&T Policy Institute, RAND.

"As a company, we realize that about 20 percent of the fleet will be about 60 years old in about 15 years. But there are a series of questions that arise. What will technology be at that point? And if one even knows the technology status, what will the regulations be over a period of five years or ten to fifteen years? This is what drives the question about new capital investment. The longer the period of warning about regulatory changes, the more one can effectively plan for changes in investment and technology upgrades. We are more likely to see more benefit if given a longer phase-in period because then there would be more choice over technology and there would be less concern that the technology that is invested in would soon need to be scrapped because of short-term changes in regulations." (Interview 1)

Regulations may also affect the timing of capital investments if they treat new plants more severely than older ones. Such *grandfathering* of older plants may lower the cost of the regulatory regime and allow firms valuable flexibility in choosing the most auspicious time to invest in new capital. But it can also discourage new investment. For instance, only new plants, or plants that have been significantly modified, are subject to the Clean Air Act's new source performance standards for SO_2 and nitrogen oxides (NO_X). These grandfathering provisions were put in place on the assumptions that it would be expensive to bring existing power plants into compliance and that such plants would retire in any event within a few decades.[42] The Clean Air Act's New Source Review provisions also describe the plant modifications that cause an older plant to fall under these emissions standards. Some firms we interviewed said that uncertainty about how the government would apply these rules caused them to be cautious about investing in large maintenance projects for their existing plants.

In addition, permitting and siting regulations can often slow investment in new plants. We can return to our earlier example of the existing coal plant on a piece of land zoned for industrial activities, with railroad and electric rights-of-way going into and out of the site. Such locations are rare and very valuable. Communities often oppose the construction of new industrial facilities in their areas, which can make it difficult to site new plants.

The firms we interviewed differed in the impact they ascribed to grandfathering and siting issues on their capital investment decisions. Few mentioned it as a significant influence. For example, one of the two utilities we interviewed has only a small number of older plants. However, the other utility in our sample owns a large number of older coal plants and asserted that New Source Review provides a major disincentive to its efforts to invest in upgrading its older plants.

Old Plants Are Not Always Retired

It is important to note that when declining markets force a firm to retire plants, the equipment does not necessarily stop its effects on the atmosphere. Often a plant is dismantled, and the firm sells the equipment to be redeployed someplace else, for example in a developing country. In the utility industry, firms routinely decrease the utilization rates of older plants during periods when their output is not needed. But these plants remain in commission and can be used again during periods of growing demand. In some sectors, such as pulp and paper, old equipment can become so degraded that it must be disposed of entirely when retired.

C. The Role of Uncertainty

Uncertainty was a theme not only raised in every interview; it ran through the entire course of most conversations. This should not be surprising. Investment in capital stock represents a long-term, largely irreversible commitment. As such, it is a classic case of a decision whose ultimate success is often determined by unpredictable events years into the future. Thus, uncertainty plays a pivotal role in shaping capital investment decisions.

The firms we interviewed generally emphasized five sources of uncertainty. *Market uncertainties* relate to the larger issues of the business cycle and the state of the industry. *Business uncertainties* are more local, related to the risks of operating any business. *Technical uncertainties* surround many investment decisions because the firm must decide among technologies with proven track records or new technologies promising outstanding future performance. Even when there is available literature or a base of experience with a technology, the lack of local expertise is a hurdle to be overcome. *State of the world uncertainties* relate to such things as politics, potential for litigation, and cultural shifts that managers often find exceedingly difficult to address systematically. As discussed above, *regulatory uncertainties* were also a frequent refrain in our interviews.

It is useful to consider another distinction between types of uncertainty. Decision-theorists often distinguish between those uncertainties that can be readily described by assigning likelihoods to alternative outcomes and those that cannot. The former, referred to as "risk," is commonly addressed by standard theories and traditional mathematical tools of decision-making found in microeconomics, finance, and decision theory. For capital investments, these methods treat the risk using expected discounted case flow, that is, DCF weighted by the assumed likelihood of different future scenarios. The latter type of uncertainty is often given a variety of names: "ambiguity," "deep uncertainty," or just plain "uncertainty."[43] Under conditions of deep uncertainty the available information is insufficient to support confident judgments about the likelihood[44] (and hence risk) of various plausible outcomes or to resolve disagreements among parties to the decision who make different judgements about likelihood. The firms we interviewed all described decision-making processes for capital investment consistent with a belief that they face significant deep uncertainty. They responded to this deep uncertainty with three general types of actions and decision criteria.

First, the firms' managers generally use multiple metrics of performance in order to compare alternative investment decisions. In no instance did we find that a firm relies solely on a single statistic, indicator, or criterion, such as DCF, to trigger a positive decision on capital investment or to rank alternative investment options. The firms certainly used various DCF metrics, but these were always combined with consideration of other indicators or with reference to the particularities of each firm's internal situation and business goals. For instance, each firm divided its investment opportunities into *must-do* and *discretionary* investments, and further categorized the discretionary investments by the extent to which they advanced key corporate goals, such as entering a particular new market or meeting levels of environmental performance. The firms would often use DCF metrics within each investment category to compare alternative means for reaching each goal.

> *"The most important question is: Will I be able to recover my money? Money recovery is a prime driver of investment decisions. It's a classic problem: building decisions, investment decisions are based on looking at forward price curves to determine NPV and to look to the possibility of hedging portions of investment. As uncertainty increases, it decreases not only the willingness to build but also means that it becomes harder to find any way to hedge. The biggest problem in making*

> *investments is uncertainty. The basic NPV model will still be relied upon, that calculation will be made, but because of uncertain factors we will run a series of curves, do sensitivity analyses."* (Interview 1)

Second, firms often rely heavily on rules of thumb. For example, many of the firms we interviewed set hurdle rates that a DCF calculation must exceed for a project to be considered. This hurdle rate would often be adjusted to reflect the particulars of that investment or the general situation of the firm. For instance, threshold hurdle rates might fall (that is, become easier to meet) during rosy economic times and rise when times were hard. Some firms raised hurdle rates for investments seen as particularly risky. Thus, required hurdle rates for project approval are often much higher than the average return on capital (30 to 35 percent is an oft-quoted required hurdle rate), not because firms actually demand return on investment at this rate, but rather as a rule of thumb to ensure to the extent possible that the actual long-term return from deeply uncertain investments should be positive.

> *"Historically, capital decisions come down to relative return. Now we don't just look at financial numbers. All numbers included in our calculations are forward-looking assumptions based on historical information. But no one has a crystal ball, so no one calculation will prove accurate per se. We know the market. We know our competitors. This is usually more valuable than financial calculations."* (Interview 7)

In addition, the firms adjusted their criteria iteratively over time. Plants or divisions forward their project list for capital expenditure to a central decision authority. Upon examining the details of specific projects, the central decision-making authority might alter the hurdle rates or approve or disapprove projects despite their meeting or failing to meet those targets. In other words, the decision-makers bring to bear experiential and qualitative understandings that are ancillary to the quantitative analyses due to the limited means for incorporating such insights into formal decision systems.

Third, firms focus their decisions on avoiding regret. Formally, the regret for a decision made under uncertainty is the difference between the payoff of the decision actually made and the payoff of the decision that would have been made with perfect information. For instance, an individual who sells a stock at $30 would have a regret of $10 if the stock's price jumped to $40 the next day. Some firms explicitly mentioned that they tried to avoid regret; for others the concept is implicit in the descriptions of their decision-making process.

> *"In the presence of uncertainty, what senior management will do is assign a risk premium—but not in any classic analytic way. Management will almost always choose the lesser of the absolute amount among investment strategies. For example, in choosing whether to make a large new investment in fundamentally new technology or new plant, versus a smaller retrofit, they will choose the latter because it places a lesser amount at risk—even though the large investment can be shown under most circumstances to be more efficient."* (Interview 2)

Often, firms attempt to avoid regret by postponing capital investment decisions as long as possible. Firms will attempt to reduce the sphere of uncertainty surrounding a decision by seeking to gain more information, usually requiring a passage of time. Firms also avoid regret by focusing on investments with which they are intimately familiar. Investments in technical processes or product alternatives of which the firm lacks direct experience will often be treated with considerable caution if not suspicion. There is a powerful inducement to rely upon systems and processes that have been proven and are familiar. However, firms also use the language of regret to support risky investments in new markets. For instance, one firm explained that it adjusted its required hurdle rates downwards for investment options needed to enter markets the firm deemed critical to its future. The firm believed most investments in promising new markets would be risky, but the firm as a whole would take a risk by investing insufficiently in a promising new area for growth.

IV. Findings

This is a small study with several key caveats on the results. First, only nine firms in five sectors were interviewed, most affiliated with the Pew Center on Global Climate Change as members of its Business Environmental Leadership Council (BELC) and sharing its interest in creating effective solutions to the climate change problem. Thus, this study cannot draw statistically significant conclusions. In addition, only firms based in the United States were interviewed, and interviews focused on their U.S. operations. Patterns of capital investment are at least as important to climate change policy in other parts of the world, particularly in developing countries. We also had little opportunity to gather independent information to corroborate that provided in our firm interviews. Finally, we focus only on large capital production equipment operated by firms and not other physical capital such as commercial and residential buildings, consumer goods such as automobiles and refrigerators, and small pieces of capital equipment such as computers. Large capital production equipment is a significant and long-lived source of GHG emissions. Other forms of capital stock generally have shorter lifetimes, though they may be a significant source of emissions. The patterns of investment in other forms of stock may be dependent on different influences than those examined here.

Nonetheless, there were several consistent and clear findings from the study.

Capital has no fixed cycle. Despite the name, there is no fixed capital cycle. Rather, external market conditions are the most significant influence on a firm's decision to invest or disinvest in large pieces of physical capital stock. Capital is expensive, so firms strive to invest in it only when necessary to meet growing demand for current or new products that cannot be met with existing facilities. Firms retire capital stock when there is no longer a market for the products it produces. Firms also disinvest when a plant is struck by multiple failures, or the costs for upgrades to meet safety or environmental standards grow too high.

Capital investments may have long-term implications. Today's capital investment decisions can have implications that extend for decades. Capital investment decisions made today can shape U.S. GHG emissions well into the 21st century. The performance of capital stock is not fixed over time. It can improve as a firm makes minor and major upgrades, so that the emissions and efficiency of a plant decades old can approach that of newly installed equipment. Capital often conforms to the story of "the grandfather's axe"—over the years a woodsman replaces his tool's handle and blade, but he still claims to chop wood with the axe his grandfather used. But such incremental improvements in factories and power plants can have two types of limits imposed by the original design choices. First, the physical design of the original plant may make it difficult to install the latest technology. Second, investments in major performance improvements are often sufficiently expensive so that firms treat them as if they were investments in new capital. Thus, the initial decision to install one type of technology, such as a coal plant rather than a natural gas plant, can have environmental implications that persist for many decades

Equipment lifetime and more efficient technology are not significant drivers. We find that a number of other factors commonly thought to be important influences on firms' capital investment decisions appear in practice as relatively less significant. The engineering and nominal service lifetimes of physical equipment are often assumed to be important determinants of the timing of capital investment. The phrase "capital cycle" derives at least in part from the notion that capital equipment in each sector has some fixed lifetime, which drives the industry's patterns of capital investment. The physical lifetime of equipment does drive its patterns of routine maintenance expenses in different economic sectors. But it appears to be a less significant driver of plant retirement and investment in new facilities. Because new capital is so expensive, firms have strong economic incentives to keep older capital operating for as long as possible. With regular maintenance, capital stock can often last decades longer than its rated lifetime.

In addition, discussions of climate change policy often highlight the potential of new technology to enable low-cost reductions in GHG emissions. We find that however beneficial such technology may be, it will likely have little influence on the rate at which firms retire older, more polluting plants in the absence of emissions-reducing policy incentives or requirements. New process technology, that is, technology that improves the efficiency and cost-effectiveness of a factory or power plant, requires performance improvements of an exceptional magnitude to induce a firm to retire existing equipment whose

Box 3

Forced Retirements

Georgia Pacific's paper and pulp mill in Palatka, Florida has been running for 55 years. Over the decades the plant's capacity has significantly expanded and the mix of products it produces has shifted, but none of the plant's lines have been shut down. The five lines that have been changed were revised to meet changing markets and more stringent environmental standards.

The Hudson Pulp and Paper Company built the first pulp line and paper machine at Palatka in 1947 to produce the brown paper bags used in grocery stores. In the early 1950s, Hudson added a second paper machine and pulp line to produce additional brown bags and lighter-weight wrapping paper. In the early 1960s, Hudson expanded the plant again, adding a new paper mill for producing tissue, a third pulp line, a bleach plant, and a pulp dryer. The pulp dryer used excess capacity from the plant's pulp lines to produce thick paper boards that Hudson could sell as raw material to firms with paper mills that lacked their own pulp lines.

In the late 1970s, environmental regulations forced Hudson to replace the Palatka plant's three recovery lines. The old recovery boilers and lime kilns were replaced by a single, more energy-efficient, more environmentally-friendly technology. The old equipment, too corroded to resell, was scrapped. At the same time, Hudson added another tissue mill to the facility.

Georgia Pacific bought the Palatka plant in the mid 1980s, immediately adding a third tissue machine. The paper and tissue machines now consumed all of the plants' pulp capacity. The pulp dryer, whose input materials were now diverted to serve more profitable markets, was gradually retired. The firm also modified the facility's original paper mills to produce more bleached, rather than brown, paper as the demand for plain grocery bags declined relative to demand for the decorated bags used in department and specialty stores.

Last year Georgia Pacific replaced the old bleach plant with a new facility to meet more stringent environmental regulations. The Palatka facility now produces pulp without chlorine and the dioxins that can come from chlorine-based bleaching.

capital costs have already been paid. Firms do adopt new process technology, but only when other factors, particularly changes in external markets or regulations, drive them to invest in new capital stock.

Firms focus investment towards key corporate goals. The firms we interviewed all follow the same basic procedures in making their capital investment decisions, although these similar procedures manifest themselves very differently across firms and economic sectors. Each year a firm's leadership decides how much money to allocate to capital investment, based on the perceived economic conditions and the firm's financial situation. These funds are allocated first to *must-do* investments, required to maintain equipment and to meet required health, safety, and environmental standards. The remaining funds are allocated to *discretionary* investments. Business units propose investment opportunities to the firm's leadership, who prioritize the competing investment alternatives according to their ability to address key corporate goals. Financial measures are used to distinguish among the alternative investments to reach each goal.

Box 4

Retired After 132 Years

The Kalamazoo Paper Company built its first paper mills just after the end of the American Civil War. The mills ran until the end of the 20th century before their final owners, Georgia Pacific, shut them down. The mills finally surrendered to adverse market forces after 132 years. Their story suggests the long-term implications and great risks inherent in capital investment decisions.

Throughout their history, the Kalamazoo mills relied on recycled rags and vegetable fiber, not wood pulp, as their raw materials. The original mills were built in Kalamazoo to take advantage of available water power and, located between Detroit and Chicago, a ready supply of recycled rags. In the mid-19th century, there were few trees in the region and no need for a pulp line. The plant prospered over the decades, reaching its heyday between 1940 and 1960, when thousands of employees worked at the site to produce a wide range of high-value-added, coated papers for writing.

By the early 1960s, much of the plant's equipment was becoming uneconomical to run. The Kalamazoo Paper Company began a major program of capital expansion, refocusing the plant from high-value added papers to commodity paper products. The market for the latter was booming at the time, but Kalamazoo ran out of cash before it could complete its expansion, and failed to capture a significant share of this market.

Georgia Pacific bought the plant in 1967 and finished the expansion project. Georgia Pacific retired mills built during the 1920s and 1930s and replaced them with three large paper machines. The plant still relied on recycled fiber, rather than an on-site wood pulp line. Georgia Pacific added another de-inking machine to support paper recycling in the mid 1970s. Nonetheless, the plant was not competitive with other commodity paper producers, so Georgia Pacific used the plant as the initial production site for new products. Georgia Pacific would introduce a new product and produce it at the Kalamazoo plant while it built larger, permanent production facilities with integrated pulp lines and paper mills.

A tornado hit the Kalamazoo plant in 1980, severely damaging one of its mills, which was then retired. The plant continued to struggle during the 1980s and 1990s. It lacked a reputation within Georgia Pacific for excelling in any market. Capital investment decisions over the years had left the plant with equipment that was too large to support specialty production and too small to compete effectively in commodity markets. After several more rounds of investment in upgrades and de-inking facilities, Georgia Pacific tried to sell the mill in the late 1990s. When they found no buyers, they shut the plant down after 132 years.

The patterns of capital investment among firms and sectors are thus driven by the competitive strategies each firm adopts, the extent to which the firm faces required investments, and the amount of funds available to the firm for capital investment. Electric utilities have long-lived capital stock because they cannot differentiate their product and must compete largely on price, while manufacturers of computer chips have relatively short-lived capital stock because they compete by regularly introducing significantly new products. Finally, the significance of uncertainty was a recurring theme in all of the interviews. To a greater or lesser degree, the decision processes managers use to make capital investment decisions are shaped by the desire to reduce the regret of missed opportunities or wasted investment over the long lifetime of capital stock.

V. Policy Implications

One of the factors that makes climate change such a difficult policy problem is that decisions made today can have significant, uncertain, and difficult to reverse consequences extending many years into the future. One important example of such a decision is investment in the large-scale physical capital that constitutes the United States' factories and energy infrastructure. This study has reviewed the timing of such capital investments and the key factors that influence the patterns of investment and retirement of such capital. Although based on interviews with a small number of firms, these results suggest four important implications for climate change policy.

(1) The long lifetime of much capital stock may slow the rate at which the United States can reduce GHG emissions. Firms are often reluctant to retire capital and attempts to force them to do so on a short-term timetable can be costly. Sporadic and unpredictable waves of capital investment make it more difficult for climate policy to guarantee low-cost achievement of fixed targets and timetables for GHG emissions reductions. Reductions may be more rapid during periods of significant capital turnover.

(2) Policy-makers should consider early and consistent incentives for firms to reduce GHGs in order to take advantage of those rare times when firms make major investments in new capital. Relatively low-cost opportunities to achieve GHG reductions are often available during such periods of investment.

(3) Policy-makers should avoid regulations or other rules that discourage capital retirement, since such retirement often provides the opportunity for low-cost deployment of new, emissions-reducing technologies.

(4) The most profound long-term effect policy-makers can have on the timing of capital investment may be actions, such as supporting research on new technologies and development of policies that shape long-term market forces and the opportunities perceived by firms.

The patterns of capital investment described in this study—characterized by long equipment lifetimes punctuated by bursts of investment and disinvestment at the firm level—suggest the need for early, flexible, and modest actions to slow GHG emissions. The existing stock of capital equipment in the United States imposes constraints on the rate at which the economy can reduce GHG emissions. Market incentives make firms reluctant to retire this capital, and climate policies that force them to do so on a short-term timetable could greatly increase the total cost of achieving climate-related goals. However, firms occasionally undergo bursts of capital investment, largely driven by external market forces, when they retire and replace their capital stock. During these periods, firms may have the opportunity to take relatively low-cost actions that can significantly reduce their future GHG emissions. Firms may be more likely to make such investments if even modest policy incentives are in place at the time they make their investment. If firms fail to make climate-friendly investments during these periods, the costs of achieving similar reductions at a later date could be much higher.

Policy-makers find it particularly difficult to address the consequences of near-term capital investment decisions because of the long-term nature of climate change and the deep uncertainty regarding the timing and impacts of global climate change. Policy-makers face competing risks setting GHG mitigation policies under such conditions of deep uncertainty. If they demand too stringent near-term emission reductions, they can impose unnecessary costs on the economy. If they demand too lax near-term reductions, they will make it much more costly for people in the future to respond successfully to the climate change problem. The dynamics of capital investment suggest that one key component of the path out of this dilemma is to impose near-term incentives for firms to reduce GHG emissions, but give firms the maximum flexibility in deciding when and how to respond to such incentives.

There are a variety of ways in which policy-makers could create such flexible incentives. Early action credit or "baseline protection" programs[45] would allow firms to receive credits towards any future regulatory requirements for GHG reductions by taking voluntary actions to reduce emissions before such regulations go into effect. For example, if a firm reduced its emissions this year by 10 percent, it could apply those reductions to some future emissions reductions requirement, even if it didn't go into effect for a number of years. Such early action proposals run the risk of unduly constraining the options of future policy-makers, because any rules they devise must be consistent with the early action credits already granted. But early action programs would help remove the disincentives for early reductions inherent in the current period of regulatory uncertainty, in which firms do not know whether and when they will face regulatory requirements to reduce GHGs.

Several bills before Congress have proposed such early action credit or “baseline protection” programs.[46] The Bush Administration also has proposed, and many states have already implemented,[47] improved inventories of the sources of GHG emissions. These inventories provide firms and the public clearer information on emissions generated by individual firms and the effectiveness of firms’ actions to reduce them. Such inventories could serve as a basis for baseline protection, recognize innovative leaders, and spur action by those firms that are lagging in reductions.

In addition to these voluntary programs, policy-makers could implement an emissions trading program that would create financial incentives for firms to reduce GHG emissions. Such a trading program could be purely domestic or could link to the emissions trading and technology transfer programs being implemented by other nations. In principle, in the near term such trading programs need not guarantee large emissions reductions in order to have significant long-term benefit. Our interviews suggest that an emissions trading program with even a very modest price for credits would bring GHG emissions concerns into most firms’ capital investment decisions. Firms would then be far more likely to identify opportunities to reduce emissions as part of their capital investment decision process.

Trading programs provide firms significant flexibility as to how they allocate emissions reductions among themselves and among plants. The flexibility of such trading programs over time can be enhanced by allowing the banking of emissions reductions or the trading of emission permits valid in different years, so that parties can earn, or borrow against, credits earned during their windows of opportunity for cost-effective emission reductions.

In addition to external market forces, government environmental and safety regulations can also affect the timing of capital investment and retirement. In contrast to market forces, firms are provided notice of new regulations. Thus, major regulatory changes, unrelated to climate change, may provide an important opportunity for low-cost reductions in GHG emissions. For instance, the Bush Administration has proposed significant changes in the regulatory requirements for electric utilities for emissions of three pollutants: SO_2, NO_X, and mercury (Hg).[48] There are also "four-pollutant" bills before Congress that include emissions limitations on CO_2 as well as the three conventional pollutants.[49] The proponents of such legislation view it as a means to exploit an important "window of opportunity" for relatively low-cost carbon reductions, since firms will need to invest in new capital to address the other three pollutants. If utilities are induced to invest to address the first three pollutants only, the costs of delaying regulations on carbon may be high.[50]

Policy-makers should also consider reducing the disincentives for plant retirement generated by tax laws, environmental regulations, and other regulatory requirements. For example, the New Source Review provisions of the Clean Air Act exempt older plants from certain requirements. These provisions were originally crafted to take advantage of the patterns of capital investment. It was assumed that forcing existing plants to comply with emissions regulations would be very expensive while new plants could achieve compliance at much lower cost. It was also assumed that the bulk of existing power plants, many of them about 20 years old at the time, would naturally be retired within a decade or two. However, retirement rates for these power plants have been much lower than expected at the time. Our interviews suggest that New Source Review plays only a minor role in slowing such retirements. Nonetheless, policy-makers could beneficially address climate change as well as a host of other environmental issues through more consistent application of environmental rules (to new and old plants alike) while providing flexibility through mechanisms such as emissions trading.

Over the long term, perhaps policy-makers can have their most significant impact on firms' investment and disinvestment decisions by promoting new technologies that will shape the market forces firms face in the future. The goal of stabilizing atmospheric concentrations of GHGs will eventually require, over decades or centuries, society to reduce net GHG emissions to near-zero.[51] To achieve such reductions will require a significant transformation of the technology used throughout society to produce energy, manufacture goods, and provide transportation. Policy-makers can play several key roles in shaping the firms' incentives to adopt new technology at the time when they choose to invest in new capital. First and foremost, government-funded research plays an essential role in creating new, emissions-reducing technologies. However, research in the energy sector declined significantly over the last decade.[52]

In addition, the government can also play an important role in advancing new process technologies to market readiness. Recent research suggests that "learning by doing" may play an important role in decreasing the future costs of reducing GHG emissions.[53] "Learning by doing" describes the process by which the costs of new technologies drop over time as experience is gained in their production and use. However, firms are often reluctant to invest in new technology that lacks a significant track record. Policy-makers may need to pursue policies that enhance the development and promote the initial market diffusion of new technologies with policies such as tax credits, accelerated depreciation of investments reducing GHG emissions, and government procurement of low-emitting technologies.[54] Such policies may play an important role in reducing firms' uncertainty about the performance of new technologies and accelerating "learning by doing," and thus increase the likelihood that new technologies will be deployed during periods of rapid capital turnover.[55]

As suggested by the results of this study, the dynamics of capital investment and retirement can slow the adoption of promising new, emissions-reducing technologies. Notwithstanding the technology's potential merits, firms most often make significant changes in their technology base when unrelated external factors force them to invest in new capital stock. Policy-makers may speed the pace of capital investment by pursuing policies that seem to have little immediate relationship to climate change policy. First and foremost, they can promote the rapid economic growth that helps provide new, investment-inducing market demand. Over the last decade, rapid economic growth in the United States has been accompanied by a decline in emissions intensity, the emissions per unit economic activity, in many sectors of the economy.

In addition, policy-makers may be able to foster the new product technologies that induce firms not only to invest in new capital stock but also to retire the old. In the past, innovation in product technologies such as automobiles, jet aircraft, and the Internet have shifted consumer demand and induced waves of capital retirement and investment by firms in response. Such innovation may already be affecting investment in some of the sectors we addressed in this study. For instance, advances in information technology and gas-fired generation turbines, combined with regulatory reform in the electric sector, are beginning to make small-scale, on-site power plants effective to service the electricity demand for individual customers. This capability offers the promise of selling electric power, not as a commodity, but as a service with a package of features including higher reliability. If this market develops, firms will invest to enter it. Policy-makers can promote this type of product innovation by: funding scientific and technology research, encouraging the development of new markets through market incentives for the diffusion of new technologies, removing barriers to technology adoption such as subsidies for incumbent technologies, focusing trade and development policies to encourage adoption overseas, and introducing standards, green labeling, and other information dissemination programs that promote environmentally-conscious consumer demand.[56]

Finally, policy-makers must contend with the deep uncertainty pervading the climate change problem. Firms frequently demand more certainty regarding climate change policy. This request is reasonable, since capital investment decisions are difficult enough for firms without the additional worry of changing regulations. But policy-makers must strive to increase regulatory certainty in a situation where it is unknown what level and pace of emissions reductions are ultimately required to achieve the long-term goal of stabilizing atmospheric concentrations of GHGs at environmentally and economically safe levels. Understanding the patterns of capital investment is one key to resolving this dilemma.

As described in this study, the capital allocation process within firms is driven by the need to grapple with deep uncertainty about future markets and technologies. Regulatory uncertainty affects the scope, not the character, of a firm's decision problem. Accordingly, policy-makers should strive for certainty in the policy process, rather than the precise long-term goals of that process. More research is needed, but the patterns of capital investment suggest important constraints that would enhance the effectiveness of such an adaptive climate-change policy process. As one example, firms tend to use a time horizon of ten to fifteen years in their capital investment planning. Climate change policy-makers should send clear signals about long-term goals, but allow firms roughly a decade to adjust to changing requirements for reducing GHGs. Thus, the pattern of setting ten-year milestones on the path to our long-term stabilization goals, as envisioned in the Framework Convention on Climate Change and as echoed by the Kyoto Protocol, may be a crucial component of climate change policy.[57] Such periodically updated, decadal milestones will help firms plan confidently for the relative near term within the context of long-term, highly uncertain, evolving regulatory requirements.

VI. Conclusions

Capital cycles pose important and conflicting constraints on climate change policy-makers. Once built, large units of physical capital—the factories, power generation plants, and transportation infrastructure that support the nation's economic activity and are major sources of climate-altering GHG emissions—can operate for many decades. The long lifetime of the United States' existing capital stock slows the rate at which emissions can be reduced because premature retirement can be expensive. On the other hand, delayed action can raise the costs of future reductions because capital built today may still be emitting decades from now.

This study aims to help policy-makers navigate between these conflicting tensions by providing an understanding of the actual patterns of capital investment and retirement and the key factors that influence these patterns. The study is based on reviews of existing empirical and theoretical literature, but focuses on a small number of in-depth case studies with key decision-makers in U.S. firms.

One common view, occasionally reflected in the decisions of policy-makers and the proposals of policy analysts, is that capital has a fixed lifetime based on its physical characteristics. That is, each factory or power plant has some fixed operational lifespan and, when it expires, the plant is retired. This study finds that this is not an accurate representation of actual conditions. Rather, patterns of capital investment are largely driven by external market conditions. Capital is scarce and expensive, and firms strive to invest in new capital only when it is necessary to implement their business strategies. Generally, firms prefer to invest in new capital stock only when necessary to capture new markets. Firms seek to disinvest in old capital stock only when that capital no longer produces products that the market demands.

There are exceptions to these rules. Environmental and safety regulations can force firms to retire old capital. Plants do require regular maintenance, which, over time, can lead to significant improvements in their capabilities. On occasion, firms will retire plants when multiple failures become too expensive to fix. Nonetheless, firms strive as much as possible to focus their capital investments on capturing new and growing markets and confine their disinvestments to plants which no longer meet market demand.

These patterns of capital investment have several important implications. First, capital does not last for any fixed period of time. The differing capital lifetimes observed across various industries are due in significant part to differences in the rate at which new products, incompatible with existing production facilities, are introduced. Capital is relatively short-lived in the electronics industry because firms must rapidly introduce new products, many of which cannot be produced on existing production lines. Capital is particularly long-lived in the electric generation industry because consumers cannot distinguish between electricity produced by a new plant and one decades old. Second, new technology that increases efficiency and reduces cost generally has little influence on the patterns of capital investment. Firms will adopt such technology, but only when other forces influence them to invest in new technology.

These patterns of capital investment and disinvestment have important implications for climate change policy. The long shadow that capital investment decisions cast over time suggest that climate policy should pursue a portfolio of policies designed to encourage modest, near-term efforts to reduce emissions with more aggressive efforts to shape capital investment decisions over the long term. In particular:

Capital turnover may limit rates of GHG reductions. In the near term, patterns of capital investment and retirement are driven by forces largely unrelated to climate change policy. Any attempt to use climate policy to force firms to retire capital in the short term may be very expensive. Because capital is scarce and large-scale capital investments risky, firms try to avoid the expense of replacing existing plants with new capital equipment. Generally, firms only make such investments when there is no other way to exploit significant changes in their markets (e.g., strong demand growth or technology-enabled shifts in the types of products consumers prefer) or when forced to do so to meet safety or environmental regulations. There are many ways to reduce GHG emissions other than replacing capital stock, including investing in efficiency improvements and more measured use of resources. Nonetheless, the inertia embodied in current capital stock may impose significant constraints on the rate at which the United States can reduce emissions.

Miss no opportunity for near-term, low-cost emissions reductions. The longevity of capital stock strongly suggests that policy-makers miss no opportunity to encourage firms to consider the potential for GHG reductions when, for whatever set of reasons, the firms decide to invest in new capital stock. The ebb and flow of capital investment across firms and industries will present “windows of opportunity”—

defined less by the calendar than by points in the development of individual businesses—when firms may be able to make choices with significant, long-term reductions in future GHG emissions at little incremental cost. For example, a firm may invest in a gas power plant rather than coal or design a new chemical plant to reduce its carbon emissions. Policy-makers are unlikely to be able to anticipate such opportunities, however, so their best option is to provide modest, but consistent incentives to firms to make such investments. Such incentives could include domestic trading programs that place a small price on carbon and technology programs ensuring that a variety of market-tested, low-risk options for GHG reductions are available when firms choose to make capital investments. In addition, policy-makers should coordinate major regulatory changes so that firms consider GHG reductions when forced to respond to other regulatory requirements. For example, policy-makers could consider the benefits of including carbon emission restrictions in future updates to the Clean Air Act—e.g., through "four-pollutant" legislation. One key window of opportunity, not addressed in this study, is that presented by fast-growing developing nations that may invest $1.5 trillion on new power generation over the next two decades.[58]

Do not discourage retirements. Delaying the retirement of existing capital stock offers both opportunities and costs for GHG mitigation. On the one hand, the retirement of older plants offers an immediate opportunity for firms to invest in more modern, low-polluting equipment. On the other hand, extending the lifetime of an existing plant may allow a firm to await the maturation of new technology, which will allow it to achieve even higher levels of environmental performance. While forcing the retirement of capital would increase the cost of climate change policies, policy-makers should also avoid incentives that would encourage firms to delay retirement. For instance, some environmental regulations currently allow grandfathering, that is, they exempt older plants from compliance. Policy-makers should consider replacing such grandfathering provisions with alternatives such as market-based emissions allocations, which include older plants but allow firms flexibility in the timing of investments to reduce the emissions of such plants.

Help shape long-term market forces. In the near term, climate change policy may have a relatively small influence over most firms' patterns of capital investment. Over the long term, however, policy-makers can aspire to enabling more significant change. One key means at their disposal is to support research and development of new emissions-reducing technologies. Ultimately, the goal of stabilizing atmospheric concentrations of GHGs will require very large reductions of net emissions, to near zero,[59] though it is uncertain whether such large reductions may be required now or in fifty, a hundred, or more years from now. The technology to enable such large reductions does not currently exist. Government-funded research and incentives for early deployment may be vital to its emergence.

No matter how impressive any new technology, however, firms may only invest in it slowly unless they perceive it as opening important new markets. Policy-makers should thus be mindful of opportunities to help create markets for new emissions-reducing technologies. One key advantage of market-based incentives for regulating carbon, such as emissions trading, compared to traditional standards, may be the open-ended possibilities the former offers for low-carbon technologies to become a strategic growth market. Expanding competition in previously regulated sectors may also provide such market opportunities. Deregulation in the electricity industry may help open markets for on-site distributed generation, which can allow providers to compete on the basis of energy services, including quality and reliability of power, not just cost. Finally, policy-makers can encourage the development of new markets, such as a market for off-grid renewables in developing countries, through development and trade policies and the reduction in subsidies for incumbent technologies. Ultimately, however, one of the most important drivers of strategic markets may be strong demand for environmentally-friendly products among the world's consumers.

Endnotes

1. National Research Council (2001) and Houghton (2001).

2. Energy Information Agency (2002).

3. The debate over the timing of GHG abatement policies makes significant reference to the lifetime of capital. For instance, Wigley, Richels, and Edmonds (1996) invoke the long lifetime of capital stock to argue for emissions reduction programs that begin slowly. Grubb, Chapuis, and Ha-Duong (1995) invoke the "inertia" in the economic system resulting from long capital lifetimes to argue that emissions reductions should not be delayed. But these analyses, as with even the most sophisticated economic models used to adjudicate among alternative climate change policies, generally treat capital as having some exogenous, fixed lifetime, contrary to the findings in this study.

4. This is intended as a simplistic illustration of the interactions between a variety of phenomena; the exceptions to this basic story are legion.

5. This illustrates the differences between change wrought through incremental improvements to an existing technology and the revolutionary introduction of a completely new-in-principle technology. See, e.g., Sahal (1981).

6. Biewald et al. (1998).

7. The technical issues involved in estimating depreciation rates and fixed asset service life are well beyond the scope of this discussion. The interested reader will find useful discussions in Katz and Herman (1997) and Fraumeni (1997).

8. Among the complicating factors in gaining more accurate estimates are the facts that some data are reported on an establishment basis while others are reported at the company level; further, owing to problems of asymmetric information (now generally referred to as the "market for lemons effect" for which G. Akerlof received the 2001 Nobel Prize in Economics), used asset prices may understate the true value of the aging capital stock as a whole. This presents just two reasons why estimates of service life may vary from those actually observed in any specific instance.

9. Energy Information Agency, *Form EIA-860A Database, Annual Electric Generator Report–Utility, Year 2000*, Revised April 8, 2002.

10. Doms and Dunne (1998).

11. For good overview discussions, see the articles on "capital as a force of production" and "capital budgeting" in Eatwell et al. (1987), pp. 327-333 and 341-342, respectively.

12. The discounted cash flow (DCF) is an estimate of future cash flows that has been discounted into the present by applying an appropriate time-sensitive factor such as a company's estimated cost of capital.

13. The net present value (NPV) is the future income expected from a project, after bringing it into the present by applying the appropriate time discount rate, net the investment costs.

14. That is, calculate the annualized savings or increased net income from an investment project, divide into the project investment cost, and determine the years required to pay back the costs of the project.

15. See, as a good overview of the standard microeconomic treatment of investment, Nickell (1978).

16. The bet is that the extra revenue gained by having production facilities in place to take advantage of an upswing will offset the potential losses occasioned by a downturn in prices.

17. See the treatment in Nickell, op. cit., pp. 82-84, and similar treatments in K. R. Smith (1971) and Rothschild and Stiglitz (1971).

18. Herbert Simon first described this "satisficing" behavior of firms. See Simon (1959).

19. Lefley (1996).

20. The principal objections to payback are that it is a cash concept, does not measure profitability or returns after the payback period, and does not take into account timing of returns to investment (i.e., the time cost of money). It also carries a built-in bias against longer-term investments that may, in fact, be crucial for survival for the firm. See Pike (1985).

21. A principal–agent relationship arises when the owner (the principal) of an asset is not the same as the individual or organization empowered to make decisions over its utilization (the agent). There are a variety of reasons the principal may endow the agent with certain rights and responsibilities for action—including convenience, expertise, and desire for consumption—but the interests of both the principal and agent are rarely completely congruent in every conceivable respect. The typical U.S. publicly-owned corporation is the classic example of a principal (shareholder)–agent (management) relationship.

22. Lefley, op. cit., pp. 211-213, contains a discussion of this literature.

23. "A further interesting feature of this review is the fact that payback is apparently an important method used extensively in the evaluation of new technology projects, such as AMT [advanced manufacturing technologies]. This is to some extent surprising as intuitively one may have expected to see the use of more sophisticated methods of appraisal used in what may be described as sophisticated technology projects. This does not, however, appear to be the case." (Lefley, op. cit., p. 215).

24. See Weingartner (1969).

25. See Sundem (1975).

26. Wilke and Pecar (1995).

27. Noaker (1994).

28. Noaker, op. cit.

29. Alessandri (2001).

30. See Trigeorgis (1996).

31. See Courtney, Kirkland, and Viguerie (1997), pp. 76-79.

32. The Pew Center on Global Climate Change describes its Business Environmental Leadership Council (BELC) as "a group of 38 leading companies worldwide that are responding to the challenges posed by climate change. In addition to agreeing to a Joint Statement of Principles, the members of the BELC serve in an advisory role, offering suggestions and input regarding the Center's activities. The BELC companies do not contribute financially to the Center."

33. The BELC companies have all agreed to the following principles: 1) We accept the views of most scientists that enough is known about the science and environmental impacts of climate change for us to take actions to address its consequences; 2) Businesses can and should take concrete steps now in the United States and abroad to assess opportunities for emission reductions, establish and meet emission reduction objectives, and invest in new, more efficient products, practices and technologies; 3) The Kyoto agreement represents a first step in the international process, but more must be done both to implement the market-based mechanisms that were adopted in principle in Kyoto and to more fully involve the rest of the world in the solution; 4) We can make significant progress in addressing climate change and sustaining economic growth in the United States by adopting reasonable policies, programs and transition strategies.

34. This is a quotation from our seventh interview. Quotations are not attributed to specific firms.

35. Sunk costs are those investments and expenditures made in previous time periods. That is, they represent allocations that have already occurred. Theory unequivocally indicates that attention to sunk costs, though superficially attractive, is a fallacious basis for decision-making.

36. Sunk costs do enter into decision-making in a regulated industry because the existing capital structure is an important factor in determining the rate base and ultimately cost recovery.

37. This generalization will also vary with respect to the industrial sector and the type of capital equipment. Chemical reactors, for example, will suffer serious decline in function after twenty years even with major overhauls and routine maintenance.

38. Biewald et al. (1998). Recent studies by the Energy Information Agency give similar estimates for the future number of coal plant retirements over the next decade under base case conditions (see EIA (2001), Table A9, p. 138), and even under potential new regulations on sulfur dioxide and nitrogen oxide emissions (see EIA (2000), Table ES4, p. xv).

39. Swift (1998).

40. Utterback (1994).

41. Christensen (2000) and Utterback (1994).

42. Hahn and Hester (1989).

43. Ellsberg (2001) provides a summary of the roots of these concepts in pioneering yet often neglected work from the 1950s and 1960s. van Asselt (2000) reviews applications of these ideas to climate change policy. Also see Metz et al. (2001), Sections 10.1.4.4 and 10.1.5, for a discussion of deep uncertainty and means to address it in the integrated assessment of climate change.

44. See Lempert (2002) for a discussion of deep uncertainty and approaches for addressing it.

45. Parker and Blodgett (1999).

46. See, e.g., Credit for Voluntary Reductions Act, S. 547, 106th Cong. (1999). Sponsored by Senators John Chafee (R-RI) and Joseph Lieberman (D-CT) (with 11 additional co-sponsors). See also Title XI (National Greenhouse Gas Database) of the Energy Policy Act of 2002 (Engrossed Amendment as Agreed to by Senate), H.R. 4 EAS, 107th Cong. (2002). Title XI originated as S.A. 3239, sponsored by Senators Sam Brownback (R-KS) and Jon Corzine (D-NJ) (with two additional co-sponsors).

47. Gander (2000).

48. The Bush Administration's "Clear Skies Initiative" was introduced in the House of Representatives as H.R. 5266, 107th Cong. (2002), by Reps. Joe Barton (R-TX) and Billy Tauzin (R-LA), and was introduced in the Senate as S. 2815, 107th Cong. (2002), by Sen. Bob Smith (R-NH).

49. An example of "four-pollutant" legislation is The Clean Power Act, S. 556, 107th Cong. (2002), sponsored by Sen. James Jeffords (I-VT) (19 co-sponsors).

50. Energy Information Agency (2000).

51. See, e.g., Edmonds (2001). Net GHG emissions are total emissions into the atmosphere less any emissions sequestered.

52. Margolis and Kammen (1999).

53. Aldy, Orszag, and Stiglitz (2001).

54. Norberg-Bohm (2000) and Duke and Kammen (1999).

55. Robalino and Lempert (2000).

56. See Christensen, Craig, and Hart (2001) for a discussion of some of these policies.

57. See Lempert (2001) for a discussion of the use of portfolios of different types of ten-year climate policy milestones as a means for addressing the uncertainty of climate change.

58. Bernstein et al. (1999).

59. Edmonds (2001).

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Appendix: Firm Questionnaire

In each of our interviews with firms, whether conducted in person or over the phone, we had a specific list of topics we intended to address. The interviews generally lasted from one to two hours. This appendix provides the list of questions we aimed to address in each interview. We never worked through these questions in order. Rather, we opened the interviews by explaining the purpose of our study and endeavored to engage the interviewees in a discussion about their capital investment decision process. We used the following questions as a checklist to ensure that by the end of the interview we had addressed all the topics of interest.

Decision-making within the firm (consider distinguishing between greenfield development, straight replacement, and upgrades)

- Can you give us a brief overview of how the capital allocation system works within your firm?
- How are budgets for capital investments determined?
- Who controls the budget (plant vs. corporate control)? What kind of variability do you see among plants? Why do you think this occurs? How is the corporate budget allocated among the plants?
- What has been the minimum/maximum investment in the last 10 years?
- How is new technology evaluated within this process? Can you tell us something about sources of new technology—internal, alliances, universities, suppliers, and customers—and if source affects the information required before implementation?
- How is this process, if at all, linked to the strategic planning process and firm position in the market?

(1) What is the average service life of your capital stock and what are the ranges?

- What usually determines the end of your capital's service life: technical or economic considerations? Roughly what percentage of your equipment is replaced before technical considerations would make it necessary? Roughly what percentage of your equipment is replaced before the end of its useful service life?
- Are there other measures of capital effectiveness that you use?

(2) How is information on technical possibilities brought in from the outside? How is it evaluated internally before being formalized as a proposal for a capital investment project? How important is external vs. internal information in laying out alternatives for a capital investment project?

(3) What criteria do you use to make a capital investment in U.S.-based plants and equipment (possibilities include ROI, payback period, IRR, risk/uncertainty measures, reward measures, real options theory)?

- Which are the most important?
- What uncertainties are presented in doing these calculations? How do they affect either the choice of method for evaluation or the outcomes of the evaluations?
- Do the hurdle rates differ by type of investment? What are these categories?
- What kind of flexibility is there in these criteria? Have the financial requirements ever been waived? For what reasons (e.g., environmental and safety regulations; competitive requirements)?
- Do you anticipate any changes in either the criteria or the hurdle rates in the future?

(4) For the last five U.S.-based capital projects proposed (define what constitutes a proposal—something more than an idea), what rationale was put forth for the investment? If the investment was not made, why was it denied?

(5) Our initial research has suggested that the level of competition and the dynamism of technology in an industry are important determinants of the capital cycle in that industry. Are these factors important influences on your capital investment decisions? What factors would you consider most critical?

(6) Imagine a matrix showing situations with differing levels of competitive pressures and technology dynamism (or whatever factors the interviewee thought were most important). Can you give us an example of one or two U.S.-based capital investments that your firm made under the conditions described in each of the corners of the matrix? In each case, what was the rationale put forth for the investment? What similar investments failed to meet your criteria? Why?

(7) Are there windows of opportunity for investing in new technology? What determines the window—e.g., availability of technology, availability of financing, state of capital stock, others?

(8) Are some types of equipment more critical than others in determining the opportunities for investment? In other words, because of system interdependencies, is there equipment that if replaced would have spillover effects on opportunities to replace other equipment?

- Can you give some examples of these?
- Are these generally longer-lived than your average of XXX years for capital service life?

(9) Is information on new technology shared among plant managers? How is this done?

(10) What are the top three most frequently experienced barriers to investing in new equipment (e.g., financing, unproven technology, risk aversion, poor information)?

(11) Are there issues unique to energy efficiency/emissions reductions capital investments (increased uncertainty, lack of cost-effective technology, etc.)? How would a doubling of the price of energy affect your investments in energy efficiency technologies (would they double, triple, or something less)? How would a halving in the price of energy affect investment?

Exogenous factors to capital investment decisions

(1) Do you have baseline information on energy use in your plant? Do you track energy use? When did you begin tracking energy?

(2) What is the energy intensity of your firm (clarify definition and timeframe)? In the future what energy source (coal, natural gas, oil, electricity) is likely to be used for production growth?

(3) How do stakeholder pressures influence decision-making on capital investment?

Definitions

- Capital – plant and equipment
- Capital intensity – gross capital stock/average annual sales or gross capital stock/unit output
- Energy intensity – energy use per unit output

Background Information

- How would you characterize the competitiveness of your sector (number of firms, profit margins, product cycle times)? What is your firm's approximate market share and competitive position? How much international competition do you face?
- How would you characterize the technology dynamism of your sector (amount available and pace at which it is incorporated into product and process)?
- How does your firm compare to others in the sector?
- Approximately what percentage of your sales is reinvested in new capital each year (assume this is the same as the IEA report's gross fixed capital formation vs. value of production)?
- How would you characterize the capital intensity of your industry in general and your firm in particular (clarify definition and timeframe)?
- Does your capital stock have relatively constant GHG emissions per unit output, or does it vary across different types of capital stock?
- How would you characterize the variability of capital stock cycles within your sector?
- Do you anticipate major changes to these values in the future given advancements in new materials and information technology?
- Make sure we have an understanding of how the firm defines capital—ask clarification questions as needed.

notes

This report examines the patterns of capital equipment investment and retirement in U.S. firms and the implications for climate change policy. The Pew Center on Global Climate Change was established by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We intend to inform this debate through wide-ranging analyses that will add new facts and perspectives in four areas: policy (domestic and international), economics, environment, and solutions.

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