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Green renewal: incorporating environmental factors in equipment replacement decisions under technological change

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ABSTRACT

Equipment replacement is a fact of life in every industrial setting, and this paper seeks to answer the question: How can firms and policy makers effectively balance environmental and economic concerns with respect to replacement decisions? A replacement model which includes both economic and environmental factors is presented. One must decide whether to keep the existing technology, upgrade to a newer technology which produces a smaller environmental burden, or wait for an even newer, cleaner technology which may be introduced soon. More than 25 000 test problems are solved, examining different objectives and covering a wide range of applications. Including environmental costs does not lead to a consistent increase in the adoption of cleaner technologies; however, including incentives to adopt newer technologies does. When one accounts for the environmental impact of producing new equipment and disposing of old equipment, earlier adoption of new technologies actually increases the total environmental burden in some cases.

1. Introduction

Equipment replacement is an important issue faced by firms in virtually every industry, and the problem has received much attention from researchers. Most of this research, however, has focused on optimizing financial performance, i.e., minimizing costs and maximizing profits. There is a growing awareness among firms, citizens, and policy makers of the importance of environmental performance as well, and there is an expanding body of research designed to measure and optimize environmental performance. But is it possible to incorporate both economic and environmental concerns into a single decision model? This paper seeks to do just that in the context of an equipment replacement decision in an environment of technological change.

To address the question posed above, we extend an existing equipment replacement model developed by Nair (1995) to incorporate environmental costs as well as financial costs and revenues. The decision maker is faced with the problem of whether to keep an existing piece of equipment or to replace it with a new technology which performs better in terms of revenues, costs, and/or environmental burden. The choice is complicated by the fact that an even newer and better-performing technology is expected to be developed in the future, but the exact timing of its appearance is uncertain. Is it better to upgrade now or wait until the newer technology appears? And do different objectives—economic and environmental—produce different decisions?

We examine five different scenarios, each of which includes different factors in the objective function. Four sets of example problems are studied using the model and detailed sensitivity analyses of different model parameters are performed. The first two sets explored are hypothetical examples based on data from the original model (Nair, 1995). The third set addresses the situation where capital costs are very high and uses data from the automobile industry as a foundation. The fourth set of examples examines the situation where capital costs are relatively low and uses refrigerator replacement data as a basis. In total, more than 25 000 example problems are solved.

This paper makes three contributions. First, it extends previous theory by adding a new dimension to the equipment replacement problem. Second, from a more practical standpoint, it gives firms a method to analyze economic and environmental trade-offs for an important decision area. While many firms are interested in 'going green', it is sometimes difficult to know where to begin and how to go about change in a way that is fiscally responsible. Third, the paper provides insights to policy makers with respect to developing and implementing mechanisms that can encourage and sustain environmentally responsible behaviour in industry.

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2. Literature review

The research related to the equipment replacement problem described above can be divided into several categories: capital budgeting and industrial applications, energy production and consumption, and operations research models. Each area is discussed below.

The typical approach to equipment replacement decisions is a variant of the traditional capital budgeting model which attempts to optimize discounted cash flows over time. Criticisms of this basic approach have come from many researchers, and various enhancements have been proposed, including the addition of inflation (Kierulff, 2007), technological change (Jones and Tanchoco, 1987; Mathew and Kennedy, 2003), and both (Hartman, 2005). To help address some of the shortcomings of generic capital budgeting models, numerous models have been developed which are tailored to a particular industry or equipment type such as wood products manufacturing (Carino et al., 1995), medical equipment (Christer and Scarf, 1994; Dondelinger, 2004), and farm equipment (Reid and Bradford, 1983). These models reveal important lessons for specific applications but lack the flexibility needed for broad usage.

The models mentioned above all focus on optimizing financial measures for an individual firm and stage of equipment life. There is a growing interest, however, in optimizing environmental measures, such as minimizing emissions, and doing so over the entire life cycle of the product. Van Nes and Cramer (2006) provide a general discussion of this concept and argue in favor of longer product lives. Research on specific product types has led to important insights. For example, there is evidence that early vehicle retirement programs do reduce emissions in the short run but may result in greater long-term environmental burdens (Kim et al., 2003; Spielmann and Althaus, 2007). Similar analyses have been performed for other applications, including fleets of automobiles (Kim et al., 2004; Spitzley et al., 2005; Lin et al., 2008) and household appliances (Kim et al., 2006; Kiatkittipong et al., 2008).

Another line of research examines the effects of technological change on energy production, energy consumption, and the environment. Knapp (1999) develops a model to examine the impact of new energy technologies on global climate change. Popp (2001) studies the effect of innovation on energy consumption, and Evans et al. (2008) develop a simulation model to study the effects of different retrofit/replacement policies with respect electrical power generation in the United States (U.S.). The research in this area tends to take a very high-level perspective; thus, while important industry- and economy-level insights are revealed, firm-level implications are less clear.

Many firm- and process-level equipment replacement models have come from the operations research (OR) perspective. Wang (2002) presents a review of the vast literature in this area. The area most relevant to the current problem is replacement models that account for technological change, i.e., situations in which the new equipment has some advantage over the equipment being replaced. Variations on this theme include deterministic timing of technology changes (Sethi and Chand, 1979), uncertain timing (Nair and Hopp, 1992), multiple replacement alternatives (Chand and Sethi, 1982), incorporating machine deterioration (Hopp and Nair, 1994), and allowing costs to vary over time (Regnier et al., 2004). Nair (1995) allows multiple technologies, each with an unknown introduction time, and this model forms the basis of the model presented in the next section.

Another area of OR research considers the challenge of optimizing multiple criteria, the most relevant of which attempts to balance performance with respect to economy and ecology. This so-called 'eco–eco' optimization has been applied to supply chain network design (Bloemhof-Ruwaard et al., 2004) as well as to specific industrial settings (Erol and Thöming, 2005). Work in this area is significant in that it explicitly attempts to balance the economic and environmental impacts; however, the possibility of technology changes over time is not addressed.

In summary, while much research has been done on various types of equipment replacement and some progress has been made in terms of incorporating environmental issues, no model to date has tackled the problem of balancing economic and environmental factors for an equipment replacement decision in an environment of technological change. The purpose of this paper is to provide a general framework—firmly grounded in OR principles—which can be used to evaluate the impact of environmental factors on equipment replacement decisions.

3. Model overview

The purpose of this model is to examine the impact of environmental factors on equipment replacement decisions in the context of changing technology. The problem is modeled using a variation of the Markov decision process framework developed by Nair (1995), and the notation used here closely follows this earlier model. To conserve space, the original model is not presented in this section; interested readers can find a summary of the model, complete notation, and main results in the online Appendix. After explaining the basic problem, we examine five different objective functions, each of which includes different combinations of components—financial, environmental, and regulatory.

3.1. Problem statement and basic notation

A firm operates a manufacturing system, and operation of the system generates revenues and incurs costs. The process technology can be upgraded as new technologies become available. The firm must pay a one-time capital cost to upgrade, and it is assumed that a new technology will enable the firms to generate more revenue. It is also assumed that a new technology will produce a smaller environmental burden. The firm's goal is to make technology adoption choices in a way that maximizes the expected discounted reward over a finite horizon.

The technology employed by the firm at the very beginning of the problem is labeled technology 0. This technology can be replaced with a new technology, labeled technology 1, which is currently available. Alternatively, the firm can wait for an even newer technology, labeled technology 2, which has yet to be introduced. This process of sequential technology development is expected to continue over time until a total of n new technologies are available. To generalize this scenario, we denote the current technology as i, a newer technology which is available now as j, and the newest available technology as k. The state of the decision process is denoted by the pair (i, k), indicating the technology currently in use and the latest available technology. At the very beginning of the problem, the state is $(i = 0, k = 1)$.

The problem is optimized over a finite horizon denoted by T, and a period within that horizon is denoted by t. Given that k is the latest technology available, then the next technology, $k + 1$, will be introduced at the beginning of the next period, $t + 1$, with probability ${p_{t+1}}^{k+1}$. The rewards earned and costs incurred in period t are discounted back to the present by the discount factor β_t, where $\beta_t < 1$ for all t.

Three extensions to Nair (1995) are proposed. First, the new model incorporates environmental costs. Second, it allows the possibility of penalties and rewards tied to compliance. Third, the optimal action is determined for multiple periods by solving the problem on a rolling basis. The details of these extensions are discussed in detail below.

3.2. Rewards and costs

Typically firms explicitly optimize only their monetary rewards. Define $R_t(i, j)$ as the monetary rewards in period t when the firm updates from technology i to technology j at the beginning of the period. The monetary rewards include revenues, defined as r_{jt}, and one-time capital costs, defined as c_{jt}; thus, we have $R_t(i, j) = r_{jt} - c_{jt}$. If the firm chooses not to upgrade at the beginning of period t, then there is no capital outlay and we have $R_t(i, i) = r_{it}$. It is assumed that $r_{it} \le r_{jt}$ for $j > i$ and all t.

Operating the system also produces an environmental burden, the cost of which is usually not borne directly by the firm. Environmental burden types could include emissions such as carbon dioxide (CO_2), non-methane hydrocarbons (NMHC), particulates (PM), or some other relevant substance. Depending on the context, one type of environmental burden may be more significant than others. In addition, they are likely to be measured in different units. To address this issue, we define $B_t(i, j)$ as the environmental burden of operating technology j in period t after upgrading from technology i at the beginning of the period. The variable $B_t(i, j)$ is a weighted average of relevant environmental impacts which enables us to express the operating burden in monetary terms. Though challenging, this type of conversion has been proposed and used previously (Kim et al., 2004; Mercuri et al., 2002; Wang and Santini, 1994). It is assumed that the new technology is cleaner (or at least as clean) as the old technology.

In addition to the environmental burden associated with operating the equipment, there is a burden associated with manufacturing the new equipment and disposing of the old equipment. Let d_{it} refer to the end-of-life environmental costs caused by the disposal of technology i in period t. Such costs may include disassembly, recovery of hazardous materials, and transporting the old equipment to a landfill. Define m_{jt} as the environmental burden associated with adopting technology j in period t. This variable will include such things as the environmental cost of extracting and processing materials, manufacturing the new equipment, and transporting the new equipment. Since these two types of environmental burden are connected by the same event, we define $D_t(i, j) = d_{it} + m_{jt}$ as the total environmental burden associated with the disposal of technology i and the manufacture of technology j in period t.

Environmental costs can be challenging to assess, and not all parties will agree on the same values. Indeed, the environmental impact of a specific type of pollutant can depend on a number of factors such as population density. For example, the costs reported for CO_2 in Mercuri et al. (2002) range from 14 to 38 US$/ton. To account for this uncertainty, the example problems are optimized based on the firm's *perceived* environmental costs. In many cases, firms will underestimate the environmental costs, so we examine cases where the perceived costs are lower than the actual environmental costs. The results for different levels of perceived costs can then be compared, revealing how sensitive the optimal choices are to the accuracy of the perceived costs.

Finally, the firm may also incur costs or earn rewards based on compliance with regulatory requirements. Rewards or incentives earned by the firm for adopting newer, cleaner technologies are denoted as u_{jt} for technology j in period t. Costs, such as fines and penalties for not meeting emissions requirements, are denoted as v_{jt} for technology j in period t. The penalties and incentives depend on the specific compliance mechanism being used, and several possible mechanisms are discussed in the next section. The total monetary impact of compliance resulting from using technology j in period t is framed as a *cost* and is defined as: $V_t(j) = v_{jt} - u_{jt}$. If the incentives exceed the penalties, then this value will be negative. It is assumed that the incentives are larger for higher technologies and the penalties are larger for lower technologies, so $u_{it} \le u_{jt}$ and $v_{it} \ge v_{jt}$ for all t when $j > i$.

3.3. Environmental compliance mechanisms

Many approaches have been used to incorporate environmental concerns in industry. Some approaches involve direct fines, while others rely on taxes and fees to encourage or discourage certain behaviours. For example, the US Environmental Protection Agency discourages the production of inefficient automobiles by imposing a 'gas guzzler tax' of 7700 US$ on vehicles that have gas mileage below 12.5 miles per gallon. The Clean Air Act of the US aims to regulate emissions by establishing air quality standards and emissions of hazardous pollutants based on 'maximum achievable control technology', meaning that performance is compared to the best possible. In addition, if firms perform major changes to their facilities, then they may be required to install new pollution controls. Some have argued that this type of regulation actually increases emissions by creating a disincentive to modernize (Gruenspecht and Stavins, 2002). In the consumer arena, many government-sponsored programs offer incentives to improve environmental outcomes. For example, consumers have been offered large payments to trade in older, fuel-inefficient vehicles (California Environmental Protection Agency Air Resources Board; US Department of Transportation) and energy-inefficient appliances (US Department of Energy). These are only a few examples. The literature on regulatory structures is vast, and a complete review of all approaches is beyond the scope of this paper (see Cordes, 2002 for a general discussion).

The model does not directly account for emissions and other environmental burdens; rather, technology generation serves as a proxy. Standards are based on achieving the performance of a particular technology, denoted as technology κ, by a specific time period, denoted as period τ. For example, a standard might be that all firms must achieve environmental performance at least as good as that of technology $\kappa = 2$ by period $\tau = 3$. If the firm is using technology i such that $i < \kappa$, then a penalty may be imposed. If the firm is using technology j such that $j > \kappa$, then an incentive may be paid to the firm. The penalties and incentives may depend on the size of the difference, or they may be flat. The ultimate value of $V_t(j)$ depends on which specific compliance mechanism is employed. The combinations of penalties and incentives described below, which represent a wide variety of those possible, are used for the example problems.

1. *Constant per period*: An incentive of u is earned each period prior to period τ for all technologies greater than κ, and penalty of v is incurred each period in τ and beyond for all technologies less than κ.
2. *Proportional to time gap*: For each $t < \tau$, an incentive of $u \times (\tau - t)$ is earned for all technologies greater than κ. A penalty of $v \times (t - \tau)$ is incurred for each period $t > \tau$ for all technologies less than κ.
3. *Proportional to technology gap*: For each $j > \kappa$, an incentive of $u \times (j - \kappa)$ is earned for each period $t < \tau$. A penalty of $v \times (\kappa - j)$ is incurred for each period $t > \tau$ for each technology $j < \kappa$.
4. *Time and technology gap*: An incentive of $u_1 \times (j - \kappa) + u_2 \times (\tau - t)$ is earned for early adoption of a cleaner technology. For late adoption, a penalty of $v_1 \times (\kappa - j) + v_2 \times (t - \tau)$ is incurred.
5. *Conditional technology gap*: Early adoption of a cleaner technology earns a flat incentive of u for each $j > \kappa$ and $t < \tau$. If the firm upgrades at any time from τ forward, then it must adopt technology κ or higher, or else pay a penalty of v.

Note that the mechanisms can be varied further by setting either the penalty or incentive level equal to zero. Note also that penalties and incentives only take effect when technology κ has been introduced, i.e., firms are not held to an impossible standard.

3.4. Objective function and scenarios studied

We will examine five scenarios, denoted by s, each having a different objective function. In a slight abuse of notation, we define $R_t^s(i, k)$ as the one-period rewards for scenario s earned by employing technology i in period t given that k is the newest technology available. Note that 'rewards' can include revenues (positive) and costs (negative). The scenarios are defined as follows:

- *Scenario s1*: Traditional financial revenues and costs, $R_t^{s1}(i, k) = R_t(i, k)$.
- *Scenario s2*: Financial rewards less environmental operating costs, $R_t^{s2}(i, k) = R_t(i, k) - B_t(i, k)$.
- *Scenario s3*: Financial rewards less environmental operating costs and environmental disposal and manufacturing costs, $R_t^{s3}(i, k) = R_t(i, k) - B_t(i, k) - D_t(i, k)$.
- *Scenario s4*: Financial rewards less compliance costs, $R_t^{s4}(i, k) = R_t(i, k) - V_t(i)$.
- *Scenario s5*: Financial rewards less all environmental costs and compliance costs, $R_t^{s5}(i, k) = R_t(i, k) - B_t(i, k) - D_t(i, k) - V_t(i)$.

Studying these different scenarios will enable us to separate the effects of including environmental costs and compliance costs.

In each period, the decision maker must choose either to keep the current technology i or to upgrade to a new technology j, where $j \le k$. Possible state transitions depend on which action is taken. The problem begins in state (0, 1), so if the decision maker chooses to keep technology 0, then the state in the next period will be (0, 1) if the new technology is not introduced and (0, 2) if the new technology is introduced. Similarly, if the decision maker chooses to upgrade from technology 0 to technology 1, then the state in the next period will either be (1, 1) or (1, 2). Once a new technology appears, it is possible to 'leapfrog' older technologies, e.g., to switch from technology 0 to 2 without adopting technology 1.

3.5. Solution procedure

The key to solving the problem is recognizing that for the initial state the decision maker need only be concerned with the *difference* between keeping the current technology and upgrading to a newer technology. The optimal action for the initial period is determined by solving the problem iteratively for successively longer time horizons. An optimality condition is checked, and if it is met, then the optimal solution has been found. Otherwise, the problem horizon is extended by one period and the problem is re-solved. It can be shown that the decision maker will not revert to an earlier technology, e.g., switch from technology 1 back to technology 0.

While it is useful to know the optimal action in the initial period, we wish to study the effects of technology evolution and regulatory policy over time. Thus, it is necessary to extend this approach to determine the replacement policy for multiple periods. This is accomplished by solving a succession of problems, each time 'rolling forward' one period and adjusting the time indices. In effect, we redefine what period 0 is and solve the problem again. This can be repeated for any number of periods, provided that one can accurately forecast the parameter values sufficiently far into the future. It should be noted, however, that this approach does not guarantee optimality over multiple periods; rather, it is a succession of single-period optimizations. Additional details of the model and solution procedure are summarized in the online Appendix.

4. Example applications

This section reports the results of example problems from a wide range of applications. The goals of these examples are threefold: first, to explore the impact of incorporating environmental costs in equipment replacement decisions; second, to examine the effects of different incentive/penalty mechanisms; and third, to shed light on the interaction between technology evolution and environmental impact.

4.1. Example 1: increasing capital costs for newer technologies

We begin by examining an environment where capital costs are increasing over time for new technologies, which is common in many industries.

4.1.1. Input data

Basic descriptions of input data are provided here, and complete data are reported in the online Appendix. The discount factors (β_t), new technology introduction probabilities (p_t^{k+1}), base revenues (r_{0t} and r_{1t}), and base capital costs (c_{1t}) are the same as those reported in Example 1 of Nair (1995). Revenues for technologies 2 through 5 are examined at three different levels. For a given technology k, the 'low' level is such that the revenues increase at a rate of 2 percent as compared to the previous technology, the 'medium' level is such that the revenues increase at a rate of 10 percent, and the 'high' level is such that the revenues increase at a rate of 25 percent. Capital costs for technologies 2 through 5 are also tested at three levels. For the 'low' level the costs increase by 5 percent per period, for the 'medium' level the costs increase by 15 percent per period and for the 'high' level the costs increase by 50 percent per period.

A key enhancement to the original examples is the inclusion of environmental costs. Four operating burden levels are tested: zero, low, medium, and high. Level 'zero' means that the environmental costs perceived by the firm are zero for all technologies. For the 'low' level, the environmental burden of technology 0 begins at 10 and increases by 10 percent each period. The burden of technology 1 is initially equal to 95 percent of technology 0's burden and increases by 5 percent per period. For technology 2 and higher, the initial burden is 90 percent of the previous generation's and increases by 2.5 percent per year.

There is also an environmental burden associated with the manufacture of new equipment and the disposal of old equipment. We treat these costs as technology-based rather than time-based, and three levels are tested. Level 'zero' means that these costs are perceived to be zero for all technologies. For the 'low' level, the costs decrease by 25 percent for new technologies, and for the 'high' level, the costs decrease by 50 percent for new technologies.

Even when firms attempt to incorporate environmental costs, there may be some disparity between the perceived costs and the true costs. The levels tested refer to the environmental costs *perceived* by the decision maker, and the true environmental costs (operating and disposal) are actually at the 'high' level. So at level 'zero', the firm does not include any environmental costs in its decision (scenario s1); however, the environmental burden of the resulting policy is determined based on the 'high' level for the operating and disposal costs.

The other key enhancement to the original problem is the inclusion of compliance mechanisms—penalties and/or incentives to achieve a desired outcome. This addition relates to scenarios s4 and s5 described in Section 3.4. We designate the target technology as $\kappa = 2$ and the target time period as $\tau = 3$ for the different compliance mechanisms and examine three incentive/penalty levels. For mechanisms 1, 2, 3, and 5, the 'low' level has a base penalty of $v = 10$ and a base incentive of $u = -10$, the 'medium' level has $v = 40$ and $u = -40$, and the 'high' level has $v = 80$ and $u = -80$. For compliance mechanism 4, which has two types of penalties and incentives, the levels are defined similarly: $v_1 = v_2 = v/2$ and $u_1 = u_2 = u/2$ for the values of v and u described above. Varying each parameter over the levels described above results in 5184 test problems for Example 1.

4.1.2. Results

The optimal choice for the original example problem reported in Nair (1995) (without environmental or compliance costs) is to upgrade from technology 0 to technology 1 immediately. Although technology 2 produces higher revenue, it also has a higher capital cost, which more than offsets the additional revenue. Thus, it is not worthwhile to wait for the appearance of technology 2. How does the decision change over time and when other factors are included?

Table 1 summarizes the results of Example 1 (detailed results including all parameter levels can be found in the online Appendix). The top section of the table reports how the optimal choices change as the environmental operating costs, environmental disposal costs, and regulatory penalties and incentives change. The first row of results in the table corresponds to scenario s1: all environmental costs are perceived to be zero and there are no compliance costs. A total of 27 problems were run for this scenario (three levels each for capital costs, revenues, and introduction probabilities), and the table reports the average results for all 27 problems. The results show that in 59 percent of the problems the optimal policy calls for the adoption of technology 1 in period 0, in 11 percent of the problems technology 1 is adopted in period 1, and in 30 percent of the problems technology 1 is not adopted in the first five periods. The adoption rates for technology 2 are also reported. On average, these policies yield actual environmental costs of 130.5 over three periods, assuming that technology 2 appears in period 1. Environmental costs over five periods and eight periods (assuming that technology 2 appears in period 2) are also reported. Note that although the problem is solved with perceived costs of zero, the environmental costs reported in the table are computed based on the true costs—'high' for both disposal and operating environmental costs. For the other scenarios, the table reports the percentage improvement in environmental costs as compared to scenario s1.

Impact of environmental costs: Scenario s2 includes environmental operating costs, and scenario s3 also includes environmental disposal costs. From the top section of Table 1, by comparing scenario s1 to scenarios s2 and s3 at the 'low' level we see that including environmental costs does change the optimal decision. Comparing the 'low' and 'high' levels for scenario s2, we see that as the perceived environmental costs increase, the adoption rate of technology 1 decreases, and the adoption rate of technology 2 increases. (*Note*: A change from the 'low' to the 'high' level in the top section of the table means that all relevant parameters are changing from the 'low' to 'high' level.) Over three periods, the environmental costs actually increase for scenario s2 as compared to the base case. This result stems from the fact that the firm perceives the environmental manufacture and disposal costs to be zero; however, they are not zero, and thus the increased adoption of technology 1 causes an increase in short-term environmental costs. Over the longer term, however, higher levels of perceived environmental operating costs do decrease the total environmental burden as compared to scenario s1. The 'improvement' levels for individual problems range from −38.4 percent to 137.7 percent (not shown in the table). Scenario s3, which also incorporates disposal and production costs, has very low technology 1 adoption when the perceived environmental costs are at the 'high' level.

Impact of compliance costs: Scenario s4 includes different technology adoption incentives and penalties. The results reported in Table 1 refer to compliance mechanism 1, which imposes a flat penalty or a flat incentive each period which depends on the technology choice (see Section 3.3 for more details). As one can see from the top section of the table, including compliance costs does change the optimal decision. As the level shifts from 'low' to 'high' for the penalties/incentives, the rate of technology 2 adoption more than doubles for scenario s4. Fig. 1a plots the environmental costs for all of the different compliance mechanisms for different penalty/incentive levels. (Mechanism 0 means that there are no incentives or penalties).

The plot depicts total environmental costs summed over three periods (assuming that technology 2 appears in period 1) and five periods (assuming that technology 2 appears in period 2) for the 'low' and 'high' penalty/incentive levels. For each case plotted, the perceived environmental costs—operating, disposal, and production—are held constant at the 'zero' level. Thus, the graph isolates the effects the compliance mechanism type and penalty/incentive level and illustrates how some compliance mechanisms are more effective than others at reducing environmental costs. Appropriate penalties and incentives can induce the same behaviour—and therefore achieve similar environmental performance—as explicitly incorporating environmental costs into the objective function. However, penalties and incentives by themselves are not guaranteed to improve environmental performance significantly.

Scenario s5 includes all environmental costs and the compliance costs. As expected, increases in both of these factors increase the level of technology 2 adoption. When both the penalty/incentive level and perceived environmental costs are at the 'high' level, adoption of technology 1 drops to 0 and adoption of technology 2 jumps to 100 percent for scenario s5. As a result, the average improvement in actual environmental costs is 14.2, 20.1, and 38.9 percent over three, five, and eight periods, respectively, for scenario s5.

Impact of capital costs, revenues, and introduction probabilities: The bottom three sections of Table 1 (below 'Environmental and compliance') report the results from changing capital costs, revenues, and introduction probabilities, respectively. To highlight the effects of changes in these parameters, environmental and penalty cost parameters are fixed. For a given parameter and level, the values reported represent averages over all levels of the other two parameters. For example, consider capital costs at the 'low' level: The numbers in this row are computed by keeping this parameter fixed at the 'low' level and averaging over all levels of revenues and introduction probabilities. Where applicable, the environmental operating costs are at the 'medium' level, the environmental disposal costs are at the 'low' level, the penalties/incentives are at the 'medium' level, and compliance mechanism 1 is used with $\kappa = 2$ and $\tau = 3$.

The capital costs increase at a fixed rate for technology 1 but increase more rapidly for technologies 2 and higher. As indicated in Table 1, as the rate of capital cost increase goes up, the level of technology 1 adoption remains steady, but the level of technology 2 adoption decreases dramatically, as one might expect. This decrease in adoption of the cleaner technology has a serious impact on environmental costs.

The revenue values of technologies 0 and 1 are fixed in this example, and the values for technologies 2 and beyond increase over time. For scenario s1, the increase in revenue induces more adoption of both technology 1 and 2, which increases the overall environmental costs because two sets of disposal costs (technology 0 and 1) and two sets of production costs (technology 1 and 2) are incurred. For the other scenarios, only the technology 2 adoption rate increases as the revenue level goes from 'low' to 'high'. In this

Table 1
Example 1—summary of policy changes and environmental costs.

Parameter(s)[a]	Level	Scenario[b]	Tech. 1 Adoption (%)[c]			Tech. 2 Adoption (%)[d]			Enviro. Costs and Improvement[e]		
			Pd. 0	Pd. 1+	Never	Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.	Eight Pds.
Environmental and compliance	Low	s1	59	11	30	15	0	85	130.5	217.5	437.7
		s2	70	7	22	15	0	85	−2.3%	0.2%	3.4%
		s3	56	22	22	15	0	85	−2.0%	0.4%	3.5%
		s4	48	7	44	30	4	67	3.1%	3.5%	6.6%
		s5	19	30	52	37	7	56	4.6%	7.8%	14.9%
	High	s2	63	11	26	30	15	56	−0.2%	3.1%	15.9%
		s3	4	41	56	48	7	44	6.8%	8.8%	18.3%
		s4	0	33	67	67	19	15	6.5%	15.3%	32.6%
		s5	0	0	100	100	0	0	14.2%	20.1%	38.9%
Capital cost	Low	s1	67	11	22	22	0	78	133.8	212.3	395.4
		s2	78	0	22	22	0	78	−0.5%	−0.3%	−0.2%
		s3	44	33	22	22	0	78	1.1%	0.7%	0.4%
		s4	22	11	67	78	11	11	8.0%	12.9%	26.3%
		s5	0	22	78	78	11	11	11.4%	14.7%	27.3%
	High	s1	56	22	22	0	0	100	131.4	225.0	476.5
		s2	78	22	0	0	11	89	−1.1%	−3.2%	10.2%
		s3	67	11	22	0	0	100	−0.6%	−0.3%	−0.2%
		s4	33	0	67	56	0	44	8.2%	10.4%	18.3%
		s5	0	22	78	56	0	44	12.3%	12.4%	19.3%
Revenue	Low	s1	44	11	44	0	0	100	123.9	227.9	522.4
		s2	78	22	0	0	0	100	−7.2%	−1.6%	15.7%
		s3	56	22	22	0	0	100	−6.1%	1.3%	8.8%
		s4	33	0	67	44	0	56	3.2%	10.5%	22.6%
		s5	0	33	67	44	0	56	5.0%	11.4%	23.0%
	High	s1	56	0	44	44	0	56	128.1	201.9	359.4
		s2	56	0	44	44	11	44	0.0%	−0.3%	3.4%
		s3	44	11	44	44	0	56	0.6%	0.4%	0.2%
		s4	11	22	67	78	22	0	3.2%	10.0%	23.4%
		s5	0	0	100	100	0	0	12.6%	13.9%	25.6%
Introduction probabilities	Low	s1	100	0	0	0	0	100	141.0	224.2	432.8
		s2	100	0	0	0	11	89	0.0%	−0.2%	2.8%
		s3	89	11	0	0	0	100	0.5%	0.3%	0.2%
		s4	78	22	0	33	22	44	−2.6%	6.2%	18.0%
		s5	0	67	33	33	22	44	7.8%	11.7%	20.8%
	High	s1	33	22	44	22	0	78	124.9	213.8	439.8
		s2	67	11	22	22	0	78	−4.5%	−1.4%	9.1%
		s3	33	33	33	22	0	78	−2.7%	0.9%	5.3%
		s4	0	0	100	89	0	11	11.1%	15.5%	29.9%
		s5	0	0	100	89	0	11	11.1%	15.5%	29.9%

[a] In the top section of the table, all of the applicable perceived environmental and compliance costs are examined at the 'low' and 'high' levels, as indicated. For example, at the 'low' level, perceived environmental operating costs, perceived environmental manufacture/disposal costs, and penalty/incentives are all 'low', and the results are averaged over all levels of capital cost, revenue, and introduction probability. In the bottom section of the table, capital costs, revenues, and introduction probabilities are examined at the 'low' and 'high' levels, as indicated. The perceived environmental operating costs and penalties/incentives are fixed at the 'medium' level, while perceived environmental manufacture/disposal costs are fixed at the 'low' level. The target technology is $\kappa = 2$, and the target period is $\tau = 3$ for scenarios s4 and s5.

[b] The scenarios are described in Section 3.4. Scenario s1 does not include any environmental or compliance costs in the objective function. Scenario s2 includes environmental operating costs, and scenario s3 also includes environmental disposal/manufacture costs. Scenario s4 includes a penalty/incentive using compliance mechanism 1 but does not include any environmental costs. Scenario s5 includes penalties/incentives using compliance mechanism 1 and also includes all environmental costs.

[c] Reports the percent of optimal policies calling for the adoption of technology 1 in the specified period: period 0, period 1 or later, or never (not in the first five periods). May not sum to 100 due to rounding.

[d] Reports the percent of optimal policies calling for the adoption of technology 2 in the specified period: period 1, period 2 or later, or never (not in the first five periods). Assumes that technology 2 appears in period 1. May not sum to 100 due to rounding.

[e] For scenario s1, the table reports the total actual environmental costs for a particular parameter and level averaged over the other parameters. Averages are reported for the first three periods (assuming that technology 2 appears in period 1), five periods (assuming that technology 2 appears in period 2), and eight periods (assuming that technology 2 appears in period 2). For the other scenarios, the table reports the percentage improvement in the average actual environmental costs as compared to scenario s1. The actual environmental cost level is 'high' for all example problems; regardless of the perceived costs, the total actual costs and improvements reported are based on 'high' environmental operating, manufacture, and disposal costs.

instance, the firm's economic interests are naturally aligned with the environmental concerns, because technology 2 is more attractive both in terms of environmental costs and revenue. As a result, the total environmental costs are lower for scenarios s2 through s5 as compared to scenario s1.

The last section of Table 1 shows how the optimal policies and resulting environmental costs change as a function of the new technology introduction probabilities. When the introduction probability level is 'low', scenarios s1 and s2 maintain the default policy of adopting technology 1 right away and foregoing technology 2 altogether. This result is intuitive, because the likelihood of technology 2 appearing is so small. However, when the probability level increases (meaning that newer technologies are more likely to be introduced sooner), then the optimal policy shifts away from technology 1 and towards technology 2. In general, adopting technology 2 reduces the environmental costs. However, some

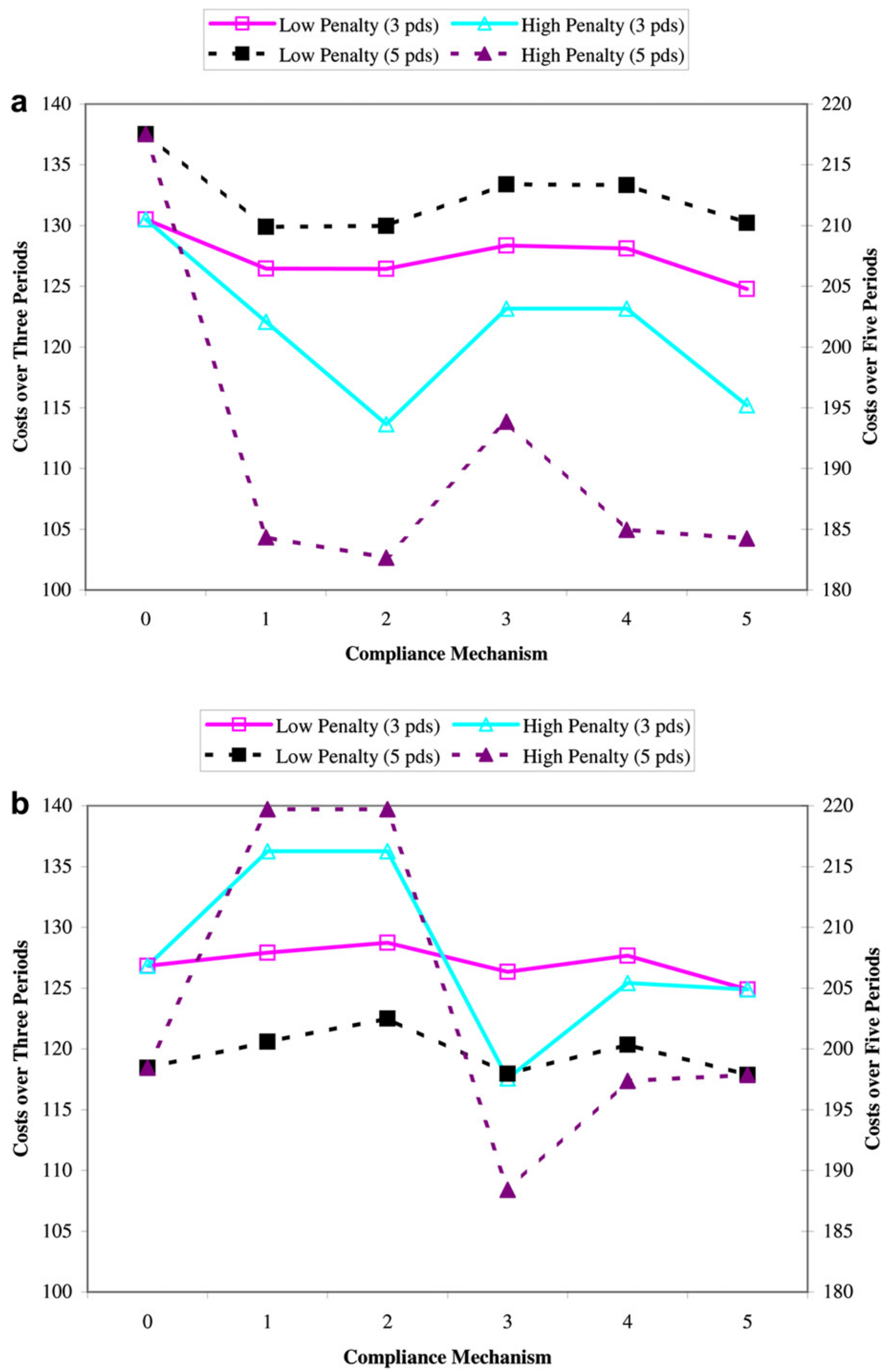


Fig. 1. Scenario s4 vs. s1—Actual Environmental Costs for Different Compliance Mechanisms for Example 1 (a) and Example 2 (b).

scenarios call for the adoption of both technology 1 and 2, which increases total environmental costs in the short run.

Example 1 summary: Two main conclusions can be drawn from the analysis of Example 1. First, incorporating environmental costs into the objective function can change the optimal policy. However, this change does not necessarily result in lower total environmental costs, particularly in the short run. To have a positive impact, the perceived environmental costs and actual environmental costs must be close. When this happens, the firm tends to increase its technology 2 adoption rate and decrease its technology 1 adoption rate, which lowers environmental costs significantly. Second, compliance mechanisms can be effective in changing the pattern of technology adoption. As illustrated in Fig. 1, however, not all compliance mechanisms are equally effective.

4.2. *Example 2: decreasing capital costs for newer technologies*

Next we examine an environment where capital costs are decreasing over time for new technologies. This phenomenon has been observed in many high-technology industries.

4.2.1. *Input data*

All parameter values for the second example are the same as for the first except the capital costs and compliance targets. (All data used are reported in the online Appendix.) In this example, the capital costs for newer technologies decrease over time, and three rates of decrease are tested for technologies 2 through 5. Solving one problem for each of the possible parameter values requires 5184 test problems for Example 2.

4.2.2. Results

The optimal choice for the original problem (without environmental costs or compliance mechanisms) is to keep the existing technology. The logic behind this decision is clear: by waiting for technology 2 to appear, the firm can get more revenue while paying a lower capital cost. Indeed, when this base case is extended beyond the initial period, the optimal choice is to adopt technology 2 as soon as it is available. Since including environmental costs only makes technology 2 more desirable, the optimal policy does not change when these costs are added. Similarly, if $\kappa = 2$, then there is even more incentive to adopt technology 2. To better assess the impact of compliance mechanisms, we change the target technology to $\kappa = 1$ and the target time period to $\tau = 2$. Results are summarized in Table 2. As expected, scenario s1 calls for significantly more technology 2 adoption than in Example 1, resulting in lower overall environmental costs.

In the top portion of the table, we see that incorporating environmental costs makes technology 2 more attractive. Scenario s3, which includes environmental operating and disposal costs, has very high rates of technology 2 adoption, especially at the ‘high’ level. Greater levels of technology 2 adoption lead to significantly lower overall environmental costs.

Including compliance costs is effective at pushing the adoption of the target technology. However, in this example doing so actually increases the environmental burden, because the target (technology 1) is not as clean as technology 2. At the ‘high’ penalty/incentive level, scenario s4 yields an overall environmental burden that is more than 10 percent higher than scenario s1 over five periods and nearly 20 percent higher over eight periods. Fig. 1b plots the environmental costs for all of the different compliance mechanisms, and it is interesting to note the contrast with Fig. 1a. For example, the effectiveness of compliance mechanism 2 significantly lowers the environmental costs in Example 1 but actually increases the environmental costs in Example 2, because the target technology has changed. Compliance mechanism 5, in contrast, imposes a penalty for failing to upgrade to the latest technology, and thus performs well in both examples.

In the bottom portion of Table 2, we observe that changes in capital cost have a predictable effect: the larger the decrease in costs, the greater the adoption of technology 2. Similarly, larger revenues for the newer technologies (2 and higher) lead the firm to adopt technology 1 less and technology 2 more. With respect to the new technology introduction probabilities, when the probability is very low, the adoption rate for technology 1 is very high. The adoption rate for technology 1 drops significantly and the adoption rate for technology 2 rises significantly as the introduction probability increases. In all of these cases, this trend is less pronounced in scenario s4 due to the penalties and incentives intended to push technology 1.

In summary, the lessons gleaned from Example 1 also apply to Example 2. Incorporating environmental costs can change the optimal decision and corresponding environmental costs when the perceived and actual environmental costs are close. The key to lowering environmental costs is early adoption of technology 2. To the extent that compliance mechanisms support this, they are effective in reducing the total environmental burden. However, in many Example 2 problems, compliance mechanisms change the natural alignment between economic and environmental concerns, resulting in delayed adoption of technology 2 and higher overall environmental costs. Thus, the details of the compliance mechanisms are important.

4.3. Example 3: high capital costs

The next example examines the situation for which the capital costs are much higher than the revenues and environmental costs. For example, the semiconductor manufacturing and steel production industries have extremely high capital costs. In the consumer arena, this situation is comparable to an automobile purchase. Plentiful economic and environmental data are available for automobiles, making it useful for illustrative purposes.

It is widely known that automobile technology does not change rapidly, especially with respect to fuel economy. To make the comparisons more interesting and meaningful, we examine technology choices over a longer time horizon: technology 0 is equivalent to an average 1995 midsize car, and technology 1 is equivalent to a 2005 model year vehicle. Four additional technologies are expected, and the input data for these future technologies are based on different projections of future trends with regard to fuel economy, emissions, and so on.

4.3.1. Input data

To conserve space, the details of the input data are provided in the online Appendix. The discount rates and new technology introduction probabilities are the same as for the previous examples. Capital costs for future technologies are decreasing and are tested at three levels. In this context, revenues are not heavily influenced by the technology used, but operating and maintenance costs are, so the ‘revenues’ are actually costs in this example. Operating costs are tested at three levels for future technologies.

Base levels for the environmental burdens come from a detailed life cycle inventory reported in Sullivan et al. (1998) and changes based on trends reported in Kim et al. (2003). The costs associated with the environmental burdens are based on Mercuri et al. (2002). The environmental operating burden is expected to decrease with new technologies, and the rate of change is tested at three levels. The environmental impact of producing a new car and disposing of an old car are also included. Both are assumed to be technology-based (rather than age-based) and are tested at two levels.

Although penalties are common in some industrial settings, it is much more common to offer positive incentives, especially in the consumer products arena. Voluntary vehicle retirement programs, which pay consumers for trading in older vehicles, are a prime example of this approach. The recent Car Allowance Rebate System (commonly known as ‘Cash for Clunkers’) program in the U.S. provided payments of up to 4500 US$ for retiring an old vehicle and purchasing a new vehicle (US Department of Transportation). To examine this type of situation, we set $v = 0$, and test the incentive value at three levels: $u = -2500$ is ‘low’, $u = -5000$ is ‘medium’, and $u = -10\,000$ is ‘high’. Two target technology levels are tested in this example: one with $\kappa = 2$ (technology) and $\tau = 3$ (time period), the other with $\kappa = 1$ and $\tau = 2$. Note that since $v = 0$, compliance mechanism 5 (conditional) is equivalent to mechanism 1 (constant) and is therefore not included in the analyses below. In total, 8100 different test problems are solved for this example by varying each parameter over several levels.

4.3.2. Results

Table 3 summarizes the Example 3 results. Technology 1 is not adopted in any of the problems, so the table reports only technology 2 adoption. In the top section of the table, changes in environmental costs and incentives are examined at two levels for the different scenarios. In the bottom three sections of the table, the

Table 2
Example 2—summary of policy changes and environmental costs.

Parameter(s)[a]	Level	Scenario[b]	Tech. 1 Adoption (%)[c]			Tech. 2 Adoption (%)[d]			Enviro. Costs and Improvement[e]		
			Pd. 0	Pd. 1+	Never	Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.	Eight Pds.
Environmental and compliance	Low	s1	41	11	48	48	4	48	126.8	198.4	347.4
		s2	41	15	44	44	4	52	−0.7%	−0.8%	−1.7%
		s3	22	11	67	67	0	33	4.7%	4.3%	7.3%
		s4	44	11	44	44	4	52	−0.8%	−1.1%	−1.8%
		s5	22	33	44	44	4	52	0.3%	−0.4%	−1.5%
	High	s2	33	4	63	78	19	4	2.7%	4.9%	17.5%
		s3	0	15	85	85	4	11	9.1%	9.0%	17.4%
		s4	44	48	7	7	4	89	−7.4%	−10.7%	−19.6%
		s5	0	89	11	11	26	63	−5.3%	−7.2%	−9.0%
Capital cost	Low	s1	56	22	22	22	0	78	133.1	211.6	394.6
		s2	56	0	44	44	11	44	3.8%	4.3%	12.0%
		s3	33	22	44	44	0	56	4.9%	5.3%	9.3%
		s4	67	22	11	11	0	89	−2.4%	−3.1%	−4.9%
		s5	44	44	11	11	0	89	−1.3%	−3.2%	−4.9%
	High	s1	22	11	67	67	11	22	122.5	187.5	306.6
		s2	33	0	67	78	0	22	0.1%	−0.4%	−0.2%
		s3	11	11	78	78	0	22	3.9%	1.7%	1.0%
		s4	22	44	33	33	11	56	−6.1%	−9.2%	−18.1%
		s5	11	33	56	56	11	33	−1.4%	−1.4%	−5.0%
Revenue increase rate	Low	s1	67	0	33	33	0	67	131.3	207.5	377.7
		s2	56	11	33	33	0	67	0.6%	0.4%	0.2%
		s3	44	11	44	44	0	56	3.0%	3.0%	5.1%
		s4	67	33	0	0	0	100	−5.7%	−8.3%	−14.7%
		s5	56	33	11	11	0	89	−3.3%	−5.6%	−9.8%
	High	s1	22	11	67	67	11	22	122.5	187.5	306.6
		s2	33	0	67	78	22	0	0.1%	0.0%	8.3%
		s3	0	22	78	78	0	22	4.5%	2.0%	1.2%
		s4	22	44	33	33	11	56	−6.1%	−9.2%	−18.1%
		s5	0	56	44	44	11	44	−2.9%	−4.1%	−10.8%
Introduction probabilities	Low	s1	89	11	0	0	11	89	141.9	221.0	416.8
		s2	100	0	0	11	22	67	0.1%	0.0%	6.1%
		s3	56	33	11	11	0	89	4.4%	2.1%	1.1%
		s4	89	11	0	0	11	89	0.0%	0.0%	0.0%
		s5	56	44	0	0	11	89	1.5%	2.1%	1.1%
	High	s1	11	11	78	78	0	22	117.7	184.4	303.6
		s2	11	0	89	89	0	11	2.1%	2.6%	5.8%
		s3	0	11	89	89	0	11	2.7%	3.0%	6.0%
		s4	11	56	33	33	0	67	−8.5%	−12.4%	−24.4%
		s5	11	33	56	56	0	44	−4.3%	−6.7%	−12.5%

[a] In the top section of the table, all of the applicable perceived environmental and compliance costs are examined at the 'low' and 'high' levels, as indicated. For example, at the 'low' level, environmental operating costs, environmental manufacture/disposal costs, and penalty/incentives are all 'low', and the results are averaged over all levels of capital cost, revenue, and introduction probability. In the bottom section of the table, capital costs, revenues, and introduction probabilities are examined at the 'low' and 'high' levels, as indicated. The environmental operating costs and penalties/incentives are fixed at the 'medium' level, while environmental manufacture/disposal costs are fixed at the 'low' level. The target technology is $\kappa = 1$, and the target period is $\tau = 2$ for scenarios s4 and s5.

[b] The scenarios are described in Section 3.4. Scenario s1 does not include any environmental or compliance costs in the objective function. Scenario s2 includes environmental operating costs, and scenario s3 also includes environmental disposal/manufacture costs. Scenario s4 includes a penalty/incentive using compliance mechanism 1 but does not include any environmental costs. Scenario s5 includes penalties/incentives using compliance mechanism 1 and also includes all environmental costs.

[c] Reports the percent of optimal policies calling for the adoption of technology 1 in the specified period: period 0, period 1 or later, or never (not in the first five periods). May not sum to 100 due to rounding.

[d] Reports the percent of optimal policies calling for the adoption of technology 2 in the specified period: period 1, period 2 or later, or never (not in the first five periods). Assumes that technology 2 appears in period 1. May not sum to 100 due to rounding.

[e] For scenario s1, the table reports the total actual environmental costs for a particular parameter and level averaged over the other parameters. Averages are reported for the first three periods (assuming that technology 2 appears in period 1), five periods (assuming that technology 2 appears in period 2), and eight periods (assuming that technology 2 appears in period 2). For the other scenarios, the table reports the percentage improvement in the average actual environmental costs as compared to scenario s1. The actual environmental cost level is 'high' for all example problems; regardless of the perceived costs, the total actual costs and improvements reported are based on 'high' environmental operating, manufacture, and disposal costs.

environmental and compliance factors are fixed and the other parameters (capital costs, revenues, and new technology introduction probabilities) are varied.

Some of the key conclusions drawn from Examples 1 and 2 appear to be contradicted by Example 3. First, the environmental costs in this example are so much smaller than the capital costs that just incorporating environmental costs is not sufficient to change the optimal policy, in contrast to the earlier examples. Second, compliance mechanisms can be effective in changing the optimal policy. However, the high capital costs in this example must be offset by extremely large incentives if the compliance mechanisms are to be effective. Furthermore, pushing the adoption of cleaner technologies without accounting for the environmental impact associated with production and disposal can significantly distort

Table 3
summary of policy changes and environmental costs.

Parameter(s)[a]	Level	Scenario[b]	$\kappa = 2, \tau = 3$					$\kappa = 1, \tau = 2$				
			Tech. 2 Adoption (%)[c]			Enviro. Costs and Improvement[d]		Tech. 2 Adoption (%)[c]			Enviro. Costs and Improvement[d]	
			Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.	Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.
Environmental and compliance costs	Low	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	11	0	89	−4.9%	0.4%	0	0	100	0.0%	0.0%
		s5	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
	High	s2	0	15	85	0.0%	−4.0%	0	15	85	0.0%	−4.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	100	0	0	−44.5%	3.9%	56	0	44	−24.7%	2.2%
		s5	100	0	0	−44.5%	3.9%	56	0	44	−24.7%	2.2%
Capital cost decrease rate	Low	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	11	0	89	−4.9%	0.4%	0	0	100	0.0%	0.0%
		s5	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
	High	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	100	0	0	−44.5%	3.9%	33	0	67	−14.8%	1.3%
		s5	100	0	0	−44.5%	3.9%	11	0	89	−4.9%	0.4%
Revenue increase rate	Low	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	44	0	56	−19.8%	1.7%	11	0	89	−4.9%	0.4%
		s5	44	0	56	−19.8%	1.7%	0	0	100	0.0%	0.0%
	High	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	56	0	44	−24.7%	2.2%	11	0	89	−4.9%	0.4%
		s5	44	0	56	−19.8%	1.7%	11	0	89	−4.9%	0.4%
Introduction probabilities	Low	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	78	0	22	−34.6%	3.0%	33	0	67	−14.8%	1.3%
		s5	67	0	33	−29.6%	2.6%	11	0	89	−4.9%	0.4%
	High	s1	0	0	100	2429.8	4924.5	0	0	100	2429.8	4924.5
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	33	0	67	−14.8%	1.3%	0	0	100	0.0%	0.0%
		s5	33	0	67	−14.8%	1.3%	0	0	100	0.0%	0.0%

[a] In the top section of the table, all of the applicable perceived environmental and compliance costs are fixed at the ‘low’ or ‘high’ level, as indicated; results are averaged over all levels of capital cost, revenue, and introduction probability. In the bottom section of the table, capital costs, revenues, and introduction probabilities are fixed at the ‘low’ or ‘high’ level, as indicated; results are reported for the ‘medium’ level of environmental operating costs and penalties/incentives and the ‘low’ level of environmental manufacture/disposal costs.

[b] The scenarios are described in Section 3.4. Scenario s1 does not include any environmental or compliance costs in the objective function. Scenario s2 includes environmental operating costs, and scenario s3 also includes environmental disposal/manufacture costs. Scenario s4 includes a penalty/incentive using compliance mechanism 1 but does not include any environmental costs. Scenario s5 includes penalties/incentives using compliance mechanism 1 and also includes all environmental costs.

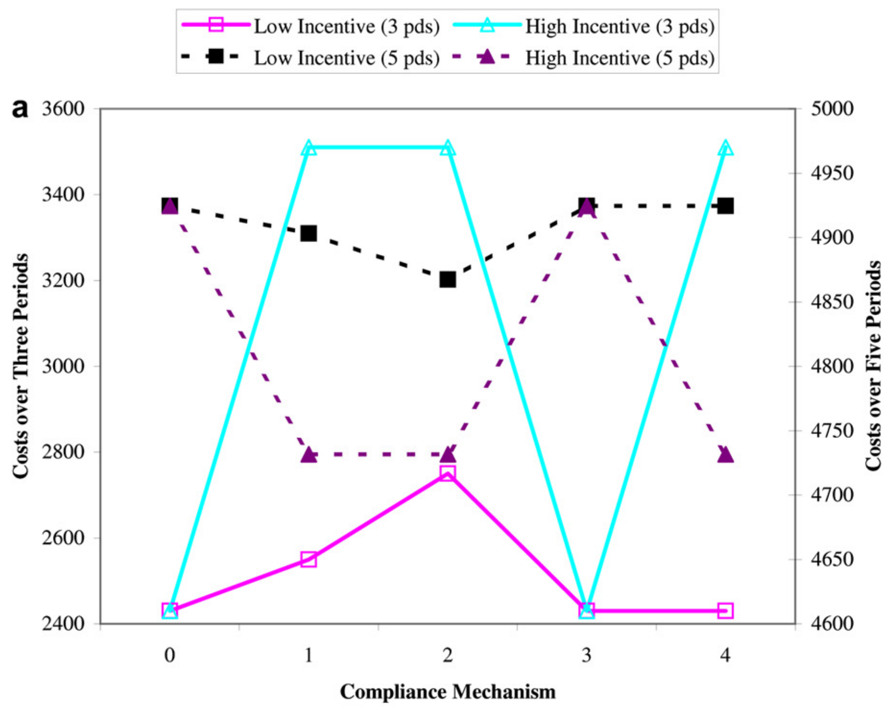
[c] Reports the percent of optimal policies calling for the adoption of technology 2 in the specified period: period 1, period 2 or later, or never (not in the first five periods). Assumes that technology 2 appears in period 1.

[d] For scenario s1, the table reports the total actual environmental costs for a particular parameter and level averaged over the other parameters. Averages are reported for the first three periods (assuming that technology 2 appears in period 1) and five periods (assuming that technology 2 appears in period 2). For the other scenarios, the table reports the percentage improvement in the average actual environmental costs as compared to scenario s1. The actual environmental cost level is ‘high’ for all example problems; regardless of the perceived costs, the total actual costs and improvements reported are based on ‘high’ environmental operating, manufacture, and disposal costs.

the optimal choices, as illustrated in Fig. 2. These results support the findings of Kim et al. (2003), who observe that early vehicle retirement programs do not produce a net environmental benefit when the burden over a vehicle’s entire life cycle is taken into account. The default behaviour in scenario s1 suggests that there is an alignment between the consumer’s desire to minimize financial costs and society’s desire to minimize environmental costs over a vehicle’s life.

4.4. *Example 4: low capital costs*

The fourth set of example problems examines a situation where the capital costs are low in relation to the operating and environmental costs. For example, the basic equipment needed for a machine shop is not very costly as compared to the large capital outlays described in the last example. This situation has parallels with a consumer’s choice about replacing a household refrigerator.



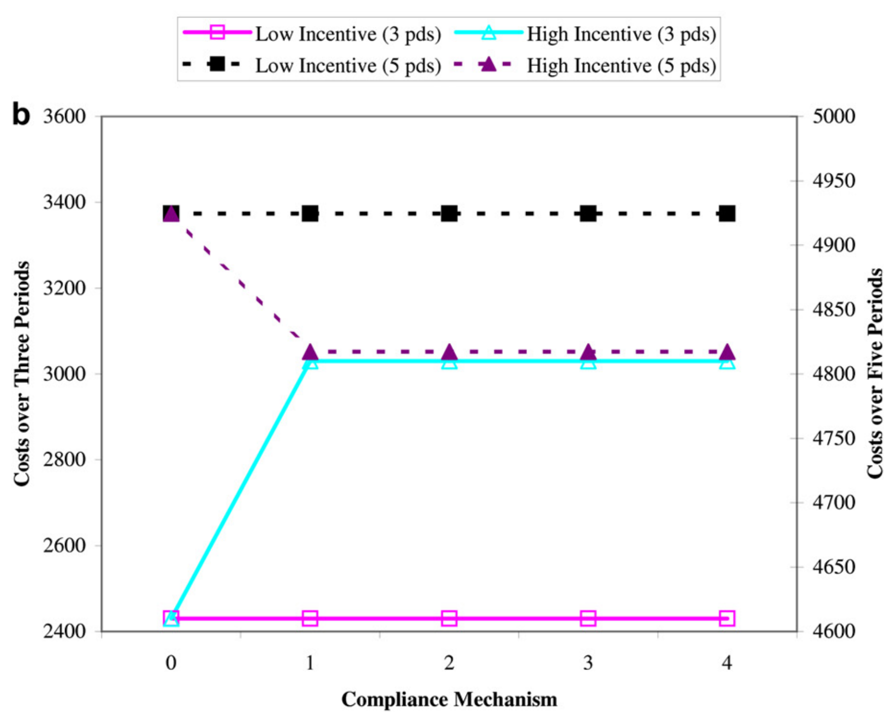


Fig. 2. Scenario s4 vs. s1—Actual Environmental Costs for Different Compliance Mechanisms for Example 3 (a: $\kappa = 3$, $\tau = 2$, b: $\kappa = 2$, $\tau = 1$).

Since plentiful data are available for this type of decision, it provides a useful backdrop for our analyses and can teach some valuable lessons which can be applied in industry.

Unlike automobile technology, household appliance technology has improved dramatically over the past 20–30 years (Kim et al., 2006). Over a 10-year period, a reduction of 20–30 percent in energy use and emissions is common. Two sets of problems are examined. In the first set (referred to as Example 4a), technology 0 corresponds to a typical 1987 model year refrigerator, while technology 1 represents a typical 1997 model, and technology 2 corresponds to a hypothetical 2007 refrigerator. In the second set of problems (referred to as Example 4b), the time frame is advanced 10 years, so technology 0 is a 1997 model, and so on. This approach enables us to study the effects of the technological rate of change as well as the starting point.

4.4.1. Input data

As with the previous examples, a total of six technologies are included in these problems. All technologies are refrigerator-freezers with automatic defrost and top-mounted freezer, but

Table 4
Example 4—summary of policy changes and environmental costs.

Parameter(s)[a]	Level	Scenario[b]	Tech. 0 is 1987 model					Tech. 0 is 1997 model				
			Tech. 2 Adoption (%)[c]			Enviro. Costs and Improvement[d]		Tech. 2 Adoption (%)[c]			Enviro. Costs and Improvement[d]	
			Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.	Pd. 1	Pd. 2+	Never	Three Pds.	Five Pds.
Environmental costs and incentives	Low	s1	11	0	89	61.4	104.8	0	0	100	38.3	70.0
		s2	11	0	89	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	4	0	96	6.0%	1.8%	0	0	100	0.0%	0.0%
		s4	33	0	67	−18.0%	−5.4%	15	0	85	2.9%	5.2%
		s5	26	0	74	−12.0%	−3.6%	15	0	85	2.9%	5.2%
	High	s2	19	0	81	−6.0%	−1.8%	4	0	96	0.7%	1.3%
		s3	7	0	93	3.0%	0.9%	4	0	96	0.7%	1.3%
		s4	100	0	0	−71.9%	−21.8%	100	0	0	19.4%	34.9%
		s5	100	0	0	−71.9%	−21.8%	100	0	0	19.4%	34.9%
Capital cost increase rate	Low	s1	0	0	100	55.9	102.0	0	0	100	38.3	70.0
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s5	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
	High	s1	33	0	67	72.4	110.5	0	0	100	38.3	70.0
		s2	33	0	67	0.0%	0.0%	11	0	89	2.2%	3.9%
		s3	22	0	78	7.6%	2.6%	0	0	100	0.0%	0.0%
		s4	100	0	0	−45.7%	−15.5%	100	0	0	19.4%	34.9%
		s5	100	0	0	−45.7%	−15.5%	100	0	0	19.4%	34.9%
Revenue increase rate	Low	s1	0	0	100	55.9	102.0	0	0	100	38.3	70.0
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	44	0	56	−39.5%	−11.2%	33	0	67	6.5%	11.6%
		s5	44	0	56	−39.5%	−11.2%	33	0	67	6.5%	11.6%
	High	s1	22	0	78	66.9	107.7	0	0	100	38.3	70.0
		s2	22	0	78	0.0%	0.0%	11	0	89	2.2%	3.9%
		s3	11	0	89	8.3%	2.7%	0	0	100	0.0%	0.0%
		s4	67	0	33	−33.0%	−10.6%	44	0	56	8.6%	15.5%
		s5	67	0	33	−33.0%	−10.6%	44	0	56	8.6%	15.5%
Introduction probabilities	Low	s1	22	0	78	66.9	107.7	0	0	100	38.3	70.0
		s2	22	0	78	0.0%	0.0%	11	0	89	2.2%	3.9%
		s3	22	0	78	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	67	0	33	−33.0%	−10.6%	44	0	56	8.6%	15.5%
		s5	67	0	33	−33.0%	−10.6%	56	0	44	10.8%	19.4%
	High	s1	0	0	100	55.9	102.0	0	0	100	38.3	70.0
		s2	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s3	0	0	100	0.0%	0.0%	0	0	100	0.0%	0.0%
		s4	44	0	56	−39.5%	−11.2%	33	0	67	6.5%	11.6%
		s5	44	0	56	−39.5%	−11.2%	33	0	67	6.5%	11.6%

[a] In the top section of the table, all of the applicable perceived environmental and compliance costs are fixed at the 'low' or 'high' level, as indicated; results are averaged over all levels of capital cost, revenue, and introduction probability. In the bottom section of the table, capital costs, revenues, and introduction probabilities are fixed at the 'low' or 'high' level, as indicated; results are reported for the 'medium' level of environmental operating costs and penalties/incentives and the 'low' level of environmental manufacture/disposal costs.

[b] The scenarios are described in Section 3.4. Scenario s1 does not include any environmental or compliance costs in the objective function. Scenario s2 includes environmental operating costs, and scenario s3 also includes environmental disposal/manufacture costs. Scenario s4 includes a penalty/incentive using compliance mechanism 1 but does not include any environmental costs. Scenario s5 includes penalties/incentives using compliance mechanism 1 and also includes all environmental costs.

[c] Reports the percent of optimal policies calling for the adoption of technology 2 in the specified period: period 1, period 2 or later, or never (not in the first five periods). Assumes that technology 2 appears in period 1.

[d] For scenario s1, the table reports the total actual environmental costs for a particular parameter and level averaged over the other parameters. Averages are reported for the first three periods (assuming that technology 2 appears in period 1) and five periods (assuming that technology 2 appears in period 2). For the other scenarios, the table reports the percentage improvement in the average actual environmental costs as compared to scenario s1. The actual environmental cost level is 'high' for all example problems; regardless of the perceived costs, the total actual costs and improvements reported are based on 'high' environmental operating, manufacture, and disposal costs.

without through-the-door ice service. Details can be found in the online Appendix. The discount rates and technology introduction probabilities are the same as those used for the previous examples. The other parameters have the same patterns in Examples 4a and b but have different starting values. Cost values are determined based on data from Horie (2004). For the new technologies, three levels of capital cost are examined: increasing moderately ('low'), decreasing moderately ('medium'), and decreasing significantly ('high'). The 'revenues' in this example are really operating costs, which are based on energy consumption data from Horie (2004) and energy costs from the US Energy Information Agency. The efficiency of a refrigerator decreases over time, so more energy is consumed as it ages (Kim et al., 2006). For technologies 2 and higher, three levels of operating cost change are tested.

Environmental operating burdens are based on CO_2 emissions reported by the US Environmental Protection Agency and costs from Mercuri et al. (2002). The initial values are different for the different sets of problems, and three levels of change are tested.

Environmental impacts associated with manufacturing of new units and disposal of old units are treated as technology-based and are tested at two levels.

As in the automobile example problems, we set the penalty level to zero ($v = 0$), which reflects the fact that it is more common to offer positive incentives to upgrade rather than penalties in this context. Incentives are tested at three levels: $u = -50$ ('low'), $u = -100$ ('medium'), and $u = -200$ ('high'). These values are in line with incentives offered recently in the U.S. for trading in old appliances and buying new, energy-efficient appliances (US Department of Energy). For both sets of problems, the target technology is $\kappa = 2$ and the target time period is $\tau = 3$. Since $v = 0$ in these problems, compliance mechanism 5 (conditional) is equivalent to mechanism 1 (constant) and is therefore not included in the analyses below. Varying the parameters over several different levels requires a total of 8424 problems for this example.

4.4.2. Results

Table 4 reports a summary of the results for this example. Technology 1 is never adopted in any of the problems studied, so the table reports results only for technology 2. The top portion of Table 4 highlights the effects of changes in environmental costs and compliance costs. The bottom portions of the table examines changes in capital costs, revenues, and new technology introduction probabilities, respectively.

Even major increases in efficiency provided by new technologies are generally not enough of an incentive to upgrade, even though the capital costs are relatively low in this example. These findings are consistent with those of Kim et al. (2006), who find that optimizing only financial costs results in long optimal lifetimes (i.e., consumers do not upgrade frequently). These baseline results are similar to those of Example 3. Unlike Example 3, however, even fairly moderate incentives (20 to 30 percent of the capital cost) are sufficient to induce upgrades. Adopting the new, more-efficient technologies does have a significant, positive impact on the environmental operating burden. However, the overall environmental burden depends heavily on the beginning- and end-of-life impacts. For example, trading in the least efficient refrigerator (1987 model year) for the most efficient refrigerator available reduces environmental operating costs by more than 50 percent but *increases* the total burden by more than 70 percent due to the high cost of disposal. Thus, it is important for policy makers to have a thorough understanding of the total life cycle impacts in order to produce the desired results.

5. Summary and conclusion

The problem of when to replace a piece of equipment in an environment of technological change has been examined by many researchers. This paper extends the problem to include environmental factors, which are of growing concern to consumers, businesses, and policy makers. The model of Nair (1995) is used as a starting point, and three important features are added. First, environmental costs are incorporated into the objective function. Second, compliance mechanisms, which provide incentives for achieving certain levels of environmental performance and penalties for not achieving that level of performance, are included. And third, the decision scope is extended beyond the initial period.

Four sets of example problems are studied. The first two sets are based on hypothetical examples from Nair (1995). The third set of problems addresses the situation where capital costs are very high relative to operating costs, and data from the automobile industry are used for this set of problems. The last set of problems examines environments in which capital costs are relatively low compared to the operating costs, and data from the refrigerator industry are used for this set of problems. For each set of example problems, five scenarios are examined, each of which includes different combinations of factors in the objective function. All of the model parameters are tested at several different levels; in total, more than 25 000 test problems are solved.

Some common insights emerge from these example problems. First, even though newer technologies are more environmentally friendly, including environmental costs in the objective function does not lead to a consistent increase in their adoption. The rate of new technology adoption depends on many factors. The second main lesson from this study is that penalties and incentives can have a significant impact on behaviour. Offering incentives to adopt newer, cleaner technologies and/or imposing penalties for keeping older, less-efficient technologies is a common practice as evidenced by the high-profile 'Cash for Clunkers' program in the U.S., designed to induce consumers to trade in older cars for new cars. The analysis shows that these kinds of programs can be effective at promoting changes. However, in the problems studied, only relatively high incentives and/or penalties have a significant effect.

The third main lesson of this paper is that adopting newer, cleaner technologies does not always produce the expected results. Although upgrading does generally yield lower environmental operating costs, the net effect on the total environmental burden may be negative. In many example problems, upgrading actually resulted in much *higher* overall environmental costs due to the burden of disposing of the old equipment and producing the new equipment. In addition, if the incentives and penalties are not structured properly, the decision maker can actually be induced to choose something other than the cleanest technology. Therefore, it is important to account for environmental impacts over the entire life cycle of equipment, and it is important to structure compliance mechanisms in a way that encourages adoption of the cleanest available technology.

The model and results presented in this paper can benefit both researchers and practitioners, and it is hoped that the findings will serve as a springboard for future research along several dimensions. In particular, it would be useful to consider uncertainty with respect to parameters other than timing—e.g., environmental impacts. In addition, it would be valuable to extend the analysis to multiple pieces of equipment or fleets of vehicles—e.g., switching a fleet of public buses to alternatively-fueled vehicles.

Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jclepro.2010.08.017.

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