Technology Prizes for Climate Change Mitigation

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Abstract

We analyze whether technology inducement prizes could be a useful complement to standard research grants and contracts in developing climate change mitigation technologies. We find that there are important conceptual advantages to using inducement prizes in certain circumstances. These conceptual inferences are borne out by an examination of the track record of prizes inducing research into public goods, including relevant energy technologies. However, we also find that the prizes' successes are contingent on their proper design. We analyze how several important design elements could influence the effectiveness of a climate technology prize.

Key Words: inducement prize, research and development, climate change, technology, policy
JEL Classification Numbers: Q28, D81, C68

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1. Introduction

Ninety percent of the energy consumed globally comes from fossil fuels, whose combustion generates the bulk of the greenhouse gases (GHG) that are linked to global climate change. In response to growing concern about the potential damages from climate change, many of the world's governments, including the government of the United States, have agreed on the goal of stabilizing GHG concentrations. If stabilization is to be accomplished without drastically reducing energy consumption, the world needs a new energy system capable of meeting demand, but with close to zero net emissions. The adoption of such an energy system is conditional on the development of new technologies. At present, the most commonly cited technology options for reducing GHG emissions are increased energy efficiency, renewable energy sources, advanced nuclear generation, and carbon capture and storage.

Although there is broad agreement on the need for more research, private sector incentives to research GHG-reducing technologies fall short of being socially efficient. Notwithstanding the recent adoption of the Kyoto Protocol and other domestic and international policies, the market largely fails to internalize the impact of human activities on the climate. In the absence of policies that would place a market price on GHG emissions—such as a carbon tax or cap-and-trade system—consumers and firms do not have adequate incentives to constrain emissions through adoption of better technologies. Even if policies are implemented to internalize some of the expected costs of GHG emissions, it will likely be politically difficult to

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fully internalize the expected social costs of climate damage any time soon. Moreover, it is extremely difficult for national governments and the international community to credibly commit to a long-term future path of climate policies involving more dramatic reductions. These factors significantly curtail current corporate interest in developing GHG-reduction technologies.

Even if there were not institutional impediments that prevented environmental costs from being accounted for in the marketplace, the level of research spending on climate change mitigation technologies would probably still fall short of the socially efficient level (Jaffe, Newell, and Stavins 2005). This reflects the fact that research is characterized by market imperfections that reduce incentives for investment. First, the benefits of developing a new technology or product do not accrue only to its discoverer. Rather, they spill over, benefiting society and other firms. This is the inverse of the pollution externality problem, where the benefits are concentrated in the polluter and the environmental damages are diffuse.

Second, the impact of a technological advance tends to be positively associated with the extent of its adoption, which means that the innovating firm’s returns are contingent on factors beyond its control. If other firms develop compatible technologies, the innovator will benefit more, but if a different technological standard becomes the norm, the innovator’s profits will be markedly less. The implied uncertainty of being dependent on others’ behaviors could reduce firms’ incentives to innovate.

Third, other forms of incomplete information also characterize the innovation and diffusion of a technology. For example, in the context of environmental problems such as climate change, returns on investment are contingent on the size and shape of future government policies and international negotiations. Such widespread uncertainty makes estimating returns extremely difficult, which can lead to underinvestment in research. Because of these complicating factors, an innovation that could lead to an overall improvement in social welfare will sometimes not be pursued because the private incentives for its development are not sufficiently large.

The externalities that characterize both the economics of the environment and technology suggest that it may be efficient to add proactive inducement policies to the traditional incentive system of patents and intellectual property rights to encourage new GHG mitigation technologies. The traditional system encourages research by granting innovators temporary monopoly rents on what they develop. The federal government complements this framework through the use of inducement mechanisms, including: tax credits for specific types of research and development (R&D); direct subsidization of research through grants or contracts to the private or academic sector; and active pursuit of new research through its laboratories or other research facilities (Macauley 2005).

Despite their differences, each of these efforts, including tax credits, incentivizes the development of new technologies primarily by subsidizing the cost of research inputs. These research subsidy methods have achieved considerable successes in stimulating research in the past, including in the area of global climate change. In particular, university- and lab-based research contracts and grants have been used in pursuit of climate change technology R&D. Despite these policies' past efficacy, there is growing interest in the possibility that government research policy could be improved by also using a different type of mechanism, one that pays for outputs rather than inputs. Scholars have shown that output-oriented policy levers can achieve significant results by changing the incentives faced by researchers. Among these output-oriented policies, the option that consistently receives the most attention is the award of technology inducement prizes.

In theory, a prize focusing on technology would seem to be quite straightforward: It should reward an individual or group for some novel or innovative technological achievement. In implementation, however, technologically oriented prizes are considerably complex. First, they can be divided into two categories depending on when the prize giver's goal is specified. An ex post prize provides an award (financial, honorary, or both) for work that has already been done and that likely would have been conducted even in the absence of the award. Also known as reward prizes, this type of prize is common in the public and the private sectors.[1]

Although ex post awards are useful methods of recognizing researchers who have done outstanding work, they are an indirect way of spurring new R&D investment in a given direction. When specific innovations are desired, prize givers are more likely to use an ex ante prize, in which the technological threshold or target is specified prior to when the research takes place. This type of prize induces new innovations, rather than rewards past breakthroughs (Maurer and Scotchmer 2003; Davis and Davis 2004). Like reward prizes, inducement prizes have a long history, dating back at least to the early 18th century. Until very recently, their modern usage has been mainly in the private sector. Over the past 10 years, however, there has been significant growth in governmental use of inducement prizes aimed at various stages of the innovation process. Prominent examples include both the U.S. National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency (DARPA). Prizes have even been included in the U.S. Senate's proposed energy bill.[2]

In this paper, we focus primarily on inducement prizes targeted at the middle stages of the technological change process: applied research, development, and demonstration. We note, however, that in practice many of the technology development and procurement contracts currently given by government agencies such as the U.S. Department of Defense (DoD) are a type of technology prize, often awarded through a competitive bidding process (Taylor 1995). The prize, in that case, may take the form of a commitment to procure a certain amount of equipment of a particular quality at a particular price. Whereas an award established to

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[1] Several prominent governmental examples of such reward prizes include: the Malcolm Baldridge National Quality Award given by the National Institute for Standards and Technology of the U.S. Department of Commerce; the U.S. National medals for Science and Technology given by the White House Office for Science and Technology Policy and the Department of Commerce; and the Enrico Fermi Award administered by the Department of Energy (National Academy of Engineering 1999). (There are also many private sector examples.)

[2] The bill authorizes the Energy Secretary to establish a program to award cash prizes in recognition of scientific achievements. Details are not provided on the level of funding or specific technological targets. A copy of the proposal can be found at http://energy.senate.gov/public/_files/TitleXDOEManagement.pdf as of June 1, 2005.

encourage a path-breaking new development would necessarily need to be structured somewhat differently from one focusing on developing a demonstration model or commercializing an already proven technology, there are lessons to be shared across these experiences.

Scholars have begun to pay more attention to how prizes function and whether they may be used to counter some of the problems associated with both the patent system and input-oriented inducement policies. Our paper contributes to this literature by examining whether or not technology inducement prizes for GHG-reducing technologies would be a useful complement to the standard policy tools (contracts and grants) already being used. We begin in Section 2 by examining the economics characteristics of prizes. Next, in Section 3, we briefly analyze how inducement prizes have been used in the past and how they are being used today. In Section 4 we discuss the design structure for prizes and how and why it might vary. Throughout Section 4, we examine how climate change prizes might be influenced by these considerations. We conclude the paper in Section 5.

2. Economics of Prizes

In this section, we establish a framework and vocabulary through which to discuss the economic characteristics of inducement prizes. Although designs can differ considerably, prizes in any setting share some common elements. These factors appear to be common to all types of technology prizes and are not likely to be substantially different for the goal of stimulating GHG-reducing technologies. First, we develop a simple model to compare prizes to traditional R&D subsidization methods (Section 2.1); then we demonstrate how prizes differ from other technology policy instruments in how they deal with uncertainty (Section 2.2). Finally, we consider the intertwined issues of researcher participation and duplicative research (Section 2.3). Some advantages and disadvantages of prizes and of the grant and contracting processes are summarized in Table 1.

2.1. A Simple Model of Prizes

Some prize characteristics emerge from an examination of how prizes induce innovation. In considering this process, we use a qualitative model built on Wright's (1983) work on innovative activity.[3] For the sake of clarity, the model is highly simplified. We make use of it not because we believe it to be fully realistic but rather because it illustrates some key points.[4]

Consider a situation in which a number of firms that are pursuing a given, discrete invention. For the firm that successfully discovers it, the invention leads to a certain amount of private gains. In addition to these private gains, the discovery leads to an increase in social benefits that is not captured by the discovering firm. In pursuit of the innovation, each firm incurs certain costs, which are a function of the firm's private research expenditures and the total amount of research by all firms. The probability that the innovation will be developed is a function of the total amount of research. Assume that the incremental probability of success decreases as the total amount of research spending grows. In other words, over the relevant range of research investment spending, each additional dollar has a smaller impact on increasing the probability of successfully developing the innovation.

The economic problem from society's perspective is to maximize net benefits from research—that is, the difference between the expected overall social value of the prize and the research costs. The optimal value of aggregate research occurs at the point where the expected incremental social benefit from more research equals its incremental cost. The amount of research that the firm will undertake simply because of private incentives will be optimal only if the market perfectly captures all of the benefits and costs to the development of the new technology. As noted above, scholars have shown that this rarely occurs, because of various

[3] Readers who are interested in the mathematical formulation can find it in the Appendix, where much of the following discussion is reproduced and complemented with a formal quantitative model.

[4] Some key assumptions are embedded in the model. An important informational assumption is that all parties are aware of each other's costs, benefits, and probabilities of innovation. Competitors know how much money they can expect to earn in the market from the successful development of the innovation, and the prize sponsor knows the impact the innovation will have on overall social welfare. We come back to this issue below in Sections 2.2 and 2.3.

spillover effects. For innovations connected to public goods such as the environment, this optimal amount of research is even more unlikely (Jaffe, Newell, and Stavins 2005; Maurer and Scotchmer 2003; Shavell and Ypersele 1999).

An interested policy maker can remedy the market's failure to produce the optimal amount of research by using inducement mechanisms to increase the level of research spending from the level induced by the intellectual property rights system to the optimal level. The traditional method for intervening in this way has been for the policy maker to subsidize inputs to research by buying research through the use of contracts or grants.[5]

Prizes work somewhat more subtly than contracts or grants. By offering a prize of a given amount for the development of the innovation, the prize sponsor changes the profit maximization problem that research firms face. A competitor's new expected returns would be a function both of the overall likelihood that the innovation will be developed and of their unique probability of being the innovator. In this new scenario, a firm's optimal level of research expenditures will be determined by the average probability of the successful development of the innovation—by any firm—rather than the incremental probability of successful innovation, as is desired to maximize social net benefits. This has significant implications for the proper size of the technology prize.

Because the incremental probability of innovative success is decreasing in the level of research spending, the average probability of success will tend to be greater than the incremental probability of success. Therefore, if the prize is set equal to the full social value of the innovation (that is not otherwise captured by the private sector), the use of a prize will lead to excessive research. This means that the prize sponsor should make the prize amount a fraction of the uncaptured social value. This implies that the sponsors can, in principle, achieve the optimal level of research investment with less of a financial outlay by using a prize mechanism than by using grants or contracts. In practice, prizes also have other characteristics that distinguish them

[5] It should be noted that the optimal level of research spending is not easy to determine. This has led some scholars to suggest that the optimal solution is for contestants themselves to propose the size of the prize, as they are better informed about research costs and the likelihood of success (Che and Gale 2003).

from grants and contracts. Perhaps the most obvious such characteristics are the non-financial benefits, such as media attention and prestige, which can accompany prizes.

2.2. Technology Policy Choice under Uncertainty

The foregoing discussion highlights some of the theoretical and practical advantages of technology prizes. It is, however, highly abstracted from real world considerations that are difficult to incorporate into a simple model. Of special importance is that it neglects differences in the availability of certain information to research performers versus research sponsors. That is, the research process can be characterized by significant information asymmetry problems, particularly with regard to the cost of research and the likelihood of success. Different types of technology inducement mechanisms address informational asymmetries in different ways. Thus, when choosing whether to use prizes or subsidies to encourage research in a given area, policy makers should consider the specific situation.

In particular, economic problems can result from situations in which the party with less information bears the risk of failure. If individuals do not bear full responsibility for their actions, they have implicit or explicit incentives to act in inefficient ways, leading to so-called principal-agent problems. For example, consider a situation where one party—the principal—contracts with another—the agent—to pursue a given goal. If payment is not conditional on success and the principal's ability to observe and measure effort is limited, the agent can shirk or behave in such a way that is aligned with its own, but not the principal's, incentives. More efficient outcomes result if the risk for failure is borne by the agent, who has better information on the chance of success given its knowledge of its own behavior.

With respect to technology policy, it seems reasonable to conclude that researchers typically have better information than the policy maker on their own chances of success. Therefore, economics theory suggests that, other things being equal, it is better if researchers bear the risk of failure. Technology prizes allocate risk in this manner by paying for research only in the event of success. A firm that participates in a prize competition will be penalized both for any cost overruns in the pursuit of the specified innovation and for being overly optimistic about its chances of success. Any deviation from the specific goal of the prize increases the firm’s likelihood of not winning the award and not recouping its costs; and if a research firm lacks confidence in its chances of success it will have an incentive not to pursue the prize. Thus, the economic characteristics of prizes help to limit the research pool to the most qualified firms, which should efficiently tailor their research activities in the pursuit of the goal.

Where they do not bear the risk of failure, the researchers will have less incentive to be efficient in both the innovations they pursue and the manner in which they pursue them. Under a stereotypical grant and contract process, the research sponsor assumes the risks from researchers, and subsidizes their efforts regardless of whether or not they achieve their goals. This situation is vulnerable to principal-agent problems. For example, if failure does not cost them anything, researchers might solicit contracts or grants even when they know that their efforts have little chance of success. If the agency sponsor cannot fully discriminate between deserving and undeserving proposals, this can lead to an inefficient allocation of research funds (Kremer 2000).

It must be noted, however, that in practice research subsidy policies do not always lead to inefficient outcomes. In particular, R&D contracts and grants may be well suited to support basic research because the incentives of the government and the researcher are aligned. The sponsor’s goal is to expand the pool of what is known and to disseminate this knowledge quickly so as to maximize knowledge spillovers. Those on the receiving end of government research grants tend to be scientists located either in academic institutions or government laboratories, where they have career incentives to publish pure research papers as quickly as possible. Thus, they may have little reason to deviate from what the government wants them to do.

Where this synchronicity of incentives does not exist, however, the contract and grant processes may be less suitable. In particular, there may be problems when the government wishes to spur applied R&D or commercialization of proven technologies, realms where government success has been much more checkered (Cohen and Noll 1991). Because the government cannot perfectly monitor behavior after a contract has been awarded, researchers may be consciously or subconsciously tempted to deviate from the specific goal to pursue more fundamental science, which is where most of them have career incentives to publish (Kremer 2000). Although deserving of attention, the costs of shirking or inefficient research subsidization should not be exaggerated. Most researchers and associated institutions likely wish to receive grants on multiple occasions. Therefore, it is not in their interest to alienate sponsors by gaining a reputation for inefficient behavior. It is also worth pointing out that many flawed or failed research programs' problems stemmed from factors other than principal-agent issues.

In an effort to reduce inefficiency, policy makers have incorporated prize-like elements into contracts and grants in an effort to address information asymmetry problems (Taylor 1995; Che and Gale 2003). For example, it is now common for a grant or contract to be awarded after a review of researchers' competitive proposals. The information asymmetry problem can be further reduced through the use of a multistaged proposal process in which the government sponsor solicits information on how researchers would respond to possible contracts. It can then use this information to rescale or otherwise modify the contract. Such steps help to mitigate—although they do not completely remove—the informational asymmetry problem faced by policy makers when using grants or contracts.

In conclusion, the presence of information asymmetries influences the choice of inducement mechanism. Where policy makers do not have a particular technological output in mind, they may be better off eschewing prizes. Instead, they could allow researchers to submit bids for a contract or grant, which would then be peer reviewed to ascertain their quality. However, when policy makers are able to identify a technologically specific area that they believe is underserved by market incentives, there may be efficiency gains to using a prize to attract investigation. Overall, the offsetting characteristics of the different technology policy levers suggest that when policy makers want additional research in a broad variety of technological areas, the optimal portfolio of stimulus mechanisms should include prizes in addition to contracts and grants.

2.3. Research Participation and Duplication

In addition to dealing with uncertainty differently than contracts or grants, prizes also have a different impact on the level and nature of research participation. The most important reason for this is that prizes can reduce the bureaucratic and accounting barriers to entry that accompany the grant and contracting processes. Such hurdles are costly and complicated, frequently making it hard for small firms and other newcomers to compete for research support under the standard research subsidy framework (Holtz-Eakin 2004; Kremer 2000). The ability to attract these smaller players is one of prizes' allures, because small players may have greater willingness than the institutionalized competitors for grants and contracts to depart from the mainstream technological paradigm. Scholars explain this by suggesting that contests can induce participants to become less risk averse, causing them to pursue more technologically radical concepts (Nalebuff and Stiglitz 1983).

Although they lower bureaucratic barriers to entry, prizes shift risk in a way that may create an impediment to participation. This is because, unlike contracts and grants, technology prizes typically offer competitors no funding up front. Competitors must self-finance all their research spending, and are reimbursed only in the event that they win the competition. If participants are risk neutral and not credit constrained, this arrangement may have no effect on their decision to participate in the contest. However, in the more likely case that researchers are risk averse and do face cash-flow constraints, the unavailability of up-front funding could dissuade them from competing. Small firms may be most susceptible to this problem because they are least able to afford expenditures without compensation. Thus, although prizes can be argued to reduce the bureaucratic barriers to entry, they raise a liquidity obstacle.

Overall, historic evidence (discussed in Section 3.1) seems to indicate that the first effect tends to outweigh the latter, but a prize designer must pay attention to the question to ensure that specific circumstances do not lead to an undesirable outcome. That analysis should include consideration of the fact that more competitors are not necessarily a good thing. For several reasons, an overabundance of research investment is not always better from the perspective of social welfare. First, there is the problem of diminishing returns to investment: There comes a point where an additional dollar of research expenditures will not produce sufficient additional expected benefits to justify the cost. In addition, there tends to be only a finite number of innovative ideas for any given technology at a given time. Research firms "fish" in this "common pool." As the number of competitors increases, the likelihood that multiple entrants will pursue the same research idea also increases, resulting in a greater likelihood of wasteful duplication of effort. The marginal increases in the likelihood of development are outweighed by the higher costs incurred.

An excessive number of competitors also can lead to other efficiency penalties, because it affects firms' effort levels. As the number of entrants increases, drawn by the promise of a financial award and media attention, the probability of victory for the other participants declines. Under the conditions we specified, this should cause a reduction of each individual firm's effort (as measured by each firm's research spending). If the "first" entrants are highest in quality and have a better chance of overall victory, then the addition of each new marginal competitor could cut into the expected social benefit from the prize (Nalebuff and Stiglitz 1983; Fullerton and McAfee 1999).

Although we need to take these problems seriously, they should not be overstressed. In practice, given existing budgetary pressures, the probability of an excessively high prize is unlikely to be as large a problem as the reverse. Moreover, duplicative and wasteful research endeavors are common to other research-incentivizing processes (e.g., patent races), as are issues associated with efficient spending levels in a competitive situation (Baumol 2002).[6] Depending on the magnitude of the social benefit that the new innovation could bring, some degree of duplication may be efficient. This is especially the case because scholars have found that it is typically necessary for firms to engage in their own research in order for them to be capable of absorbing the results of knowledge generated by others—a type of learning by doing. There are also ways for technology prize designers to potentially limit duplicative research. Perhaps the most prominent methods are intermediary competitive steps or requiring firms to pay to compete (Fullerton and McAfee 1999). Both methods eliminate contestants who are—or feel themselves to be—less likely to win the overall competition. These methods are discussed in greater length in Section 4.5.

In the end, the choice between prizes and contracts or grants must reflect an analysis of the costliness of the necessary research as well as the efficient number of participants. In some cases, prizes may be “scaled” out of policy relevance by the necessary level of spending. Where costs are lower, prize givers may need to strike a balance between encouraging the number of entrants and the need to minimize excessive investment.

3. Prize Implementation

Having established a conceptual understanding of how prizes work, we now discuss how they have actually been implemented. First, we consider historic examples; second, we analyze the growing use of prizes. Many of the historic and contemporary examples are summarized in Table 2.

[6] Only under a grant- or contract-based system—one in which there are no competitive steps—could such problems be avoided. Because the research would not occur without the subsidy, the policy-wielder can ensure that no duplication takes place by funding only one researcher.

3.1. Historic Examples of Technology Prizes

Longitude. Perhaps the most famous use of a technology inducement prize dates from 1714 when the British government received a joint petition from the Royal Navy, London merchants, and commercial ships' captains. All were greatly concerned about their losses due to ships' poor navigational capabilities. The government responded by offering three increasingly large prizes to the inventors of devices capable of measuring longitude with a given degree of accuracy. A method accurate to within one degree would receive £10,000; a method accurate to within 40 minutes would earn £15,000; and a method accurate to within one-half of a degree would receive £20,000. In today's currency, the largest award would be worth almost US$3.1 million.[7] The prizes led to wide public interest, which is reflected by their presence in both *Gulliver's Travels* and a Hogarth illustration. They also produced a boom in navigational research. Eventually, John Harrison, a self-educated clockmaker, succeeded where the experts failed, devising sufficiently accurate and durable chronometers to earn him the £20,000 in 1773 (Davis 2002).

Alkali and Canning. Later in the 18th century, the French government used technology prizes to achieve two major industrial breakthroughs. The first prize was instituted in 1775, when the French Academy of Sciences announced a reward of 100,000 francs to whoever could systematically produce an artificial form of alkali, which was in great demand by both the soap and glass industries. The competition led to the successful development of a commercially viable process that became the foundation of the French chemical industry (Davis 2002; Mokyr 1990; Macauley 2005). Another French technology prize came 20 years later, as Napoleon pondered a way to keep his Revolutionary army supplied with food in the field. In an attempt to solve this longstanding logistical problem, Napoleon's Society for the Encouragement of Industry offered a

[7] Currency calculations performed using two online currency converters. EH.net's "How Much is That Worth Today?" was used to convert from 1714 British pounds to 2002 British pounds, while www.oanda.com's historical conversion was used to convert from the arbitrarily selected date of April 7, 2002, pounds to April 13, 2005, U.S. dollars.

prize of 12,000 francs to the inventor of a method for preserving food. After 15 years of experimentation, Nicolas Appert won the prize in 1810 for his invention of a method of vacuum sealing cooked food in glass bottles (Mokyr 1990; Wright 1983; Maurer and Scotchmer 2003).

Automobiles. Despite their early history as instruments of government policy, technology inducement prizes became much more affiliated with interested private sector parties beginning in the 19th century. That does not mean, however, that they ceased to have large social impacts. For example, inducement awards played a prominent role in the development of several of the 20th century's most important industries. For example, in 1895 the publisher of the *Chicago Times-Herald* sponsored a particularly well-publicized series of prizes built around a race. In addition to the winner of the race itself, prizes were set aside for new achievements in speed, durability (as measured by distance traveled), aesthetics, and economy (Macauley 2005; Wright 1996). The publicity surrounding the race and attendant prizes led to significant public interest in cars, which, in combination with the prizes themselves, ensured continued entrepreneurial interest for the fledgling American automobile industry.

Airplanes. Technology prizes were also integral to the development of the aviation industry (Macauley 2005; Davis and Davis 2004). Interestingly, two different types of technology prize were used. For improvements in the distance airplanes could travel, prizes that specified a particular threshold were used. "Famous examples include the first flight across the English channel in 1909 ($5,000), the first flight across the North Atlantic in 1919 (£10,000), and the first nonstop flight from New York to Paris in 1927 ($50,000) " (Maurer and Scotchmer 2003, p. 11). By contrast, more contest-like contests spurred incremental improvements in other areas (e.g., speed and endurance). Instead of targeting a given technological area, sponsors set up large races, which offered $5,000 to $10,000 to the winner. (Entrants could compete in multiple races.) Some of the resources supporting the race entrants came from governments interested in aviation's military potential, but private investors also played a large role (Maurer and Scotchmer 2003). In addition to their financial incentive for innovation, both types of prizes played a powerful role in supporting the early aviation industry by attracting and maintaining popular interest. This further incentivized commercial interest in developing the technology.

Super-Efficient Refrigerator Program. Despite the decline in governmental use of technology prizes in the 20th century, the U.S. Environmental Protection Agency (EPA) experimented with them as a method for incentivizing environmentally friendly innovation in the 1980s. Instead of using its regulatory "stick" to drive firm behavior, the EPA considered developing "Golden Carrot" programs that would offer an incentive for the development of products meeting certain design criteria. As of 2005, there has only been one large-scale Golden Carrot effort: the Super-Efficient Refrigerator Program (SERP), which was formed in 1991 (Gillingham, Newell, and Palmer 2004). Under SERP, 25 electric utilities agreed to pool $30.7 million of demand-side management funds. This guaranteed sum would be available on a piece-rate basis to the manufacturers of a competitively priced refrigerator that emitted no carbon fluorocarbons and used at least 25% less energy than required under then-existing regulations.

To enter the contest, a company had to have produced at least 100,000 refrigerators the previous year. Ultimately, SERP received 14 bids, which were narrowed down to two finalists, with Whirlpool winning the competition in June 1993. The SERP model refrigerator ultimately did not sell as well as expected, and Whirlpool never received the total allotment of prize money. Some scholars have nevertheless argued that SERP paid significant social dividends by proving that more efficient refrigerators could be economically produced, making possible the stricter 2001 technological standard (Davis and Davis 2004; Gillingham, Newell, and Palmer 2004).

Ansari X-Prize. The recent resurgence in technology inducement prizes' popularity owes much to two privately funded space flights in October 2004 (Maurer and Scotchmer 2003). Whereas the broad goal of these flights was to demonstrate the potential for commercial space travel, the proximate incentive was the Ansari X-Prize. Established in the mid-1990s in conscious emulation of the prizes used to incentivize improvements in the early aviation industry, the X-Prize was intended to encourage nongovernmental space research by offering

$10 million to the first team to prove that space travel could be regularized. Specifically, the winner had to reach an altitude of at least 100 kilometers twice within two weeks. The X-Prize and its $10 million award received significant media attention, which helped attract many participants.[8] Ultimately, 26 teams from seven different countries competed, resulting in over $100 million of private R&D, before SpaceShipOne claimed the prize on October 4, 2004.

Though technology prizes' proponents tend to consider only their successes, it is worth pointing out that the above examples also suggest some of the drawbacks that we discussed in Section 2. Consider the X-Prize. Looked at from the prize designers' perspective, which prioritizes space research, the prize was an enormous success. In exchange for $10 million, they encouraged $100 million dollars to be invested in pursuit of their cause, leveraging 10 times their investment. From a social welfare perspective, however, the enthusiastic response may have been inefficient. There might have been an excessive amount of research or duplicative research given the potential social benefit, and resources might have been better off supporting other projects. It is hard to know how this balances out without further analysis, but the danger is clearly there. Similar analyses could also be directed at the other historic cases outlined in Section 3.1, and contemporary efforts outlined in Section 3.2.

3.2. Current Technology Prizes

Today, most technology inducement prizes are used by interested parties in the private sector to encourage research in areas of particular concern to them. The interested parties often establish legally distinct non-profit organizations to administer and coordinate the prize. The X-Prize was an especially mediagenic example of this practice. Although private institutions sponsor the bulk of current prizes, there is also growing interest in using prizes as an instrument of government policy.

[8] More information on the Ansari X-Prize can be found at http://www.xprizefoundation.com/about_us/history.asp.

Computing. Like the X-Prize, the Electronic Frontier Foundation's (EFF) Cooperative Computing Challenge is an example of a technology prize set up by a private foundation. It aims to encourage research into using computers cooperatively to address computational issues that are too large for even a supercomputer. In order to provide a specific goal to incentivize such research, EFF specified that the test of the system would be to discover prime numbers of record size. The maximum prize is $250,000 for the first individual or group to discover a prime number with at least one billion digits (National Academy of Engineering 1999).[9] Another major example of a privately established technology prize is the Loebner Prize. It is a formalization of Alan Turing's famous test: to create a computer whose responses in a conversation with a human being are indistinguishable from those of a human being. The grand prize for successfully creating such a computer is $100,000. Until that prize is won, the team whose computer most closely approximates human interaction in any given year receives $2,000 (National Academy of Engineering 1999).[10]

NASA Centennial Challenges. In spite of the suspension of large Golden Carrot programs, technology prizes continue to be used by the U.S. government to induce particular types of research. Achieving considerable attention in the wake of the X-Prize, perhaps the most high-profile current federal effort is NASA's Centennial Challenges. In conjunction with its non-profit partner, the Spaceward Foundation, NASA is offering prizes totaling $400,000 for specific innovations over the years 2005 and 2006. There are two research areas where prizes are offered: wireless power transmission ("power beaming"), and strong, lightweight tether materials, to be used in the creation of a "space elevator." It seems worth noting that while neither technology was specifically selected with climate change mitigation in mind, both could be useful in that context. For example, some have suggested that tethers could be used to place extremely

[9] For more information, consult the EFF Cooperative Computing Awards web site: http://www.eff.org/awards/coop.html.

[10] For more information, consult the Loebner Prize web site: http://www.loebner.net/Prizef/loebner-prize.html.

efficient wind turbines in the stratosphere (Cohn 2005), and power beaming could be used to allow photovoltaic cells on satellites to beam power back to earth (David 2001; Macauley et al. 2000; Macauley and Davis 2001).

As with the automobile and aviation examples, the NASA prizes have been set up to repeat in the same technological area from one year to the next. In 2005, the winners in both categories would receive $50,000. In 2006, the victory conditions become more stringent and the grand award increases to $100,000 ($40,000 and $10,000 prizes for second and third place will also be given). In both Challenges, all applicants are examined at the same time and the best entry is selected as the winner. This is slightly different from the first past-the-post method that we have seen in other historic examples. The differences between these prize structures are explored in greater depth in Section 4.5.[11]

DARPA Grand Challenge. DARPA has also recently begun using technology prizes to induce specific types of research. In 2003, the agency established the $1 million DARPA Grand Challenge to accelerate research into the development of driverless vehicles, with an overall goal of reducing the number of American lives lost on the battlefield. The winner of the prize was to be determined by a race across the Mojave Desert in fall 2004. Despite the fact that 15 entrants emerged from the qualifying round at the California Speedway, the overall prize went unclaimed because none successfully completed the desert course. The lack of winner notwithstanding, DARPA viewed the response to the first Grand Challenge as successful enough to repeat the competition in 2005, increasing the prize to $2 million. As of February 2005, over 195 teams had entered the competition, which will conclude with another desert race in October 2005 (Maurer and Scotchmer 2003).[12] The massive amount of interest in the Challenge can be seen as evidence of the non-market incentives that prizes are able to leverage. DARPA's use of an intermediary

[11] For more information on the Centennial Challenges, see the official NASA web site: http://exploration.nasa.gov/centennialchallenge/cc_index.html.

[12] For more information on the Grand Challenge, see the official DARPA web site: http://www.darpa.mil/grandchallenge/index.html.

step functions as a way of limiting the amount of waste that such a large number of competitors could potentially produce.

Developing World. Besides reduction of GHGs, there are several other areas where scholars have suggested that technology prizes could be used to good effect. Perhaps the most credible would be in providing a guaranteed market for goods desired by the developing world (Kremer 2000; Masters 2004). Of particular focus are vaccines for diseases such as malaria, and products that increase agricultural yields. The social welfare gains to innovations in these areas are huge, but firms' expected benefits from developing them are quite small. There are two key problems. The first is that the developing world lacks the resources to purchase and distribute new developments. Further inhibiting investigation is the threat that the technology may be expropriated on humanitarian grounds. To counter these concerns, donors in the developed world would commit to the purchase of a given amount of a developed product (e.g., vaccine or seed). With the guarantee of a profitable market, private research funds would hopefully flow into previously unattractive areas (Masters 2004; Kremer 2000, 2000)

4. Designing a Prize

In this section, we examine the common elements around which specific prizes can be designed. Where relevant, we focus on the impact these differences might have on a climate prize.

The first element we consider is the actual process of creating a prize. Next, we examine the institutional setting for the prize. To a large extent, both elements lead to distinctions that result from a public sector versus a private sector prize. Even if the prize sponsors' goals are the same, differences in these "meta" components will have a considerable impact on the overall nature of the prize because of political economy considerations.

More specific elements of the prize's design can be divided into three categories: the technological target, the size and nature of the prize, and the method for selecting the winner (i.e., the victory conditions). Decisions with respect to any of these factors will influence the level of participation and overall success of the contest. Throughout, we draw inferences from previously introduced examples of past and present prizes. Pertinent aspects of each design element are summarized in Table 3.

4.1. The Creation Process

To a considerable extent, the formation of a private sector technology prize is not that complicated. If one or more parties decide that the combination of the patent system and governmental contracts and grants are doing an insufficient job of incentivizing a given type of research, they could pool resources in order to create a prize. This might be done by setting up a legally distinct foundation, as was done by the X-Prize's founders. Alternatively, sponsors might simply set aside some of their own capital, as was more common in the early 20th century.

The issue becomes more complicated if the prize is a tool of government policy. Although it is possible that an inducement prize could be established without mandate from the U.S. Congress, it is fairly unlikely and all but impossible if the financial award is sizable. For the goal of further developing technologies capable of substantially reducing GHG emissions, it seems very likely that Congress would have to pass some form of enabling legislation. The specificity of the bill could vary, but it almost certainly would identify several factors, most notably where the prize would be administered, and possibly how the prize would be funded and the level of funding.

In the case of climate change, there are several obvious administrative options. Given the clear relevance of energy technologies to GHG emissions, one or more offices in the U.S. Department of Energy (DOE) would appear to be suitable. This is especially true because DOE is one of the federal government's chief science-supporting organizations. Global climate change is an environmental issue, so an argument could also be made for locating the prize's administration within EPA, although EPA currently does little research. Alternatively, one could envision elements of the DoD (such as DARPA) becoming involved, given the potential national security ramifications of energy policy as well as DoD's considerable experience with technology funding. There is also the National Science Foundation, the Advanced Technology Program within the National Institute of Standards and Technology, or the Small Business Innovation Research programs within many departments.

The ultimate choice of a government administrator would likely reflect the specific technological goal that was targeted. A prize focusing on components of advanced nuclear reactors would be more appropriate for DOE, whereas the development of a device capable of constraining emissions in power plants might be better placed in EPA or DOE. If bureaucratic hurdles did not prove insurmountable, it might be advantageous to allow the prize to be established as a collaborative endeavor between two or more agencies. Bringing together individuals with different areas of expertise could reduce information asymmetries. For example, officials from DOE could bring insight into nuclear technology, whereas DARPA or NASA employees could offer additional insight into the administration of a competitive technology prize.

Partnering with a non-profit foundation is another way the federal government could achieve efficiency gains. This was the approach taken with the NASA Centennial Challenges: NASA provides the prize money and has designed the challenges, but the non-profit Spaceward Foundation will handle most of the administration.[13] It is possible but not guaranteed that the use of a foundation could lower the overall costs of offering a prize or reduce the impact of biases within an agency. It might also be a way for the federal government to assure competitors that political biases would not affect the prize. We believe these are fertile areas for further research into policy design.

The question of how to fund a federal prize is not trivial. There are two issues that must be addressed. First, the government's budgetary process works on a yearly basis, which could be

[13] For more information on the Spaceward Foundation, see its web site: http://www.spaceward.org/.

problematic because technology prizes are not always awarded in the same year that they are announced. Second, the funding must be set up in a way that assures competitors that the government will not renege at a later date if attitudes toward the prize's goals change (Holtz-Eakin 2004). If there is a significant possibility that a prize's winner might not emerge for a considerable period, then a method for ensuring payment is required. The funds might be allocated up front and placed in a private sector escrow account, for instance. Alternatively, the federal government could imitate the X-Prize's structure by purchasing an insurance policy that guarantees that the funds will be available (Holtz-Eakin 2004).

In the case of the DARPA Grand Challenge, the funding concern was not particularly large. The appropriation was set up to take account of the possibility that no contestant would complete the Challenge and win the prize. Although $1 million was set aside to cover the prize, DARPA was able to release the funds and use them for other authorized purposes when no one completed the Mojave course (Holtz-Eakin 2004). DARPA's ease in reallocating the funds stemmed at least in part from the fact that the award was quite small relative to the agency's $2.8 billion budget. A climate prize might not be so fortunate, depending on where the prize was located, which technological goal was specified, the magnitude of the award, and how the winner was chosen. Prize designers should take these factors into consideration.

4.2. The Institutional Setting

When set up and run by the private sector, the magnitude and technological focus of the prize are delimited mainly by the resources and particular interests of the parties involved. For example, a group of uranium mining firms might have an incentive to establish a technological prize aimed at speeding the commercial development of Generation IV Nuclear Energy Systems. By contrast, an environmental organization concerned about both nuclear waste and GHG emissions might prefer to incentivize research into energy efficiency or renewable technologies.

A public sector technology prize faces different problems because of political economy concerns. These stem from the fact that the government already engages in considerable amounts of R&D support. In some ways, prizes could have advantages over contracts and grants in this regard. For example, the use of a prize could lessen the influence of politics on research funding. Cohen and Noll (1991) describe many instances in which political economy considerations have led to inefficient research spending. In some cases, the wrong programs—from a greater societal perspective—receive support. In others, although the initial investment might have been appropriate, subsequent events indicated that success would not be forthcoming, but bureaucratic inertia and lobbying ensured that the funding was not discontinued. Using prizes could substantially reduce the likelihood of both of these situations, especially the latter.

However, prizes might also have important political economy disadvantages. One particularly important disadvantage is that they will require support by at least some of the institutions associated with preexisting research support programs. Because these institutions could perceive the prizes as an implicit threat, they might react by working to reduce (or at least not improve) their effectiveness. There are several different parts of the government that might be against new technology programs, but one could have a particularly significant impact: the U.S. Congress.

Congress has considerable latitude in designating specific areas of research for funding. In practice, the use of earmarked funds allows it to wield considerable power over how and to whom grants and subsidies are dispersed, allowing elected officials to use research funds as a form of "pork" to be distributed to supporters or constituents (Kremer 2000; Abramowicz 2003; Banks, Cohen, and Noll 1991). Not surprisingly, the allocation of funds in this manner may fall significantly short of what is optimal. For example, lobbying by interested parties caused the Synfuels program to focus on Appalachian coal, although Western coal was better suited to Synfuels's purposes.

By making the receipt of funds independent of any governmental oversight, technology prizes could considerably disrupt this arrangement, removing politicians' capacity to target rewards to specific recipients. To repress this possible transfer of power, Congress could choose to weaken the design of prizes in several ways. First, the relevant appropriations committees could specify that funding must be earmarked for non-prize-related activities. Second, Congress could place limits on the magnitude of the prize award being offered. This could sharply reduce the attractiveness of participation, cutting into its effectiveness. Third, Congress could attempt to target the prize to specific contestants by playing an active role in specifying the technological goal.

These types of political economy complications may have bedeviled the establishment of the NASA Centennial Challenges. As stated in Section 3.2, the current prize money totals $400,000, which will be given out over two years in eight different competitions. The Centennial Challenges were not always intended to be this modest in scope. As of December 2004, there was still considerable talk about having the Centennial Challenges offer up to $50 million for major achievements, possibly including private human space travel. However, in order to give individual prizes larger than $250,000, NASA requires congressional action (Zimmerman 2004). Similarly, there are large bureaucratic hurdles to overcome in order for NASA to encourage private space travel. Despite having made public statements supporting the pursuit of space prizes, Congress has not moved to increase NASA's authority to disperse funds or to facilitate private space travel. Indeed, the only relevant bills being considered as of December 2004 would have specifically limited NASA from ever being able to give a prize larger than $1 million and would have tightened the safety restrictions on any future space flight competitions such as the X-Prize (Zimmerman 2004). It is not difficult to foresee similar problems arising in the case of climate change mitigation technology research. A fuller treatment on the political economy of prizes would be a welcome addition to the discussion of how and where technology inducement prizes could be usefully implemented.

4.3. Specifying the Technological Goal

Once the institutional setting of the prize has been established, the specific details of the prize's design must be worked out. No doubt, the most important element is what type of research the prize seeks to encourage. It is useful to make a distinction between the overarching goal and the proximate means objective. The goal represents the social outcome that the designer seeks as a result of the efforts induced by the prize. The means objective advances toward that goal. Whereas the goal may be quite broad, the research objective should be as specific and measurable as possible in order to create clearly understood victory conditions. This narrowness of definition allows competitors to know where they should focus their efforts, increasing their confidence in their probability of success.

The relationship between the overarching goal and the proximate means objective can be obvious. For example, in the case of John Harrison and his chronometer, the goal of the British government was to reduce losses due to navigational errors. Because the chief impediment to improving a ship's ability to navigate was the inability to determine longitude, the choice of specific research targets was relatively easy. In other cases, an obvious linkage between the proximate and the overall objectives may not exist. Consider, for example, the case of the EFF Cooperative Computing Prize. The means objective of calculating a prime number of at least a specific number of digits does not immediately follow from the Foundation's belief that cooperative computer networks will lead to significant social benefit. Instead, the EFF prize's designers had to determine what type of behavior could be easily specified and would also support their much more theoretical overall goal.

In many ways, those with an interest in designing prizes to combat global climate change face a situation that falls between these two examples. The overarching goal is clear: to slow or stop the rise of net GHG emissions in order to mitigate the risk of global climate change. Selecting a proximate means by which to obtain this goal requires more work.

One could simply set the research target as some innovation that curbs net emissions by a given amount. This would have the advantage of incentivizing researchers in any technological area to participate in the prize. Setting such a broad target would also have disadvantages, however. Chief among them would be the increased subjectivity in judging the winner because the means by which the major climate technologies mitigate net emissions are significantly different. For example, energy efficiency improvements could reduce the overall demand for energy, but they would not reduce continuing reliance on GHG-emitting fossil fuels. By contrast, research into better renewable technologies could lead to the eventual displacement of fossil fuels and might pay dividends by furthering the political goal of reduced fuel imports. However, renewables are increasingly alleged to have significant negative externalities. Other possibilities include efforts to make fossil fuel consumption more climate friendly through carbon capture and storage.

The differences between these approaches could make judging which entrant had a greater aggregate social benefit on the environment highly problematic. Consider a situation where two competitors are competing for a prize based on achieving a given net reduction in emissions. The entrants meet that goal, but do so using different technological approaches. In addition to having other non-climate differences, it is likely that the cost structures of the two technologies would differ. Even if both had the same overall cost per dollar of reduction, one might require more up-front capital expenditures, whereas the other might have higher operating costs. Deciding which entrant was superior would become a contentious and subjective process. Without restrictions on the technology included in the prize’s rules, possible competitors would be aware of the potential for confusion over the prize’s winner. This would reduce their expected benefit from competing and therefore reduce their willingness to participate.

Given the possible problems associated with a broad set of victory conditions, it seems more reasonable that each climate technology prize focus on one research area at a time. Within the given area, the climate prize’s designer could make use of substantial expert judgment and the growing body of work on “technology roadmaps” to select an aspect for incremental improvement or radical innovation as the means objective of the prize. If funds were available, different prizes could be offered for improvements in any of the major technologies.

If the federal government sponsored a climate prize, the choice of technological focus might be further complicated by its preexisting use of grants and contracts to research ways of reducing GHG emissions. Although the costs of duplicative research must be taken into account, there are reasons to believe that a prize could have a beneficial effect regardless of whether it was used in an established or new research area. In either case, it could be a good way of filling in gaps in the research framework, particularly for applied R&D.

As noted above, prize competitions have an ability to attract new ideas and new participants, in part because they use more than just monetary incentives. In contrast with the basic, mainstream research that grants induce, anecdotal evidence implies that prizes attract the attention of less hidebound thinkers who are willing to challenge technological orthodoxies (National Academy of Engineering 1999). By attracting such practitioners to established research avenues such as carbon sequestration or renewable fuels, inducement prizes could trigger an advance in GHG-reducing technologies that research-subsidizing levers might not have produced. A prize established in more avant-garde areas could be used to encourage conventional research groups to pursue less conventional research directions. Although it might be inefficient for the government to assume the risk of up-front funding of such research given relatively low probabilities of success, a prize could provoke focused private R&D investment among the researchers most knowledgeable in those areas.

4.4. Determining the Financial Award

After the specific research area is selected, the organizers must determine the magnitude of the financial award. In practice, it might make sense in many cases to determine the available financing first, because financial considerations can have a significant impact on the choice of technological goals. If funding is constrained—either by the federal budgetary process or by the resources of the private individuals involved—then some research areas might be simply unrealistic due to their high cost levels. For example, picking a research target of a major advance in nuclear generation is unlikely to have an effect, if one only has the resources to offer a modest award. The costs involved in the research would dwarf the prize's incentive capabilities.

When funding does not dictate the research target, the technological focus plays a substantial role in deciding the magnitude of the financial reward. Informing the issue is the model, discussed in Section 2.1, that indicates that higher development costs, a greater social gain from the innovation, and lower probabilities of success all require higher prizes. Sponsors should bear this in mind—as well as the possible inefficiency of overly large prizes—when making their decisions. Thus, for a given social benefit, a goal expected to incur moderate research costs, such as an incremental improvement in energy efficiency in a given appliance, should be paired with a moderate financial award. A grander technological goal, incurring higher costs and a lower likelihood of success—such as the development of a commercially viable hydrogen storage system for cars—should be matched with a larger financial reward. The more quantitative information that can be brought to bear on the costs, benefits, and research effectiveness variables discussed earlier, the more carefully the award amount could be determined.

This type of information needs to be better developed. Uncertainty over the damages from climate change and the stringency and likelihood of future policy actions impede estimation of the social and private gain to any invention that mitigates GHG emissions. The low stringency of policies that account for the environmental costs of emissions means that there is insufficient incentive for firms to adopt GHG-reducing technologies. This would suggest, on the one hand, that the private benefit to climate-oriented innovation could be small, meaning that the financial magnitude of the prize would have to be fairly large. On the other hand, domestic and international action is growing, which could make the patents to low emission technologies financially lucrative and reduce the difference between social and private benefits to innovation. Any climate prize designer must balance these uncertainties with others. For example, how would the media receive a climate-oriented prize? Would such a prize attract more or less attention than a space travel–oriented prize from the media? Could relevant firms engaged in energy, environmental, and transportation technology research translate that attention into some form of reputational or monetary gain? One could imagine that it would in the case of automobile manufacturers, but perhaps would not in the case of manufacturers of building products. The answers to these questions would affect the size of the prize being offered, as well as whether or not it is designed to purchase the property rights to the technology.

Che and Gale (2003) suggest another method for determining the size of the prize that seeks to circumvent the sponsor's need for information. The authors argue that the optimal solution can be reached by allowing researchers to, in effect, compete in two ways. First, they would compete technically by means of their research proposals. Second, they could vie (i.e., bid) in terms of the size of the prize they would accept for their efforts. As a general notion, economists argue that in a situation such as this with asymmetric information, it is more efficient for the party with better information to choose the price (Tirole 1993). Che and Gale (2003) show that adding the second competitive element increases efficiency by allowing technologically disadvantaged researchers to remain viable by lowering the payoff they would accept. Although this method offers some efficiency gains in theory, it would likely raise other issues, because the sponsor would have to decide how to judge different entrants' bids.

The issue of financial magnitude is further complicated if one incorporates flexibility into what exactly is being incentivized. Our earlier conception discussion implicitly laid prizes on top of the patent system: The prize designer simply adds an extra incentive for a company to develop a technology for its own future use or sale. Thus, the prizewinner would own the intellectual property to the technology that won. This need not be the only way a prize could be used.

Several commentators have suggested that prizes should be used to incentivize research that would subsequently be placed in the public sphere (Wright 1983; Davis 2002; Holtz-Eakin 2004; Tirole 1993). The financial award in this case would in effect be purchasing the patent rights to the new development.

Such a "patent buyout" approach is actually a refinement of an anti-patent intellectual movement that dates back to the 19th century and beyond (Davis 2002; Kremer 1998; Polanvyi 1944; Shavell and Ypersele 1999). The proponents of this patent buyout approach argue that the property rights system should be replaced by a scheme where the government pays a lump sum to an inventor based on the societal benefit derived from the innovation. The knowledge would then be publicly available to anyone interested in using it, avoiding the deadweight losses attributable to inventors' temporary patent monopolies. Various scholars have shown that when the values of inventions are knowable, prize-based systems dominate traditional property-rights systems (Wright 1983; Maurer and Scotchmer 2003). Despite their theoretical superiority, such systems have never been widely implemented because of the great difficulty that authorities face in determining the value of an innovation before it has been adopted.

Though still a major drawback, the need for information would be less of a problem if used on a limited basis, such as in the case of targeted technology prizes. If a sponsor felt suitably convinced that the social good required immediate broad access to a given technology, it could set up a patent-buyout prize competition. In exchange for a significantly higher monetary award (to compensate for the loss of private benefits), the winning entrant would give up the intellectual property rights to the innovations (Holtz-Eakin 2004). For example, if DARPA sought to create several competitive suppliers of driverless vehicles, it would have set up the Grand Challenge so that the prize-winning technology would become available to other firms. Instead, the rules to the Challenge clearly specified that this is not the case: "DARPA claims no intellectual property (IP) rights from entrants, semifinalists, finalists, or the winner. . . . All trade secrets, copyrights, patent rights, and software rights will remain with each respective team" (DARPA 2004).

Another key issue that a prize designer must confront is how the award is structured. One option is to simply give the winner one or more cash payments, which has traditionally been the most common method. But the prize could come in other forms. One of the most obvious alternatives would be the use of a pre-specified supply contract (Kremer 2000). The prize designer would promise to award a contract to purchase a given number of units that incorporate the newly developed technology at a given price. Using this type of prize formula could have implications that differ from those of a more straightforward reward payment. By linking the award to production, the prize designer incentivizes the development of not just a new technology, but also of one that can be reproduced commercially. There are downsides to such a program, however. It is difficult to anticipate many entrants that specialize in research but not mass production, or for them to develop a commercially replicable process on their own. The costs would simply be too high, particularly for GHG reduction.

The example of the SERP prize mentioned in Section 3.1 helps expose some of the issues that can arise from a more complex reward structure. In that case, Whirlpool won the right to collect demand-side rebate money that could add up to $30.7 million if it sold 250,000 units. Scholars offer several reasons for the failure of Whirlpool to collect the full amount. First, the prize sponsor may have misjudged the market, incentivizing the development of a high-end, high-cost product for which there was little demand. But at least as important as the failure to pick a suitable means objective was the remuneration structure. In order to receive the rebate per unit sold, the Whirlpool dealers had to submit considerable amounts of paperwork. Although this may have led to inadequate attention from sales staff in and of itself, take-up of the new unit was further inhibited by the fact that instructions were poorly explained to the sales staff, who did not realize that some of the SERP units’ high costs would be defrayed by the prize money (Gillingham, Newell, and Palmer 2004).

4.5. Setting the Victory Conditions

The last major decision the prize designer must make is how the winner will be chosen—the victory conditions. To a considerable extent, the methods can be split into two categories: "first past the post" and "contests."[14] As with all the design factors, the choice can have non-trivial implications. These have opposing advantages and disadvantages, and the choice between them should reflect the priorities of the prize sponsor.

The first-past-the-post method is simple. The prize is essentially a race to achieve a given technological breakthrough with the prize designer committing to award the prize to the first competitor to achieve the stipulated goal. No other factors are taken into account. This approach to determine the winner is stereotypical, and was used by both the British government in its pursuit of accurately calculated longitude in 1714 and by the X-Prize in 2004. The virtue of this classical approach is the same as its greatest problem: simplicity. The benefits lie in the fact that there is relatively little room for subjectivity. Either the entrant is the first to meet a certain technological threshold, or it is not. Although this may not guarantee that the prize will be awarded promptly—John Harrison had to wait over a decade for royal intervention in order to receive his longitude prize—it does curtail the extent to which political or other elements could influence the prize decision. It also specifies what the prize sponsor desires: a given technological advance. If a more modest research effort is unacceptable, this method has much to recommend it.

As suggested above, such simplicity also has a downside. The chief problem is that the first-past-the-post method prioritizes speed rather than quality. It is not difficult to imagine a situation where another competitor develops a better (perhaps more efficient) method, but finishes second to a faster (perhaps more expensive) entrant. In the extreme, this could lead to a type of "lock in" whereby an inferior technology is accepted in lieu of a better one for reasons of historical contingency (David 1986).

[14] In some of the literature, contests are referred to as tournaments (Fullerton and McAfee 1999).

Using a contest-like approach to determine the winner can avoid this outcome. A contest prize typically differs from a first-past-the-post prize by not specifying a particular level of technological achievement that must be achieved. Instead, contestants have a specific amount of time to develop a technology that will be judged on a given set of criteria. Researchers pursue the level and types of research that best balances their costs and expectations of victory. At the specified time, their entries are evaluated on the basis of the prize sponsor's goals.

In some cases, a panel of experts chooses the winner in a contest-type prize. Similar to a beauty contest, the judges weigh a combination of criteria in choosing the best entrant. This review process could include the size of the payoff that the competitor would accept, if Che and Gale's (2003) framework were adopted.[15] For example, the judges might decide that, whereas one entry achieved more of a technological leap forward, it did so at such a high price that another entry is more deserving. Although such a process allows the prize sponsor great flexibility in choosing its ideal competitor, it is vulnerable to criticism for its subjectivity. Knowing that the winner will not be chosen objectively could create skepticism among potential contestants and reduce participation.

Some of this subjectivity can be removed by selecting the winner of the research contest through some form of physical test (Maurer and Scotchmer 2003). This approach has some of the characteristics of a first-past-the-post prize, but it differs in not specifying a certain threshold. For example, the DARPA Grand Challenge uses a physical contest to decide the winner. Unlike a first-past-the-post method, the prize administrators decided not to declare the first contestant to develop a driverless vehicle capable of crossing the Mojave the winner. Instead, DARPA uses a physical race to obtain better insight into the optimal balance between durability and speed in an autonomous vehicle. Using a first-past-the-post approach might achieve a given target as soon as possible, but it might not produce the "best" technology.

[15] In such cases, there would need to be a subsequent step (e.g., procurement) to ensure that the government did not simply choose the lowest bidder.

It is helpful to compare and contrast climate-oriented examples of first-past-the-post and contest prizes. For the purpose of the example, both center on furthering research into photovoltaic technologies. The first prize uses a first-past-the-post format that specifies that a certain cost per megawatt hour rate be achieved. The second prize is contest based, which simply states that the prize sponsor sought the biggest improvement in cost per megawatt hour that was achievable in a year. Depending on the specific target set for the first prize, the sponsors might have the same winner, but they just as easily might not. It is easy to imagine that the first-past-the-post method might not result in a winner within the deadline set for the second prize. Similarly, it seems unlikely that technological change achieved by the contest winner would equal that specified in the first prize (Maurer and Scotchmer 2003). The decision regarding which option is preferable should have a major impact on whether the prize sponsor sets up a contest or a first-past-the-post prize.

Both types of prize structures can be planned to at least reduce the potential for socially wasteful or duplicative research spending. Marginal entrants can be screened from both first-past-the-post and contest prizes by requiring an entry fee (Moldovanu and Sela 2001). Instead of having the sponsor arbitrarily set a fee based on a presumption of players' costs, other authors have suggested that a given number of entrants could be selected on the basis of an auction (Fullerton and McAfee 1999). Other screening mechanisms are prize-type specific. For example, contest-prizes can reduce the number of final entrants by making use of an intermediate competition, whereby those entrants who failed to achieve a given result or rank would be disallowed from competing for the final prize.

All of these contestant elimination mechanisms prevent marginal participants from pouring resources into a competition they are unlikely to win. The disadvantage of culling is that it might eliminate competitors that could subsequently develop competition-winning technologies. It might also screen out small firms without the initial capital to compete with larger firms. As we discussed in Section 2.3, however, such small firms have historically been closely associated with more revolutionary technological developments. Eliminating them may remove one of the key benefits of prizes. The prize sponsor must therefore attempt to balance the tension between too many candidates and too few candidates, both of which could lead to inefficient research levels.

The institutional setting of the prize could also play a significant role in influencing the victory conditions. A purely private prize could use either first-past-the-post or contest prizes with equal facility, but a governmental prize could have difficulty using a first-past-the-post approach if it was likely that the prize might not be won within the year. As noted in Section 4.1, getting dispensation to save money not spent in the year for which it was allocated could increase the bureaucratic hurdles to establishing the prize.

5. Conclusion

There is considerable evidence that technology prizes have a role to play in the portfolio of inducement mechanisms available to spur climate change–related technological advances. An examination of the economics of prizes revealed that they have conceptual advantages that support increasing their role in certain cases. There are almost 300 years of evidence on their successful implementation. These factors underlie the already growing resurgence of interest in using inducement prizes to increase research into public goods. In addition to these broad reasons for considering prizes, there also appear to be compelling reasons specifically related to climate change. For example, climate-mitigation technologies are already an implicit part of the renaissance: both of the NASA Centennial Challenges could have climate-friendly applications. Furthermore, the scope of technologies that could reduce GHG emissions is so broad that it is hard to imagine that there is not room for prizes to play a constructive role. Given their infrequent recent use but potential promise, policy experimentation and subsequent evaluation of prizes for GHG-reduction technologies would be clearly desirable.

As both theory and the historic evidence suggests, however, getting the design of prizes correct is critical. Therefore, interested parties from both the public and private sectors should carefully consider how their specific resources and goals relate to the different prize design elements. For the government, the process of establishing prizes devoted to developing GHG-reducing technologies could begin with congressional action that directs a more thorough investigation of the potential role and design of a federal climate technology prizes, perhaps by the National Research Council or other suitable institution. Alternatively, perhaps an interested foundation, corporation, or individual will be inspired to offer a climate technology prize. Regardless of the institutional setting of the prize, it is essential that any policy experimentation be followed by thorough evaluation to understand the actual effectiveness and efficiency of these potentially important instruments of technology policy, and how their design influences the results they achieve.

Table 1. Comparison of Alternative Technology Policy Instruments

	Prizes	Contracts and grants
Pros	• Prizes solve information problems by devolving risk onto researchers. • Prizes reward outputs. • They require less of a governmental investment than do direct contracts. • Prizes leverage considerable non-financial incentives. • They encourage small, innovative players to participate by lowering barriers to entry.	• Contracts and grants avoid duplicative research. • In case of basic research, mutually aligned incentives reduce informational asymmetries. • Modifications (e.g., use of a preproposal process) can reduce principal-agent problems. • Contracts and grants are able to encourage high-cost research.
Cons	• Prizes can lead to excessive duplication of effort. • They are less suited to high-cost projects where researchers cannot bear all risks. • Up-front liquidity constraints of prizes could lower participation.	• Participants are susceptible to shirking because of information asymmetry problems. • There are high non-financial barriers to entry. • Contracts and grants are less appropriate for applied technology research.

Table 2. History of Technology Inducement Prizes

Date Won	Prize	Description
1762	Longitude	The British government sponsored a financial prize to induce research into the development of an improved method of ascertaining longitude while at sea. It used a first-past-the-post method for determining the winner.
1810	Canning	The French government under Napoleon offered a financial prize to the first person to develop a method for preserving food.
1895	Cars	A Chicago newspaperman sponsored a race and a series of related contests, all of which used derivatives of the contest approach to determining winners. The race and its contests attracted significant attention.
1900s	Planes	Through a series of races, private sponsors incentivized incremental improvements in plane design. Other private sponsors established first-past-the-post distance prizes.
1997	Refrigerators	Established by a consortium of utility companies in association with the EPA, the Super-Efficient Refrigerator Program (SERP) encouraged the development and sale of a more energy-efficient refrigerator.
2004	Private space flight	The heavily publicized $10 million privately established Ansari X-Prize encouraged research into private space flight.
2004–5	Driverless vehicles	First attempted in 2004, DARPA’s Grand Challenge uses a race format to encourage development of technologies related to driverless vehicles.
2005–onward	Space Power Beaming and Tethers	NASA has established the Centennial Challenges program to induce pathbreaking research in several areas. Although NASA sponsors the prizes, the bulk of the administration is handled by the nonprofit Spaceward Foundation. At present, prizes have been established for 2005 and 2006, but the program is expected to extend beyond that date.

Table 3. Design Elements of Technology Prizes

Element	Relevant issues
Institutional setting	Whether a prize is established by the public or private sector could have a substantial effect. A government prize will have to address political interests and related issues, as well as complications regarding the financing of the prize.
Technological target	Creative thought is required to translate broad goals into concrete technical objectives suitable for a prize. The technological target should be carefully chosen to suit the prize sponsor's overall goals and their financial and administrative capabilities, while providing a clear signal to research competitors.
Financial award	The prize's financial award should fit the specific target. If a prize is too large, it could lead to excessive research, but if it is too small it will lead to an inefficiently small amount of attention from researchers. The award can be a single cash prize or a guarantee of future procurement. It can vest intellectual property rights in the winner or the sponsor.
Victory conditions	In deciding whether to choose the winner based on who is first past the post or on a contest basis, the prize sponsor should pay close attention to their priorities. First-past-the-post methods emphasize speed and an explicit focus on a specific technical target, whereas contests offer more flexibility for maximizing achievement over a given timeframe.

Appendix

The following discussion builds on a model of innovative activity developed by Wright (1983). The invention *I* is discrete, and its discovery leads to private gains *V* to the discovering firm. In addition to these private gains, the discovery leads to an increase in social benefits *B* that is not captured by the discovering firm. In pursuit of the innovation, each firm (denoted by *i*) incurs certain costs $c(r_i, R)$, which are a function of private research expenditures r_i and the total amount of research *R* by all firms. The probability that the innovation is developed is a function—*P*(*R*)—of the total amount of research. We assume that the marginal probability of success is decreasing in *R*. In other words, over the relevant range each additional dollar of research investment has a smaller impact on the probability of successfully developing the innovation.

The economic problem from society's perspective is to maximize the difference between the expected overall social value of the prize and the research costs:

(1) $$\underset{R}{Max}: P(R)\left(B+V\right)-C(R).$$

Put another way, taking the derivative with respect to *R* leads to the expected result that the optimal value of aggregate research R^* is the point at which the expected marginal social benefit of research equals its marginal cost:

(2) $$P'(R^*)\left(B+V\right)=c'(R^*).$$

If R^V is the amount of research that the firm would have performed simply because of private incentives, then the patent system will lead to the optimal amount of research only if $R^V = R^*$. This would imply that the market perfectly captured all of the benefits and costs to the development of the new technology. Scholars have shown that because of various spillover effects, this rarely occurs. To remedy the market's failure to produce the optimal amount of research, an interested policymaker can intervene by using inducement mechanisms to increase the level of research spending to R^*. The traditional policy lever has been to subsidize inputs to research by buying R^*-R^V of research through the use of contracts or grants. Prizes work somewhat more subtly. If the prize sponsor offers a prize of Z for the development of the innovation, firms face a different profit maximization problem. Their expected returns would be a function both of the overall likelihood that the innovation will be developed and a firm's unique probability of being the innovator. For the sake of simplicity, we approximate the latter probability as the ratio of the firm's private research investment to all investment, r_i/R. Faced with a prize Z, the private maximization problem is

(3) $$\underset{r_i}{Max}\left[P(R)\left({r_i}/{R} \right)\left(Z+V \right)-c(r_i,R) \right].$$

Maximizing with respect to r_i reveals that optimal private expenditures are

(4) $$\frac{P(R)}{R}\left(Z+V \right)=c'(r_i,R) .$$

This leads to the conclusions that

(5) $$Z=\frac{c'(r_i,R)}{P(R)/R}-V .$$

It is important to note that in this discussion we follow Wright in assuming away the possibility of duplicative research across firms. This is a significant assumption given the relevance of duplicative spending to the overall efficiency of a given technology policy.

Therefore, the optimal research expenditures will be determined by the average probability of success ($P(R)/R$), rather than the marginal probability of successful innovation ($P'(R)$), as was the case above. This has significant implications for the proper design of a technology prize. Because the marginal probability of innovative success is decreasing in the level of research spending, then for any given R,

(6) $$\frac{P(R)}{R}>P'(R).$$

In other words, the average probability of success will tend to be greater than the marginal probability of success. Therefore, if the prize is set equal to the full external social value of the innovation (*B*), then a prize will lead to excessive research. This means that the prize sponsor should make *Z* a fraction *f* of the total social value, minus the privately captured value (*V*), setting *f* equal to the ratio of the marginal to the average probability of success:

$$f = \frac{P'(R)}{P(R)/R}. \qquad (7)$$

Thus, *f* is the elasticity of the probability of successful innovation with respect to research effort, or the percent change in *P* for a 1 percent increase in *R*.

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