When Does Environmental Regulation Stimulate Technological Innovation?
A Synopsis of the Expert Literature for Policy-Makers[1]

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Introduction and Overview

Environmental regulation usually requires businesses to take actions that they would not have taken in response to market forces alone.[2] Compliance with regulation should reduce damage to the air, land, water, or living creatures that would have been caused by market-motivated business activity. Although these benefits are often difficult to measure, they outweigh the costs when regulation is well-designed.

Technological innovation allows businesses to sell new products and services and to reduce costs by introducing new production processes. It is a very important cause of improvements in living standards in modern society. A majority of long-term economic growth is attributable to technological innovation. (Tassey 2016)

Some experts argue that there is an inherent tension between these two important phenomena. Money that businesses spend on regulatory compliance cannot be invested in satisfying their customers' needs for better and cheaper goods and services. (Popp and Newell 2012) Environmental regulation, from this perspective, is a large, unmeasured tax on the economy because it stifles innovation.

Other experts argue that environmental regulation and technological innovation are complementary. Businesses explore innovative pathways in order to comply with regulation that they would not have explored in its absence, developing new products and processes that open new markets and reduce costs. Environmental regulation, from this perspective, is a win for both the public and business, because it stimulates innovation while limiting pollution. (Ashford 1995, Ashford 2000)

The literature on this topic as a whole shows that neither position is right all of the time. California's Zero Emission Vehicle regulation established in 1990, for instance, is a good example of overreach. This regulation had to be scaled back when automakers could not produce cars that would comply with it at a reasonable price. (Bedsworth and Taylor 2007) On the other hand, regulation implementing the Clean Air Act of 1970 that required electric utilities to install

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[2] Government and non-profit organizations are also subject to regulation. For example, Federal agencies must comply with the National Environmental Policy Act. To simplify the presentation in this proposal, I will focus on businesses as the regulated entities. The impacts on business dominate the literature and the public debate. However, many of the same argument made about business may also apply to government and non-profit organizations.

scrubbers to remove pollutants from power plant smokestacks proved to be inexpensive, contradicting industry predictions it would lead to bankruptcies. (Taylor *et al.* 2005)

These two examples suggest that the answer to the question "does environmental regulation stimulate technological innovation?" is "it depends." (Kemp and Pontoglio 2011, Bergek and Berggren 2014) A better question is: "*When* does environmental regulation stimulate technological innovation?" The growing expert literature seeking to answer this question yields twelve conditions, which are elaborated in the body of this paper.

1. Compliance with regulation is expected to be expensive.
2. The technological landscape for regulatory compliance is target-rich.
3. Regulated firms have slack resources.
4. The regulated industry is competitive.
5. Options for moving regulated activities offshore are limited.
6. Higher authorities are unlikely to force regulators to relax.
7. The threat of regulatory enforcement is legitimate and credible.
8. Technology policy complements regulation.
9. Regulators rely on performance standards.
10. The regulatory process induces an open exchange of information.
11. Regulators have a sophisticated understanding of the regulated industry.
12. Industry expects regulation to become increasingly stringent over time.

The presence of each condition raises the likelihood that an industry will respond to environmental regulation by innovating. But the literature does not show that any single condition (or even a combination of conditions) is a magic bullet that will ensure this outcome in any particular case.

Nonetheless, these findings point to lessons for policy-makers, even as they demonstrate the limits of expert understanding of this complex problem. They suggest rules of thumb that involve an open-minded, patient, long-term, and goal-oriented approach to regulatory policy.

In the next section, I define the key terms of this long-running argument among experts and explain why it is important enough that it occasionally takes on a quasi-religious tone. Brief sections on each of the twelve conditions that influence whether environmental regulation will stimulate technological innovation follow. I conclude by spelling out the rules of thumb for policy-makers in slightly more detail.

Innovation and Regulation: Beyond "No Free Lunch" vs. "Green and Competitive"

Pollution is the classic negative economic externality. If a company making steel (or computer chips or anything else) can dump its waste in a nearby pond (or landfill or any other place) for free, it keeps its costs down, even if the waste ultimately harms a third party. The purpose of environmental regulation is to avoiding imposing this harm on the third party, who is external to the transaction. Regulation forces the would-be polluter to pay for pollution control, internalizing the cost of avoiding the harm.

One big debate in environmental policy swirls around this cost. Particularly when the harm is uncertain or far in the future, firms that are forced to pay a large cost now to avoid it will object to being regulated. The wastewater from the steel mill in the previous paragraph might contain toxins that kill mice exposed to them in high doses in a laboratory, but scientists might not be able to tell for decades if these toxins cause serious harm to people or ecosystems in real-world concentrations. The cost of avoiding real-world exposure, however, would be borne by the company immediately.

If the levels of such toxins could be reduced at very little cost, the steel mill's objection to being regulated would lose force. Such is the promise of technological innovation. The innovation could be a filter installed at the "end of the pipe" to eliminate the effluent, or a change in the steel-making process that reduces the use of the toxic substance inside the plant. If this kind of technological fix is cheap and easy, the benefits of regulation are more likely to outweigh its costs, because the costs would go down.

Like the harm that might be caused by pollution, technological innovation that reduces the cost of regulatory compliance is usually uncertain. Until firms conduct research and development (R&D) on pollution control, they do not know whether innovation is feasible, and until they implement the results of R&D in practice, they do not know what it would cost.

These twin uncertainties often lead experts who study the relationship between environmental regulation and technological innovation to fall back on pre-existing assumptions. If one believes that competition is fierce and firms are constantly optimizing their production processes in order to sustain slim profit margins, as many economists do, the notion that they are overlooking cheap and easy technological fixes to reduce pollution seems ludicrous. "There's no such thing as a free lunch," their motto goes, and such innovations look suspiciously like one.

If one believes, however, that firms are creatures of habit that tend to follow the same standard operating procedures (SOPs) as long as their key stakeholders are happy, as many management scholars do, then shaking up those SOPs might lead to unexpected discoveries, including cheap and easy fixes to pollution. Under these assumptions, regulation can do the shaking up. In fact, the most famous hypothesis in the literature, named after Michael Porter of Harvard Business School, states that environmental regulation can make firms better off than they were before it was imposed. In other words, they become both "green and competitive," which is the title of one of the articles in which Porter advanced his hypothesis. (Porter and Van der Linde 1995)

The Porter hypothesis has stimulated a lot of research over the past twenty years. For better or worse, it has not yielded a simple right-or-wrong verdict. One recent, massive review concluded that there is "considerable heterogeneity" in the findings of this body of work. (Cohen and Tubb 2018, 371) Yet, because the hypothesis challenges the fundamental "no free lunch" assumption of economists and has important policy implications, the debate about it has often been heated.

As long as this debate is framed around a simple yes-or-no question, it is bound to generate more heat than light. Environmental regulation and technological innovation are both complex phenomena. There is no good reason to expect that the relationship between them should be simple. It makes more sense to expect complexity. The heterogeneous findings in the literature

should not be denied, but instead, used. They allow us to unpack the complexity of the relationship and identify conditions that make an innovative outcome more likely in any particular case.

The fact that the relationship between environmental regulation and technological innovation plays out over time—years or even decades—adds to its complexity. Regulators and regulated firms learn about one another, anticipate one another's moves, and adapt their behavior as they interact. Many of the conditions on which the relationship depends must therefore be understood in terms of evolving mutual perceptions and expectations among these players. Nicholas Ashford of MIT, who pioneered research on this topic, put it this way in 1979: "Regulation is not a simple, single-point-in-time phenomenon that elicits an industrial response." (Ashford and Heaton 1979, 57) Or, as Rene Kemp, another leader in the field has stated: "the stimulus-response model is too simple." (Kemp and Pontoglio 2011, 34)

The alternatives available to firms faced with environmental regulation also influence their responses to it. Firms may choose to take political or legal action designed to obstruct or alter regulation, rather than simply complying with it. They may be able to shift the location or tempo of their activities in order to limit its impact. They may be able to comply without undertaking innovation. These choices, too, may evolve over time as political and economic conditions change.

Firms will choose to search for innovative ways to reduce their costs of compliance when such a search appears to them to be the best alternative, given how they expect the regulatory process to unfold in the future. Sometimes, but not always, this search leads them to a free, or at least low cost, lunch. The literature suggests twelve conditions that are most conducive to such an outcome.

Condition #1: Compliance with Regulation Is Expected To Be Expensive

The first condition is an obvious one, but still worth stating: regulated firms must expect that compliance will be ***expensive*** if they are to innovate in response to regulation. (Colburn 2017) If compliance is cheap, firms have no incentive to invest in pollution control R&D. "Grandfathering in," that is, exempting pre-existing activities and emissions from new regulation, can slow down innovation by making compliance cheap. A chemical manufacturer whose current product is grandfathered in to a toxic substances control regime, for instance, has little incentive to develop safer new products that comply with this regime. (Heaton and Banks 1997)

A related situation occurs when all regulated firms face the same cost of compliance. As long as compliance is not more expensive for one set of firms relative to another, the industry may be able to add the cost of compliance using existing technology to its cost structure. In this case, there is no incentive to innovate. Regulatory standards that require the "best available" or even the "maximum achievable" control technology, such as those implementing some sections of the Clean Air and Clean Water Acts, have sometimes had this stultifying effect. Such standards may diffuse the current state-of-the-art in pollution control but do not necessarily encourage firms to push beyond it. (Magat 1979) Regulation that sought to reduce water pollution caused by the use

of chlorine in paper-making in the 1990s, for instance, had this effect. (Norberg-Bohm and Rossi 1998)

The expectation that compliance with regulation will be expensive, either in absolute or relative terms, may be necessary to stimulate innovation, but it is not sufficient. If regulated firms do not perceive a technological pathway that promises to reduce the cost of compliance to a reasonable level, they will do something other than try to innovate. The California Zero Emission Vehicle regulation is a good example; the regulation prompted a decade of lobbying and litigation, but not much new vehicle development. (Sperling 2018)

Condition #2: The Technological Landscape for Regulatory Compliance Is Target-Rich
This observation points toward the second of the twelve conditions: at least some firms in the regulated industry must perceive a promising technological pathway that would reduce the cost of compliance if they are to innovate in response to regulation. The more "***target-rich***" the technological landscape is, the more likely an innovative response is. In the case of regulation to reduce ozone depletion caused by chemical compounds (CFCs) used in air conditioners, manufacturers chose to try to innovate in part because they perceived that they could develop new compounds (HFCs, HCFCs) that could be "dropped in" to existing air conditioners replace the old ones. (Parson 1993)

Some industries are more accustomed than others to innovating and so may be more inclined to respond to regulation by doing so. The chemical industry, for example, spends 6.7% of its revenue on R&D, whereas the average manufacturing industry spends less than 4%. (Wolfe 2017) Other things equal, experts who study regulation expect that the chemical industry would be more likely than the average industry to innovate in response to environmental regulation, as it did in the case of ozone depletion.

Varied perceptions of the landscape of technological opportunity among firms *within* an industry are less widely recognized than variations *across* industries, but they may also have important implications for the relationship between environmental regulation and technological innovation. If some firms within an industry perceive technological targets of opportunity that others do not, regulation may create an opportunity for an innovative firm to differentiate itself from its competitors. Toyota's invention of the hybrid-electric drive, which led to the introduction of the Prius in 1997, years ahead of other carmakers, is a case in point. (Dijk and Yarime 2010)

Condition #3: Regulated Firms Have Slack Resources
In order for a firm like Toyota to make an invention as radical as the hybrid in response to a regulatory stimulus, it has to have ***slack***. Managers must have permission, implicit or explicit, from shareholders to take the risks involved in searching for innovative solutions to pollution reduction challenges. When risk-averse shareholders hold a tight rein over R&D spending or there is too little cash to place bets on game-changing new technologies, environmental regulation is unlikely to stimulate innovation.

Slack is central to the Porter hypothesis. In Porter's view, most firms have the autonomy and resources to adopt a pollution-reducing technology strategy, but managers rarely think of doing so. Their attention, which is focused on executing current SOPs as well as possible, is the factor

that limits innovation. Regulation can cause managers to step back from the day-to-day press of business and see opportunities that they had previously ignored. They can then target slack resources to realize these opportunities. (Atkinson and Garner 1987)

Porter and his colleagues uncovered many cases in which firms that were jolted by a regulatory stimulus quickly found "innovation offsets" that more than covered their immediate costs. For instance, 3M was "forced to comply with new regulations to reduce solvent emissions by 90%," so it "found a way to avoid the use of solvents altogether by coating products with safer water-based solutions." (Porter and van der Linde 1995, 126) "Innovation offsets" in the 29 chemical plants they studied, "were achieved with surprisingly low investments and very short payback times." (Porter and van der Linde 1995, 125)

As I noted above, economists who have assessed the Porter hypothesis—that innovation offsets to environmental regulation make firms better off—have not generally found support for it. (Dechezlepetre and Sato 2017) Most such studies, however, take a relatively static approach that does not explore how managerial choices play out over a period of years. Researchers who take a more dynamic perspective discover that managers often find innovation offsets, even though they may not fully compensate for the costs that regulations impose. (Ambec et al. 2011)

Condition #4: The Regulated Industry Is Competitive

Porter also argues that managers are more likely to search for innovation offsets in response to environmental regulation when they face ***competition***. A very large body of research has shown that competition has a two-sided relationship with innovation. (Aghion *et al.* 2005) Industries that are hyper-competitive, like farming or furniture-making, have low levels of innovation, because firms in such industries have little slack. In addition, even if these firms were able to invest in innovation, they would get little benefit, because their competitors would rapidly imitate them.

At the other end of the spectrum, monopolistic industries, like electric utilities, also have low levels of innovation. While the firms in such industries have plenty of slack and no fear of imitation, they also have little incentive to add the cost of R&D to their balance sheets.[3] The optimal level of competition for spurring innovation lies between these two extremes, although scholars continue to debate just what that level is.

Other things being equal, then, a reasonable but not excessive level of competition within a regulated industry raises the odds that managers will respond to regulation by innovating. However, regulation can also change the level of competition, complicating the analysis. For instance, many studies find that regulation favors larger companies, because of the specialized skills required for compliance. (Blind 2012) But regulation can also induce firms to enter the

[3] The electric utility industry carries out cooperative R&D through the Electric Power Research Institute (EPRI), which is funded by member contributions. Environmental regulation has been an important driver of EPRI's agenda. Member contributions to EPRI are frequently authorized explicitly by public utility regulators in rate-setting cases. The shift to more competitive, less regulated markets in the past 25 years has reduced such contributions. (Sanyal and Cohen 2009) The interaction between economic regulation, such as rate-setting, and environmental regulation complicates analysis of technological innovation of this industry.

regulated industry in order to offer new products or services that are made profitable by the demand for compliance. (Paraskevopoulou 2012)

The response of the auto industry to federal regulation of tailpipe emissions provides an excellent example of these dynamics. When such regulation was first considered, the response from the "Big 3" Detroit automakers of the time was so sluggish that the U.S. government sued them in 1969 for acting like monopolists and colluding to suppress emissions control technology. (Ginsburg 1980)[4] The catalytic converter, an innovation that gave automakers a way to comply with regulation at much lower cost than they had anticipated, was introduced a few years later by a new entrant to the automotive supply industry, Johnson-Mathey. (Tao et al 2010)

Condition #5: Options for Moving Regulated Activities Offshore Are Limited

The notion that the Big 3 Detroit automakers could act like monopolists is antiquated. International trade and investment have heightened competition in the auto industry since the 1970s. It has also complicated the relationship between environmental regulation and technological innovation by creating an important new choice for some firms facing regulation: ***offshoring***. If a firm can establish a production base in a jurisdiction that is less stringently regulated than the one where it faces regulation and then export to the home market from that base, it need not comply with regulation in the home market.

This "pollution haven" hypothesis involving a "race to the bottom" has prompted a large literature. Its logic seems indisputable, paralleling that of firms that seek to reduce their labor costs by offshoring production to low wage countries. Yet, an accumulating body of evidence points in the opposite direction, documenting more races to the top than the bottom. (Vogel 1995) Multinational firms often prefer to invest in innovation to serve markets that have the most stringent regulation, rather than try to avoid this cost by seeking out jurisdictions with looser regulation. These firms assume that the looser jurisdictions will catch up that with the global frontier and become more stringent over time. If their products and processes can meet the highest standard now, such firms will be well-positioned as more countries race to the top in the future.

These dynamics can be seen at work in the global auto industry in recent years. Tough emissions standards have induced compliance through innovation in leading auto-producing countries, and as developing countries expand their auto production, they import these innovations from the more advanced countries. (Perkins and Neumayer 2011) The race to the top has very recently prompted a growing number of countries to announce plans to phase out internal combustion engines altogether. These plans have two objectives: to reduce pollution and to seize competitive advantage in auto production. (Naimoli 2017)

Condition #6: Higher Authorities Are Unlikely To Force Regulators to Relax

Firms that are disinclined to comply with regulation may choose to fight it. In the United States, there are many venues in which to pursue such fights. Legislatures may overrule, intimidate, or defund regulatory agencies. Courts may overturn agency decisions. State and local

[4]Scott (1996) finds that institutions that facilitate cooperative R&D, such as research joint ventures, are more likely to foster innovative responses to environmental regulation in highly-competitive industries, where imitation might otherwise deter such investments.

implementation and enforcement partners may deviate from plans made in Washington, D.C. Firms have developed a wide repertoire of "nonmarket" strategies to pursue anti-regulatory objectives in venues other than the regulatory process itself. (Baron 2013)

Firms are more likely to respond to regulation by innovating when they expect that nonmarket strategies will fail, and they therefore have ***no appeal*** to a higher authority to avoid compliance. A societal consensus about the goals and legitimacy of regulation reinforces this condition. If firms do not expect a future phase of the electoral cycle to change environmental policy, they are less likely to try to get regulatory decisions overturned and instead get on with compliance .

The state of California is a case in point. Environmental regulation is very popular there, endorsed by many Republicans as well as Democrats. The state also has special standing in federal environmental statutes like the Clean Air Act, blocking off avenues to appeal to the federal level. One result is that the California electric power industry has become the most innovative in the country. (St. John 2018)

Condition #7: The Threat of Regulatory Enforcement Is Legitimate and Credible

Firms are also more likely to respond to environmental regulation by investing in innovation if managers believe that non-compliance will have significant negative consequences. (Gerard and Lave 2005, Lee et al. 2011) For such a belief to arise, regulators must have adequate financial and technical resources to enforce the rules they make. Regulatory enforcement, too, must be perceived to be legitimate; otherwise, it may simply open a new avenue for appeal to a higher authority.

The recent Volkswagen (VW) diesel scandal illustrates the importance of ***credible enforcement***. In Europe, the firm seems to have been trusted to comply with clean air regulation on its own, while in the United States, compliance testing was not as sophisticated or rigorous as consumers and legislators believed. Volkswagen developed "defeat devices" that detected when tests were being performed and brought diesel-powered vehicles into compliance long enough to fool the authorities. (Geebelen 2017)

The development of defeat devices by VW shows that firms may innovate to circumvent regulation, rather than comply with it. (Stewart 2011) Weak enforcement provide a perverse incentive for this kind of innovation. A firm may perceive it to be more profitable to advance technology to exploit holes in the regulatory fabric when it is weak than to innovate to achieve regulatory objectives more efficiently.

Condition #8: Technology Policy Complements Regulation

Regulators can encourage more constructive innovative responses by packaging regulation with ***technology policy***. Such packages solve "two market failures" (as a famous paper in this field is titled) – not only the externality that leads to pollution, but also the threat of "free riding" that can deter investment in innovation in competitive markets. (Jaffe *et al.* 2005) Free riding arises because innovation is usually more expensive than imitation. Imitation is a rational choice in such a situation. But if every firm makes this choice, as in the hyper-competitive industries described in the section on competition (condition #4), there will be no innovators.

Technology policy can overcome free riding in a variety of ways. Strong intellectual property rights deter imitation and increase the reward for innovation. Tax incentives for private R&D spending reduce the cost of innovation; government R&D grants and contracts can do so, too. Government R&D programs that have specific objectives (as opposed to those that support the pursuit of knowledge for its own sake) are more likely to influence private sector behavior if they require cost-sharing, which gives the recipient of R&D funding a larger stake in the outcome.

The U.S. Environmental Protection Agency's (EPA) approach to flue gas desulfurization (FGD) illustrates the benefits of packaging technology policy with regulation. In parallel with the implementation of regulation to reduce sulfur dioxide emissions from power plants under the 1970 Clean Air Act, EPA co-funded an R&D program that featured three pilot plants to test competing scrubbers being developed by power plant equipment vendors. This R&D program played a vital role in reducing the cost of this regulation far below initial industry projections. (Hart and Kallas 2010, Taylor *et al.* 2005)

Condition #9: Regulators Rely on Performance Standards

Experts exploring the relationship between environmental regulation and technological innovation have focused more intently on the design of regulation and the regulatory process than on the technological, industrial, and political conditions that I have reviewed to this point. In particular, they have debated the relative efficacy of ***performance standards*** and technology mandates. The former specify the outputs of the regulated industry, like the level of acceptable pollution, without prescribing what firms must do to achieve it, while the latter dictate which equipment and processes they must install.

In his agenda-setting work, Porter argued that performance standards would stimulate innovative responses to environmental regulation, especially when combined with industrial competition. Under these conditions, he anticipated that regulated firms would pursue diverse approaches to meet performance goals. Such experimentation would in turn yield unexpectedly inexpensive ways to meet the goals.

Tradable permits for the right to pollute offer further scope for firms to exercise creativity to comply with environmental regulation in this view. The total allocation of all permits under such a system functions as a performance standard for the entire regulated industry. Trades among permit holders may allow innovators to benefit more from innovation than they would without this option.

A growing body of research supports this argument. A series of papers by experts at the Organization for Economic Cooperation and Development (OECD), for instance, compared regulatory designs across countries and finds that performance standards are more likely than other designs to stimulate both innovation by regulated firms and their adoption of innovations developed elsewhere. (Johnstone, Hascic, and Kalamova 2010, Lanoie et al. 2011, Blind 2012)

There are important exceptions, however, to the consensus about performance standards and tradable permit. Performance standards for corporate average fuel economy (CAFÉ) standards for automobiles in the 1990s and 2000s, for instance, were so loose that automakers optimized engine power and sold heavier vehicles, rather than take advantage of innovations that improved

engine efficiency to reduce fuel consumption. (MacKenzie 2013) Another exception is the use of tradable permits for sulfur dioxide emissions from power plants under the 1990 Clean Air Act Amendments. Fuel-switching from high-sulfur eastern coal to lower-sulfur western coal by many plants allowed the industry as a whole to comply with the regulation even though the fuel-switchers did not innovate or adopt new technology. (Lange and Bellas 2005)

Condition #10: The Regulatory Process Induces an Open Exchange of Information

Such exceptions have led experts to go beyond the dichotomy between performance standards and technology mandates as they seek to determine which regulatory conditions are most conducive to technological innovation. (Kemp and Pontoglio 2011) One finding is that the process by which performance standards are set can shape their impact. An ***open exchange of information*** with industry helps regulators to establish a level of stringency that stretches the industry's technological capabilities without posing such a daunting challenge that firms would rather fight the regulation or leave the jurisdiction than try to comply with it.

An open exchange during the regulatory process cannot be taken for granted, because the parties to it have incentives to distort or conceal vital pieces of information. The regulatory process is much like a negotiation. Control over information during a negotiation shapes perceptions about what outcome would be appropriate and fair, not only among the negotiating parties, but also among third parties, such as the public and legislators, who might be drawn into the process later. Industry gains leverage when the cost of regulation is perceived to be high, while regulators gain leverage when the benefits are perceived to be large. The information that the two sides disclose may be tailored to embed such perceptions. (Harrington, Morgenstern, and Nelson 2000)

Trust built up over time may help to overcome this barrier. When the CAFÉ standards were renegotiated under the Obama administration, the parties agreed to "a detailed step-by-step process of implementation, which requires reciprocal demonstrations of good faith by regulators and industry…" (Freeman 2011, 369)

Competition among regulated firms may also lead to the revelation of new information of value to regulators. Tesla, a new entrant to the auto industry over the last ten years, has shown that an electric vehicle can be built that appeals to consumers on grounds other than environmental values, such as style and performance. Tesla's achievement gives regulators insights into the level of stringency with which the auto industry can be expected to comply. (Sperling 2018)

Condition #11: Regulators Have a Sophisticated Understanding of the Regulated Industry

Trust may be a temporary condition, however, and competition is not always vigorous. Regulators must have a ***sophisticated understanding*** of the industry they are regulating in order to verify or challenge information that they receive from that industry. Only with a high level of sophistication will they be able to calibrate performance standards so as to evoke an innovative response, rather than fight, flight, or complacency.

This condition is challenging to achieve not only because of the incentives to distort or conceal information, but because firms inevitably know more about the processes and technologies that they use, the costs they bear, and the customers they serve than regulators. This asymmetry gives

industry a strategic advantage in the regulatory process. (Bergquist et al. 2013) In order to counter it, regulatory agencies must typically hire staff with industry experience and encourage them to spend time with their industrial counterparts. Such familiarity, in turn, runs the risk that regulators will lose their independent perspective and become victim to "capture" by the regulated industry. (Ashford and Heaton 1979)

Carpenter's (2010) detailed study of the Food and Drug Administration (FDA), although it lies in the domain of health and safety rather than environmental protection, demonstrates how a regulatory agency can build a sophisticated understanding of the industry it regulates over a period of decades. Aided by scientific advisory committees, FDA has defined the core standards used to evaluate new drugs, such as safety and efficacy. It has maintained its reputation as an independent adjudicator of these standards as well, despite recurrent challenges over the years.

Condition #12: Industry Expects Regulation To Become Increasingly Stringent Over Time

The final condition that encourages firms to respond to environmental regulation by pursuing technological innovation is a ***shared expectation of increasing stringency*** over time. Sophisticated regulators who engage in an open exchange of information with the regulated industry can not only calibrate the level of performance standards so that they encourage innovation, but also the pace of their implementation. A phase-in period allows adequate time for new technologies to be tested in realistic conditions before they are put fully into practice. (Colburn 2017) It also permits adjustments to be made if the innovation process does not yield the results that the parties anticipated when the standards were set. (Yarime 2007, Nemet 2014)

This condition is particularly important in capital-intensive industries, which have long planning cycles. Innovation in such industries tends to be very costly. Aggressive regulatory timelines that managers perceive to put their investments in existing production processes at risk are likely to provoke resistance. On the other hand, once expectations of increasing stringency have been set and investments in innovation have been made, managers are likely to want to see these expectations realized. (Klier and Linn 2012)

Air conditioning and refrigeration equipment manufacturers, for instance, operate on a design cycle of five or more years. Anticipating the imposition of tighter restrictions on hydrofluorocarbon greenhouse gases (HFCs) in the near future, U.S. manufacturers have budgeted $5 billion over the next decade to commercialize the next generation of HFC-free refrigeration technology. A 2018 report by an industry association called for "regulatory certainty" and a "firm timetable" to ensure that this investment would not be jeopardized. (JMS Consulting and Inforum, 2018)

Conclusion: Rules of Thumb for Environmental Policy-Making

The promise of environmentally-friendly technologies that allow businesses to comply with regulation at an unexpectedly low cost is tantalizing. When the promise is realized, the ratio between the benefit of regulation and its cost grows. But there are no sure things about innovation; it is intrinsically uncertain. Environmental policy-makers can, at best, shape the conditions under which regulation is implemented, so as to make an innovative response by the regulated industry more likely.

A review of the expert literature on this topic has led me to list twelve such conditions. Some of these conditions, such as the use of performance standards, fall directly under the control of environmental policy-makers. Others, such as expectations of increasing stringency over time, may be brought about indirectly by them. Still others, such as the availability of slack resources to regulated firms, lie largely beyond their reach.

Although our limited understanding of this complex problem does not lead to definitive statements about what environmental policy-makers should do in any particular case, these differences in the degree of control over the twelve conditions point toward five rules of thumb that they can employ.

- First, policy-makers should study whether the conditions that they cannot control in the case at hand are likely to favor an innovative response from regulated firms or not.

- Second, when those conditions are favorable, policy-makers should set ambitious regulatory goals over the long-term and encourage compliance through innovation.

- Third, policy-makers should be patient but vigilant in the intermediate-term as regulated firms explore promising pathways that appear to have the potential to meet long-term goals.

- Fourth, policy-makers should encourage competition among regulated firms to devise specific products and processes that would aid regulatory compliance, while also using technology policy to create general knowledge that they can all can draw upon.

- Fifth, policy-makers should develop a sophisticated understanding of the technical and economic challenges facing the regulated industry, in order to credibly and independently assess its progress and to make adjustments, including loosening standards and schedules, when appropriate.

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