The international platform of Ludwig-Maximilians University's Center for Economic Studies and the Ifo Institute

CESifo Working Papers
www.cesifo.org/wp

The Role of Standards in Eco-innovation: Lessons for Policymakers

Herman R. J. Vollebergh
Edwin van der Werf

CESifo Working Paper No. 4266
Category 10: Energy and Climate Economics
June 2013

An electronic version of the paper may be downloaded
- *from the SSRN website: www.SSRN.com*
- *from the RePEc website: www.RePEc.org*
- *from the CESifo website: www.CESifo-group.org/wp*

CESifo
Center for Economic Studies & Ifo Institute

CESifo *Working Paper No. 4266*

The Role of Standards in Eco-innovation: Lessons for Policymakers

Abstract

This paper aims to help policy makers identify how standards can contribute to the effective and cost-efficient development and deployment of eco-innovations (innovations that result in a reduction of environmental impact). To that end we discuss what standards are, how the process of standardization works, and how standards are related to induced innovation and diffusion in different type of markets, e.g. markets for add-on technologies versus markets for integrated resource- or emission-saving technologies. This broad perspective enables us to identify interesting economic dimensions of standards, such as their contribution to positive network externalities, and the extent to which they are substitutes or complements to environmental policy instruments. Finally we discuss how governments might contribute to eco-innovation by selecting, stimulating or creating (inter)national standards.

JEL-Code: Q380, Q550, Q580.

Keywords: standards, technological change, eco-innovation, environmental policy instruments.

Herman R. J. Vollebergh
PBL Netherlands Environmental Assessment Agency
P.O. Box 303
NL – 3720 AH Bilthoven
The Netherlands
herman.vollebergh@pbl.nl

Edwin van der Werf
Department of Economics
Wageningen University
P.O. Box 8130
NL - 6700 EW Wageningen
The Netherlands
edwin.vanderwerf@wur.nl

May 1, 2013
This article builds on a discussion paper the authors prepared for the OECD Environment Directorate. The support of the OECD in writing this paper is gratefully acknowledged. We thank Rob Aalbers, Dallas Burtraw, David Popp and Victoria Shestalova, two anonymous referees, Suzy Leonard and the editor Charles Kolstad for comments on an earlier version. Moreover, we thank Jan Pieters, now retired from the Dutch EPA, for his unremitting efforts to convince us that the role of standards is key in understanding the dynamics of environmental policy and innovation.

Introduction

Standards and standardization processes play a key role in technological change. The success of well-known products like intermodal shipping containers or smart phones would never have existed without standardization. Standards are the result of (voluntary) agreements between market participants with the government possibly being one of them. Sometimes governments even drive standardization processes through their policies, but in other cases they just follow market developments. Environmental policy standards are often the driving force behind particular clean technologies. Scrubbers, catalysts and incineration plants are technologies that would not have existed without regulation through environmental standards. Such standards are the 'standard way' to implement environmental policy, and induce the transfer of knowledge across borders and the international diffusion of technologies (Lovely and Popp, 2011).

The role of standards in technological change suggests that governments could exploit standard setting as a means to stimulate "eco-innovation". Following OECD (2009) we define eco-innovations as innovations that result in a reduction of environmental impact, no matter whether that effect is intended. Eco-innovation in our view comprises not only of the development of *new* knowledge and technologies ('innovation'), but also of diffusion of already 'known', but not yet widely applied technologies (Popp et al., 2010). Environmental policy standards have been the key policy instrument to implement environmental policy in diverse fields as air quality regulation and waste disposal. They create 'green' market demand inducing firms not only to supply solutions based on existing knowledge and technologies, but also to develop new goods, services and technologies that reduce environmental impact. However, standards *other* than environmental policy standards (or their absence) in different, though adjacent, fields can be at least as important for environmental outcomes.

The goal of our paper is to review what governments could learn from theory and experience as to how to stimulate eco-innovation through selection of standards. Identifying this potential stimulating role of (international) standards requires a good understanding of what standards precisely are, how the process of standardization works, and how standards are related to induced innovation and diffusion. We apply a broad perspective on standards and argue that the usual perception among environmental economists that standards are just a type of command and control regulation is very limited. Moreover, our broad perspective enables us to identify interesting economic dimensions of standards, such as their contribution to positive network externalities, and to identify under which conditions standards are substitutes or complements for market-based environmental policy instruments.

The paper shows, first of all, that 'command and control' regulation is only a subset of the entire set of standards and emphasize the role of patents in standardization processes. Next we argue that standards can be both substitutes and complements to other policy instruments. We subsequently present some examples of how standards have affected eco-innovations in the past, and under what conditions they may be used to support eco-innovation in the future.

Standards and the standard-setting process

This section clarifies, first of all, the concept of a standard and how environmental standards relate to other standards in the process of technological change. Moreover, we explain that environmental standards are only a subgroup of one particular category of standards, and should be separated into technical product and process standards on the one hand and environmental performance standards on the other. Next we explain how standards are created through both market and government driven standardization processes.

Defining standards

We define a standard as *a document that specifies characteristics of technical design or rules of behavior*.[2] This definition allows standards to be both of a technical and of a behavioural nature. We follow David (1987) by not only distinguishing technical from behavioral standards, but also by making a distinction between standards regarding the specific role they play in society:[3]

- First, standards for measurement and reference are used as a rule or basis of comparison. By using common standards for measuring weight or the value of a currency, agents are able to use a common language enabling to process information more efficiently, i.e. reduce transaction cost by (partly) alleviating information asymmetries. Due to information and measurement standards (also called standards of product description) a producer can signal to consumers that a product possesses the claimed characteristics (Tassey, 1982). Energy labels are an example of a technical measurement standard used as a policy tool.
- The second type of standards are (minimum) quality and safety standards. In particular, regulatory standards (such as environmental policy standards) belong to this category. They can be of technical or of behavioural nature and their specific *design* (e.g. aimed at emissions, inputs or outputs) not only affects the firm's choice of inputs, outputs and their profits, but also social welfare (Helfand, 1991). Technology and product standards for quality or safety require particular industrial equipment to be installed in production, or a

[2] This definition explicitly refers to documents since a standard must be mutually recognized by several parties (e.g. firms, or firms and a government agency), which, in practice, means that it has to be written down to prevent ambiguities.

[3] Note that most standards have multiple functions. In addition, all standards are a source of information to agents in society (see Tassey, 2000).

product to satisfy specific requirements on some of its attributes. Behavioral standards for quality or safety are standards of performance and specify maximum or minimum input or output or emission levels. They leave agents free to select their best option to comply.

- Compatibility and interface standards, also known as interoperability standards, are especially relevant for network industries. In physical network industries, both producers and consumers are connected through cables or pipelines, like in an electricity or gas network. Delivery of these products requires a physical system of hardware that connects participants who therefore have to use technical devices that are interoperable. This interoperability is essential for virtual networks, where producers and consumers are connected using the same hardware/software system, as well.

Clearly, within this broad perspective on standards, not only environmental standards matter for eco-innovation. For eco-innovators measurement and reference standards help to signal the superiority of their innovation. Governments can use such measurement standards as a policy tool as well. The labels of the Energy Star program in the US, or the EU Energy Labels, rank the energy performance of consumer durables like refrigerators based on their energy use and thus inform consumers about the product's environmental performance. Obviously also technical compatibility and interface standards matter for eco-innovations. An international technology standard for battery exchange or plug-in charging infrastructure for electric cars is key to success of this particular eco-innovation. Note that all examples refer to the informative role of standards, which can be exploited by regulated producers, innovators and governments to signal and improve quality characteristics of technologies (equipment) and products.

Although all types of standards are relevant for eco-innovation, environmental policy standards are likely to play the most important role in promoting eco-innovations (Popp et al., 2010). Their impact, however, is likely to depend on their specific design. The EU Directive concerning Integrated Pollution Prevention and Control (IPPC Directive 2008/1/EC), for instance, explicitly notes that it is not allowed to prescribe the use of one available technique or technology. Emission limit values (ELVs) aim to influence the environmental outcome of a plant, and hence are more flexible and cost-efficient than a technical standard, and are likely to induce different inventions and innovations. The EU directive concerning IPPC, the US Clean Air Act and the US Clear Water Act all prescribe emission limits rather than technologies. In practice, however, behavioral standards may be formulated in such a way that they amount to a technology standard (Ellerman et al., 2000).

The Process of Standardization

Standardization is the action of bringing things to a uniform standard (David, 1987, p. 212). Standardization processes can be initiated by governments, but also firms and consumers demand uniformity regarding a particular good or service. In a classic contribution, David and Greenstein (1990) distinguish between four types of standardization processes.

- 'Unsponsored' standards are sets of specifications that have no identified originator holding a proprietary interest, nor any subsequent sponsoring agency, but nevertheless exist in a well-documented form in the public domain. A well-known example is the QWERTY standard for keyboards created by interaction of uncoordinated decisions by early typists and their employers, typing schools, and typewriter manufacturers (David, 1985).
- With 'sponsored' standards, one or more sponsoring entities (suppliers or users) holding a proprietary interest create inducements for other firms to adopt particular sets of specifications.
- Thirdly, standards can be agreed upon through voluntary standards-writing organizations that might or might not be created by the government as a public agency. The International Electrotechnical Commission (IEC) in the US, for example, publishes consensus-based international standards for electric and electronic products, systems and services. Participants in the standard-setting process are usually obliged to disclose relevant patents to the standards-writing organization.
- Finally, standards can be initiated or even mandated through government intervention. Governments may conclude that voluntary standardization leads to a lack of uniformity, a threat to competition, or a lack of internalization of an externality - for example a network externality (i.e. when the decision to adopt a technology, e.g. an electric car, depends on the adoption by others) or environmental externality.

The different types of standardization processes illustrate that government intervention through environmental policy standards is just one type of standardization process.[4] The discussion also shows that standardization is vulnerable for strategic behaviour by other market participants. If a standard is based on an existing technology, the firm that owns the underlying patent can benefit through royalty payments for the use of its technology. Indeed, the citation rate of a patent of a technology endorsed by a standards setting organization strongly increases after this endorsement. Thus, innovating firms have strong incentives to push their own technology to be adopted as a technical standard (Rysman and Simcoe, 2008) and governmental organizations that aim to

[4] Thompson (1954) provides an insightful account of standardization processes in the early American automobile industry.

introduce a technology standard, run a serious risk to become captured by a firm seeking a technology monopoly.

Standards, environmental policy, and technological change

Both environmental policy standards and other standards play an important role in technological change.[5] This section argues that the widely held view among economists that standards basically boil down to command and control measures is overly simplistic. While standards are often considered as substitutes to market-based and other policy instruments in the policy-maker's toolbox, we argue that in many cases they are more likely to be complements. Moreover, we argue that standards can be a necessary tool for certain types of eco-innovations. This broader view also helps to better understand the important issues of non-competitiveness and strategic behavior in the process of standardization.

Standards as substitutes in environmental regulation

The common view on standards among environmental economists is that standards boil down to 'command and control' (CAC) regulation. However, environmental policy standards may be aimed at any stage of the production or pollution process, may take many different forms, and differ in their efficiency (Helfand, 1991). Barde (2000) classifies four categories of such standards: (1) product standards define the characteristics of a firm's output, e.g. in case of a quality or safety standard for a product; (2) process standards specify the type of production process or emission reduction equipment that firms must (not) use, e.g. the ban on the use of chlorofluorocarbons; (3) emission standards are the maximum allowable discharges of pollutants into the environment (at the firm, sector, or supra-sectoral level such as the emissions cap in the European Union greenhouse gas Emission Trading System); (4) ambient quality standards specify the characteristics of the receiving environment, such as concentration levels. We can categorize the first two categories as technology standards, and the last two as behavioral or performance standards. Note that emission standards can be of absolute (prescribing maximum emission levels) or relative nature (prescribing maximum emissions per unit of output). The extent to which each type of pollution standard can be considered CAC depends on the degree of flexibility given to regulated agents. While technical standards often do not allow for flexibility, behavioral standards often do, and may in the extreme even be considered part of a market-based instrument, for example an emissions cap in a cap and trade system.

[5] We define technological change as one or more elements of the chain invention-innovation-diffusion, where the first two are jointly called research and development (R&D).

In cases where standards can indeed be considered as CAC regulation, they are usually perceived as a (bad) substitute for so-called incentive or 'market based' regulation. The main argument why CAC policies are usually ranked inferior is the (static) cost-efficiency argument (Baumol and Oates, 1988, pp. 159-176). Market-based instruments, such as Pigouvian taxes, guarantee cost-efficiency because agents select the lowest-cost options when they are confronted with a price on environmental pollution. This 'least-cost theorem' holds even in the presence of monopoly power of regulated firms on output markets. CAC instruments lack the flexibility of market based regulation and would therefore be inferior from a cost minimization perspective.

In a second-best world, however, the ranking of instruments is more complicated. For instance, in the presence of labor market distortions and a labor-leisure trade-off for households, all policies induce an increase in the relative price of dirty goods and consumption, making leisure more attractive for the household. The reduction in labor supply due to this tax-interaction effect causes a welfare loss (see e.g. Goulder et al., 1999). At the same time, emission-reduction policies introduce a rent. With auctioned permits or a pollution tax, this rent goes to the government, which can generate welfare gains by reducing the distorting tax on labor (revenue-recycling effect). With grandfathered permits, however, the rent goes to polluting firms, while in case of a standard-based policy, who obtains the rent depends on the exact design of the standard as well as on the degree of profit taxation (Fullerton and Metcalf, 2001). If the standard, such as a technology standard affecting all firms equally, does not generate a rent, then the tax interaction effect does not occur for a marginal policy change and the standard outperforms grandfathered tradable permits. Standards can also generate rent, however, such as with the New Source Performance Standards of the 1970 U.S. Clean Air Act Amendments, which differentiates between old and new firms. In this case the revenue-recycling effect can still be exploited if these rents are taxed away and used to reduce the labor tax.

The claim that market-based environmental policy instruments have a stronger *dynamic* impact than standards is not undisputed either. First it should be noted that many papers in the literature on the dynamic impacts of environmental policy instruments treat 'standards' as absolute emission standards, i.e. a maximum level of emissions at the firm level (see e.g. Milliman and Prince, 1989, Jung et al., 1996). In reality, however, many policy standards are of a relative nature, such as the pounds of sulfur dioxide (SO_2) per unit of energy emission standard of the 1970 U.S. Clean Air Act Amendments. Second, whether market-based instruments can be ranked above CAC instruments from a dynamic perspective strongly depends on the context in which the instrument is applied (Requate, 2005). Montero (2002) is one of the few papers that explicitly studies the R&D incentives of both absolute emission standards and (relative) performance standards. Allowing for imperfect competition on both the output and (in case of the tradable permit instrument) the permit market, he finds that standards may outperform market-based instruments because market power induces strategic behavior. Indeed, as we will discuss in the next section, technology and behavioral standards can even be used to trigger innovation.

Fischer and Newell (2008) illustrate that the exact ranking depends to a large extent on the particular design of the policy instrument. Using a numerical model calibrated for the U.S. electricity sector, they study the ranking of different policy instruments in case of both environmental externalities and intertemporal knowledge spillovers. The renewable energy sector can invest in R&D and benefits from learning by doing. Assuming that instruments cannot be combined, Fischer and Newell find that the ranking for a modest CO_2 reduction target is: emission price (tax or cap and trade); tradable emissions performance standard (CO_2 per unit of electricity); output tax on fossil generation; renewables portfolio standard (minimum share of renewables in generation) with tradable certificates; renewables production subsidy. This ranking shows that since both price instruments and standards can be applied in many different ways, a ranking of instruments depends on the exact formulation of the policy.

Finally, environmental policy standards may be endogenous, because regulators could respond strategically to new knowledge (Requate, 2005). To be efficient in theory, environmental policy should make sure that marginal benefits of emissions equal their marginal cost. In practice policymakers often aim at a particular environmental outcome, taking into account the costs for firms or consumers to achieve this outcome, which in turn depend on available technologies. When a new idea (technology or product) arrives, it can be used as reference point for new policy standards (see Burtraw et al., 2011).

Standards as complements in environmental policy

Although the traditional view on standards as a substitute for incentive regulation has been helpful in showing options for cost savings in environmental regulation (e.g. Anderson et al., 2012), this literature seems to neglect the wider role of standards, in particular as a complement to incentive-based policies. Not only can ‘non-environmental standards’ contribute to environmental goals of policy makers, they are also ubiquitous in environmental policy.

For instance, compatibility and interface standards are crucial for the diffusion of network technologies, where the value of a technology for a user is positively affected by the number of users, possibly through the number of providers. Because of network externalities, there are increasing returns to scale in these technologies. Examples of compatibility standards for an eco-innovation are standards for batteries and recharging technologies for electric vehicles. Without these standards users are not able to connect to providers of electricity which complicates penetration of new technology. Furthermore, when a new network technology is introduced, multiple varieties of the technology often co-exist. As long as competition between varieties of the technology (i.e. between technical standards) has not been settled, both users and providers face uncertainty over the future value of each variety, i.e. no variety may prevail. Hence none of these new technologies may achieve sufficient scale to be viable. The introduction of a uniform compatibility standard takes away this uncertainty and allows widespread adoption of a network technology. In sum, standards play a crucial role in the diffusion of a network-based eco-innovation (e.g. Katz and Shapiro, 1994).

Not only do standards play an important role in the diffusion of eco-innovations, they are also ubiquitous in the toolbox of environmental policy makers, even beyond the role they can play directly as a policy instrument on their own (discussed above). Standards for measurement and reference, such as an energy or eco-label, can be used to inform buyers about the characteristics of a product or its production process. When not accompanied with other policy instruments, product labels do not provide incentives for R&D directly, but still support the diffusion of eco-innovations amongst consumers with green preferences. This increase in market size, in turn, increases incentives for R&D (Acemoglu et al., 2012).

Institutional approaches to environmental policies rely on standards as well. Indeed, both voluntary agreements with industries and the imposition of liability on a polluter are examples of a behavioral safety standard. Although voluntary agreements are mostly non-enforceable, ex post legislation can be used to punish non-compliants. Voluntary agreements may even be preferred over emission quota (a behavioral standard) from a static point of view, depending on the industry's lobbying power (Glachant, 2007).

Also market-based instruments rely heavily on standards. Standards for measurement and reference are necessary to clearly define pollutants and agents ("a ton of CO_2") that are subject to a tax or a cap and trade system. In a cap and trade system, the cap itself is clear example of a behavioural safety standard, applied at the sectoral or supra-sectoral level.

Standards, Anti-competitive Behavior and Regulatory Capture

Because standards play a key role in the dynamics of the economic process, they are likely to be subject to strategic behavior. Indeed, different market participants have different interests in standardization processes. Innovation decisions face huge uncertainties and potential (changes in) environmental policies may contribute significantly to this uncertainty . Standards may effectively contribute to the reduction of this uncertainty. Innovators have a clear interest to get their technology adopted by the government as the new policy standard (in case of a technical standard), or lobby for implementation of a tighter behavioral standard, based on their superior technology. The new standard can then be used as a source of competitive advantage (Jaffe et al., 2002), or to increase rival firms' costs (Hackett, 1995, Puller, 2006). Standardization processes are therefore likely to be subject to regulatory capture. This capture is especially relevant when a large, existing firm introduces a radically new technology for which no competitors (yet) exist, like in the case of DuPont, the world's largest producer of Chlorofluorocarbons (CFC) at the time of the 1988 Montreal Protocol (see Barrett, 2003, p.234).

A survey study among firms, by the German Institute for Standardization, reports that standardization allows for the formation of strategic alliances and encourages cooperation with competitors (DIN, 2000). The survey also finds that a major motivation for firms to participate in standardization processes is to have early access to information and thereby a competitive edge over non-participating firms. Indeed, the degree of openness of the standard and the standardization process is of utmost importance for the welfare effects of standardization (West, 2007). As different stakeholders have different priorities regarding openness, policymakers must define which stakeholders are relevant before intervening in the process of standardization.

Successful implementation of a standard is likely to require technical knowledge from the side of the regulatory agency, especially when an ambitious future standard is announced in order to induce innovation (so-called 'technology-forcing regulation'; La Pierre, 1977, Gerard and Lave, 2005). Regulated firms may have incentives not to innovate, in order to not meet the standard and lobby for postponement of the standard so the agency must be able to understand whether such claims are valid. At the same time, such knowledge helps to prevent the government from setting targets that are clearly too ambitious, given the knowledge available at the instant of announcement of the standard.

Such technical knowledge can also help in determining the optimal timing of a technical standard initiated by the government. This timing is especially relevant in case of network technologies, where the value of a technology for a user is positively affected by the number of users, possibly through the number of providers. As long as competition between varieties of the technology (i.e. between technical standards) has not been settled, both users and providers face uncertainty over the future value of each variety, no variety may prevail, and hence none may achieve sufficient scale to be viable. Government intervention may prevent this from happening, yet two risks are present. If intervention is too early, a variety may be picked as the uniform standard that may turn out to be inferior to an alternative variety. If intervention is too late, however, many users may be stuck with an 'orphan' technology that got replaced by the uniform standard and has zero value for the user (David, 1987).

Finally, there is a risk that governments abuse standards themselves. Despite existing rules on international trade, health and environmental standards are still being (mis)used as barriers to trade.

Inducing eco-innovation by means of standards

A particular *ex ante* strategy by the government to use standards as an instrument to stimulate eco-innovation is likely to benefit from a good understanding of the conditions under which different types of standards have been successful or unsuccessful in supporting eco-innovations in the past. This section explores potential differences in the conditions that may be important for the design of tailor-made policies in this area.

Inducement in traditional abatement markets

For a long time, economists studied the dynamic impact of environmental standards mainly from the market for diffusion, implicitly assuming the *exogenous* arrival of new technologies. Traditional abatement markets were typically organized around pollution control or so-called 'end-of-pipe' technologies, such as waste water purification plants and scrubbers or catalysts to reduce emissions of air pollutants (Kemp, 1997). These markets developed in the 1970s when several countries introduced environmental policy standards to improve air, water and soil quality. Compliance with environmental policy standards was likely to occur by regulated firms installing existing abatement technologies. Only recently economists started to acknowledge that the introduction of environmental policy standards also plays a role in the generation or inducement of *new* knowledge and technologies (inventions) in these markets.

The best studied traditional abatement market is the market for technologies for reducing sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions from electricity generation plants in the U.S. The 1977 Clean Air Act Amendments (CAAA) required new coal-fired power plants to have an SO_2 emissions rate of at most 1.2 pounds per million Btu of fuel burned *and* to remove a large fraction of potential SO_2 emissions, as determined by the sulfur content of the fuel burned. The fraction of potential emissions removed, depended on the emissions rate. A removal rate of 70% was sufficient if the plant had an emissions rate below 0.6, otherwise a removal rate of 90% was required. This 'percent reduction rule' effectively required new coal-fired power plants to install flue gas desulfurization units ('scrubbers'), even if they burned low-sulfur coal (Ellerman et al., 2000, p.15), and accordingly reduced the behavioral standard to a technical standard. This prototype case of what economists label 'command and control policy' indeed triggered diffusion of existing abatement technology across regulated firms.

The introduction of these environmental policy standards, however, also induced inventors to develop new ideas that improve existing technologies. The standard itself often becomes a focal point for new inventions. In particular, behavioral standards, such as an ELV, are likely to give rise to new ideas because this type of standard allows for more degrees of freedom than a technical standard. Popp (2006) showed that *inventing firms* react to the imposition of emission standards on polluting firms. His patent counts for both SO_2 and NO_x emissions control technologies, of firms in the three main inventing countries in the world (the US, Germany and Japan) between 1970 and 2000, show a clear correlation with policy interventions through the imposition of local regulatory standards in each of these countries.

Another interesting finding from this literature is that the exact *design* of the environmental policy standard also affects the *direction* of the innovation itself. Popp (2003) found that innovation efforts in the US in the 1980s were focused on reducing the operation costs of scrubbers. The announcement, in 1990, that an SO_2 cap and trade system would be introduced in 1995, turned scrubbers into a tool for utilities to reduce emissions and to make money from selling allowances that become available as a result of scrubbing. Popp (2003) indeed confirmed that, after the announcement, innovating activities moved towards innovations aimed at improved SO_2 removal efficiency. The shift in innovations occurred *before* the actual implementation of the permit trading system and shows that inventors anticipate changes in regulations.

Inducement in complex and integrated abatement markets

Our discussion so far illustrates that the design and implementation of standards has an important impact in guiding traditional end-of-pipe pollution control technology trajectories. Pushing abatement beyond add-on technologies is a notoriously difficult task for policy makers, however. This often requires the introduction of potentially more radical innovations, i.e. development and deployment of entirely new technology trajectories. To induce such eco-innovations, not only a proper choice and design of environmental policy standards is important, but also that of potential additional standards or other (incentive) instruments. We illustrate the difficulties involved using environmental regulation of the automobile industry as an example.

Environmental regulation of the automobile industry started with hydrocarbons (HC) and carbon monoxide (CO) emissions in the 1970s. The automobile emission standards for HC and CO of the 1970 CAAA, to be implemented for the 1975 model year, could only be met with catalytic converters, a known technology that required further improvements before implementation in automobiles. Incompatibility of leaded gasoline with oxidation catalysts, as well as health considerations of lead-related air pollutants, spurred the search for alternatives. To guide this process the US government also introduced lead (Pb) standards leading to a gradual phase-out of leaded petrol in the US during the 1970s and 1980s (Kerr and Newell, 2003). Clearly the presence of lead in gasoline hampered the diffusion of the catalytic converter and an integrated approach was needed to effectively reduce HC and CO emissions. The eventual deployment of the catalyst would likely not have been obtained using a simple tax on polluting emissions (Gerard and Lave, 2005).

Still, the oxidation catalyst was not able to reduce NO_x emissions, and a completely new technology was needed. This eventually resulted in the development of the three-way catalyst, which demanded large investments in engine architecture, for example to obtain a stable air-fuel ratio. Introduction of this catalytic converter required in turn the development of precise electronic feedback control systems to monitor the composition of exhaust gases and feed that information to a microprocessor-controlled carburetor or fuel-injection system. The fact that it took much longer to reduce NO_x emissions than initially expected by the EPA suggests that technology forcing is much easier when it implies improving and diffusing an existing technology (the catalytic converter) than when it requires breakthrough inventions (the three-way catalyst; Gerard and Lave, 2005). Even the stricter regulation in the 1990s has not resulted in a major shift away from the internal combustion engine.

We conclude that more regulatory pressure on a broader range of issues through standards has a strong impact on eco-innovation in different abatement markets, but also requires a good understanding of what is required in adjacent, but related fields to make such innovations a success. Moreover, more pressure does not necessarily lead to radical different innovations. For the (environmental) standards to be effective, one should also pay attention to adjacent markets as well as to the role of the standardization processes that accompany these innovations.

Inducement of eco-innovation in global markets

In addition to the role of adjacent markets and standardization processes, a proper understanding of how knowledge and technologies flow between different countries and how, in turn, standards influence these interactions is important too. Both existing as well as new knowledge and technologies flow across borders through very different channels (Keller, 2004): trade in products and equipment between countries, firm location decisions and vertical integration in multinationals, and knowledge flows between countries in a disembodied form, e.g. through patents. The three interaction channels may also give rise to international technology spillovers (e.g. Eaton and Kortum, 1999).

Standards have an impact on both the diffusion of existing abatement technologies and on the development of new knowledge and technologies. For international technology diffusion, the spread of international (environmental) policy standards themselves is key (Lovely and Popp, 2011). If a government in some country imposes an environmental standard, the regulated local firms are likely to respond by exploiting existing abatement options, whether they come from inventing firms at home or abroad. For the technology producing firms, the overall size of the market is determined by both domestic and foreign developments of (environmental) policy standards.

With global markets for abatement, the implementation of local environmental policy standards may not only induce inventing firms to increase efforts in R&D at home, but also abroad. For the same eco-innovations in the field of SO_2 emission reduction studied by Popp (2006), both Matsuno et al. (2010) and Dekker et al. (2012) report that patenting decisions of inventing firms, in particular in Germany and Japan, not only react to changing regulations at home, but also to changes abroad. Indeed, inventing firms can transfer their knowledge intentionally by seeking patent protection abroad. Dekker et al. (2012) show that not only local policy standards are important for such knowledge transfers, but also international environmental agreements have this kind of impact.

The potential role for standards in supporting eco-innovations

An important question is under what circumstances the implementation of standards by governments can be successful in directing technological change towards a cleaner innovation path. The design of a particular *ex ante* strategy by the government is likely to benefit from insights in the characteristics of, first, the environmental issues it is supposed to address, second of the new technology involved, and third of the market where it should take off. Policy makers could use these insights to anticipate the role of asymmetric information in the standard-setting process and make their interventions likely to be more successful. Finally, there may be a role for international cooperation.

Relevant contexts for standard-setting for eco-innovation

The first issue is what *environmental issue* is at stake. Some environmental problems require immediate intervention and environmental policy standards can be imposed as restrictions or even outright prohibition of some substances or activities. Examples are contamination of water sheds with PCBs and the use of asbestos. For other environmental problems, however, a more gradual regulatory approach can be used. Air quality regulation involves ever tightening standards for automobiles and power plants. In these cases firms can anticipate future standards. Finally, there are long-run environmental problems whose impact may be far away or not yet known precisely. Two of the currently most pressing environmental problems, in particular the deterioration of biodiversity and climate change, are of this nature. These problems also leave many degrees of freedom in how and when to respond. For instance, adaptation and mitigation are just two major options and one could implement policies in the short, but also in the long run.

The second issue relates to characteristics of the new *technology*. As explained before, existing technologies require policies aimed at diffusion whereas new technologies require policies aimed at invention or innovation. Another relevant characteristic of the eco-innovation is whether it is a network technology. For instance, for large-scale diffusion of the electric vehicle, policies solely aimed at the environmental externality (be it through a tax, a standard for tailpipe emissions or an efficiency standard) are unlikely to be sufficient. Since the value to its user of the 'software' of a network technology (an electric car) depends on the number of users, as well as on the availability of compatible hardware (number of recharging stations), a positive externality exists in the adoption of the technology and the provision of hardware. Network technologies require a clear set of compatibility standards and, as we discuss below, policy makers may play an important role in the development of such standards. Identification of an eco-innovation as a network technology may hence be of crucial importance when deciding upon policies to reduce emissions from a particular source.

The third issue to be considered is *market* characteristics. Important differences exist between abatement markets. In the SO_2 abatement market the regulated and innovating firms are different entities and therefore have very different stakes in regulatory efforts by the government. In turn, the government may exploit the interest of the innovating firms in more stringent regulation to prevent the regulated firm to obstruct this process. This difference in interests between inventors and regulated firms is much less clear in the automobile market where firms nowadays coordinate their innovation decisions in joint ventures. Moreover, the process of specialization and globalization for eco-innovations differs strongly across different abatement markets (OECD, 2011). Providers of add-on abatement technologies for water purification or electric power plants are often separate from the regulated firms and even not necessarily located in the same country as the regulated firm. By contrast, in the automobile industry, car producers often have in-house R&D departments but they sell their products on different international markets.

This example illustrates that differences in stakes are also likely to influence the standardization process itself. This is hardly surprising because innovators have a clear interest to get their technology adopted by the government as the new policy standard (in case of a technical standard), or lobby for implementation of a tighter behavioral standard, based on their superior technology. The new standard can then be used as a source of competitive advantage (Jaffe et al., 2002), or to increase rival firms' costs (Hackett, 1995, Puller, 2006).

Standard-setting process and asymmetric information

Traditional environmental problems like water pollution, air pollution, or pollution from waste were relatively easily solved through simple environmental policy standards inducing add-on technology responses. These standards were imposed by the government and induced completely new markets, like waste management and disposal activities, markets for water treatment and markets for catalytic converters. Clearly these markets heavily depend on government regulation. This also explains why changes in regulation, or even their announcement or discussion, is likely to influence the inventing firms' R&D decisions in these areas.

As discussed before, different market participants clearly have different interests in standardization processes. Although the market might settle on technical standards by itself, there is a serious risk that this will take too long or might never happen. However, a technical compatibility standard can be implemented too early as well. If a technology standard is agreed upon because of its availability, there is the risk that a superior (e.g. because of faster recharging), but not yet proven technology will never mature, leading to potential welfare losses. Standards may effectively contribute to the reduction of this uncertainty.

The technology forcing experiment of emission standards in the more complex and integrated abatement market for car exhaust regulation illustrates the difficulties involved. The standards for HC and CO of the 1970 CAAA in the US were on purpose set at a level that could *not* be reached using existing technologies The initial response of the US automobile industry was to invest in innovation based on existing technologies (GM, Ford), or not to invest at all (Chrysler). These efforts were first aimed at engine architecture improvements. It soon became clear that catalytic converters were the only way to meet at least the HC and CO standards, and the EPA started to push the catalytic converter as a *de facto* technology standard. Despite R&D efforts of the industry, the National Academy of Sciences expressed doubts whether oxidation catalysts would be available and effective by 1975 (Gerard and Lave, 2005). It took until the problems with the catalytic converter were solved before these technology forcing performance standards eventually succeeded. Interestingly, no switch to a radically new technology such as the electric vehicle occurred either. A possible explanation is the competence-destroying nature of such new technologies, because they eat away the profits from products based on the conventional internal combustion engine.

Conditions for successful implementation of standards

How standardization processes could be organized to be both effective and efficient from an eco-innovation perspective is a question that has generated little attention from environmental economists.[6] Caveats, such as government failures, are paramount. In the literature on governance, stakeholder participation is often promoted. Openness of the standardization process indeed seems to be important to ensure that all relevant agents are involved in the setting of the standard, but also the proper selection of agents seems to be a key condition (West, 2007).

[6] Simcoe (2012) studies the role of standard-setting committees in setting internet-related standards and finds that increased commercial pressure slows down the decision-making process. To what extent these results can be generalized to standards for eco-innovation is open for future research.

Effective involvement of stakeholders and openness, however, clearly benefits from a proper understanding from the three conditions mentioned in the previous section. If properly designed, these processes facilitate exchange of knowledge, not only among regulators of different countries, but also between regulators, industry and other stakeholders. We next illustrate one relevant past experience and one recent eco-innovation along the lines of the previous paragraphs.

In the 1980s, SO_2 emissions largely stemmed from point sources, notably coal-fired power plants, causing environmental damages in a wide geographical area. The characteristics of the *environmental issue* allowed for immediate intervention through environmental policy standards. Also *technologies* to reduce these emissions separately were available, so the policy focus could be at technology diffusion rather than invention and there was no need for technology forcing. In addition, neither the characteristics of the environmental problem nor the characteristics of the abatement technology (Flue Gas Desulfurization, FGD) required an integrated approach involving additional policies This technology also did not have characteristics of a network technology. Finally, the *market* for the abatement technology was separated from the product market of the technology users since utilities were not involved in developing abatement technologies.

The reason why this particular technology spread around the world is deliberate cooperation by governments using organized exchange of information. Indeed, since the adoption of the Convention on Long-Range Transboundary Pollution (LRTAP) in 1979 exchange of technology and operational experience has been an important part of the international coordinated effort to reduce acid rain. With 5 year intervals, starting in 1981, seminars on the exchange of technology were organized (Sliggers and Kakebeeke, 2004, p.52). The seminars reviewed available efficient control technologies and the agenda followed the need to integrate technical knowledge into the protocols' annexes, such as the FGD technology in 1981. Accordingly, the international negotiations also offered innovating firms (and their representative governments) an excellent opportunity to promote their inventions. Inventions in FGD technology in Germany were key to compliance with new local restrictions on coal fired power plant SO_2 emissions, but these inventions also boosted LRTAP negotiations which culminated in the Helsinki protocol. If such seminars are transparent enough, potential innovators can update their information on inventions before deciding to further explore new directions of research or to transfer knowledge across different (participating) countries.

Our second example discusses the difficulties a regulator faces in the process of standardization if the aim is to stimulate more radical innovations and what might be useful strategy. Zero emission vehicles, such as the Full Electric Vehicle and the hydrogen car, rely on a fundamentally different technology as compared to the currently dominant technology, the internal combustion engine. These vehicles can reduce concentration levels of *local air pollution* as well as reduce *greenhouse gas emissions*.

The *technology* of the zero emission vehicle has two notable characteristics. First, both the electric and hydrogen vehicle (where hydrogen can be used in an internal combustion engine or in a fuel cell) are proven technologies. Despite high production costs these eco-innovations have entered the stage of diffusion, and have largely left the stages of invention and innovation. Second, both technologies are network technologies. Use of a zero emission vehicle depends on the availability of recharging points and vice versa. The positive externality of this network effect cannot be directly addressed by policies aimed at reducing the environmental externality and asks for additional policies.

The *market* for zero emission vehicles consists, on the supply side, of both incumbents on the automobile market that have extended their range of models with zero emission vehicles and newcomers. For incumbents the zero emission vehicle is to a certain extent capital- or competence-destroying. In addition, the same holds for oil and gas companies, despite their interest in delivering their products for electricity production (which can be used to power zero emission vehicles). Other important actors on the market for zero emission vehicles are producers of batteries and recharging stations, and consumers.

The network technology characteristic in particular introduces challenges in terms of standardization of the 'hardware' (recharging stations) and the 'software' (vehicles). In Europe there is a common safety standard for slow recharging of electric vehicles (recharging a battery to 80% in several hours), but a uniform compatibility standard for plugs and sockets has only just been announced by the European Commission. The lack of a uniform standard for fast plug-in recharging (recharging up to 80% in about 15 minutes) is technologically more complex. Currently, the Japanese CHAdeMO standard is competing with the Combo standard supported by (most but not all) European and American car manufacturers. The hydrogen car is one step behind the plug-in electric vehicle in technological development and large-scale diffusion requires even more standardization and a recharging network of its own.

With several co-existing technologies, and lack of experience consumers are reluctant to buy zero emission vehicles: if a consumer buys a vehicle based on one particular recharging technology, she runs the risk that this technology will be replaced by a different standard in the future, leaving her stuck with an 'orphan' technology (David, 1987). The same risk holds for suppliers of recharging stations and hence a 'chicken-and-egg problem' exists (Hacker et al., 2009, IEA, 2010).

In particular the network element calls for policy measures in addition to policies aimed at emission reductions (e.g. a carbon price). Although strictly speaking the technology involves an additional externality, adoption subsidies may not be sufficient to correct for network effects since adoption of a network technology is a dynamic process: a subsidy to buy a zero emission vehicle may not affect behavior if producers of such vehicles or providers of recharging infrastructure and services are hesitant to scale up their supply because of unfinished standardization processes.[7] Although these processes are in progress they may take too long and the momentum for zero emission vehicles may disappear. Interventions by policy-makers may be useful or even necessary, yet intervention can be too early as well since an enforced compatibility standard may prevent superior charging technologies from taking off. As noted, the key to finding an optimal time of enforcement is an open standardization process, combined with knowledge by policy-makers about recent technological developments (for example through an in-house R&D department).

Potential for international cooperation

Coordination among governments offers a relatively easy option to stimulate eco-innovation. The first main option is the screening of environmental policy standards applied abroad that offer a solution for a domestic environmental problem. In this way domestic environmental standards may spread internationally even without explicit coordination. One example is the spread of the EU Euro 1-6 standards for cars, which comprise a number of explicit standards on car exhausts (such as HC, CO, NO_x, Particulate Matter) and were later on combined with a predefined increase in stringency over time. The first set, the Euro 1 standard, became effective between 1992 and 1995, whereas the Euro 6 standard will become effective as of late 2014. Interestingly, these standards are now copied by developing countries as a focal point for their regulation. Some Asian countries or areas like Hong Kong and big cities in India closely follow this pattern, where some even start immediately with the Euro 4 standard (An et al., 2011). A similar process can be observed for SO_2 and NO_x regulation throughout the world (Lovely and Popp, 2011).

A second option for governments is to seek international coordination, for instance through negotiations on international (environmental) agreements (IEAs). These efforts are particularly useful in the case of transboundary pollution or if unilateral regulation may obstruct a level playing field for competing firms. As noted before, IEAs may not only specify country-specific emission reduction commitments but also coordinate the standardization process like monitoring and verification procedures through which countries should implement their commitments (Sliggers and Kakebeeke, 2004).

Dekker et al. (2012) show that the IEA on SO_2 reduction matters for both invention of new technology as well as their international diffusion. IEAs seem to play a separate role in the strategic decisions of firms to transfer and protect their knowledge abroad. Indeed, countries that participate in the agreement and commit themselves to stringent emission reductions are likely to provide a future export market for inventing firms.

[7] A useful alternative may be government adoption of electric vehicles, see Corts (2010).

International coordination under the authority of a supranational authority is another option. Indeed, many interesting examples exist of 'local', country-specific policies to solve environmental problems through eco-innovation.[8] Once recognized as beneficial, such local solutions could be exploited by a federal government. For instance, the regulatory conditions for incineration and landfills imposed by the Netherlands in the 1990s became an important focal point in drafting EU directives (Dijkgraaf and Vollebergh, 2004). These standards had already been shown to work in practice, i.e. existing technologies were available to comply with those standards.

Apart from coordination of environmental policy standards by governments, international coordination or even agreements on *other* standards will be particularly helpful if network externalities or scale economies are present. Technical compatibility standards for parts of the electric car (e.g. characteristics of plugs and sockets and battery characteristics) may differ too much between countries, leading to prohibitively high production costs for electric vehicle producers. Producers then have to develop and produce a separate model for each country, and are unable to exploit economies of scale. Similarly, if the technical compatibility standards for recharging infrastructure are not coordinated internationally, consumers are restricted in their use by national borders restricting large-scale adoption as well. Similar coordination problems exist for reference and measurement standards and for standards of interface compatibility. International coordination might be useful in these cases in order to prevent market fragmentation or even outright protection.

Finally, coordination in the market for ideas is another example of a standardization process where governments can directly contribute. Having an (international) standard based on a firm's invention, such as protection by well-defined patents, can be profitable. The last decade has shown a remarkable effort to standardize processes for patenting across the globe and large advances have been made in this respect, including recent efforts to create one unitary European patent. However, intellectual property rights (IPRs) are not fully enforced everywhere. If part of the innovator's profits are eroded when foreign companies start producing counterfeit products, this reduces the incentive to patent as well as to introduce one's patent as a focal point for an international standard. When it comes to the international protection of knowledge, i.e. protection of a 'homemade' invention in international markets, patent standards used to differ considerably across countries (Eaton et al., 2004).

[8] Examples are Austria with the strictest global VOC standards, chlorine free paper bleaching process in Sweden, and recently Dutch saltpeter reduction.

Conclusions

In this paper we have argued that standards may contribute to all stages of development and deployment of eco-innovations. It turns out, first of all, that environmental policy standards are only a small fraction of all known standards and other standards are often at least as important for eco-innovation. In addition, many standards are set by firms or voluntary standards writing organizations, and aim at commensurability and interface compatibility. As a result, a particular standard-setting process, even if initiated by the government, may be ineffective, take too long or lead to a degree of standardization that is too low. Finally, (institutional) differences exist across countries while at the same time new standards may also require new institutions, like IEAs, to coordinate the standardization process.

The case studies discussed also illustrate that no simple policy prescriptions are available that suit all eco-innovations. Both the variety of environmental problems and the variety of eco-innovations is enormous (see OECD, 2011). Environmental problems range from local pollutants such as solid waste to global pollutants such as greenhouse gas emissions, and their technological solutions range from add-on/end-of-pipe technologies (such as CCS) to complex, integrated approaches (such as the electric car with its infrastructure for recharging, necessary adjustments to electricity networks, etc.). Furthermore, technological solutions differ in the status of the underlying technologies (drawing board, test-phase, proven technology, widely adopted technology). Nevertheless, standards can be used to support technological change in general, they may promote investment in eco-innovations when used as an environmental policy standard, and they can support the diffusion of existing eco-innovations.

References

Acemoglu, D., P. Aghion, L. Bursztyn and D. Hemous (2012), 'The environment and directed technical change', *American Economic Review*, 102(1), 131-166

An, Feng, Robert Earley and Lucia Green-Weiskel (2011), *Global overview on fuel efficiency and motor vehicle emissions standards: policy options and perspectives for international cooperation,* UN Department of Economic and Social Affairs, New York

Anderson, Soren T., Ian W. H. Parry, James M. Sallee, and Carolyn Fischer (2012), 'Automobile fuel economy standards: impacts, efficiency, and alternatives', *Review of Environmental Economics and Policy* 5(1), 89-108

Barde, Jean-Philippe (2000), ‘Environmental policy and policy instruments’, chapter 6 in Henk Folmer and H. Landis Gabel (eds.), Principles of Environmental and Resource Economics (2nd ed.), Edward Elgar, Cheltenham

Barrett, Scott (2003), *The strategy of environmental treaty-making*, Oxford University Press, Oxford

Baumol, W.J. and W.E. Oates (1988), The theory of environmental policy, Cambridge University Press, Cambridge.

Burtraw, Dallas, Art Fraas, and Nathan Richardson (2011), ‘Greenhouse gas regulations under the Clean Air Act: a guide for economists’, *Review of Environmental Economics and Policy*, 5(2), 293-313

Corts, Kenneth S. (2010), ‘Building out alternative fuel retail infrastructure: government fleet spillovers in E85’, *Journal of Environmental Economics and Management*, 58, 219-234

David, Paul A. (1985), ‘Clio and the economics of QWERTY’, *American Economic Review* 75, 332-336

David, Paul A. (1987), ‘Some new standards for the economics of standardization in the information age’, chapter 8 in P. Dasgupta and P. Stoneman (eds.), *Economic Policy and Technological Performance*, Cambridge: Cambridge University Press

David, Paul A., and Shane Greenstein (1990), ‘The economics of compatibility standards: an introduction to recent research’, *Economics of Innovation and New Technology* 1 (1/2), 3-41

Dekker, Thijs, Herman R.J. Vollebergh, Frans P. de Vries, and Cees A. Withagen (2012), ‘Inciting Protocols’, *Journal of Environmental Economics and Management* 64, 45-67

Dijkgraaf, Elbert, and Herman Vollebergh (2004), “Burn or Bury? A Social Cost Comparison of Waste Disposal Methods”, *Ecological Economics*, 50, 233-247.

DIN (2000), Economic benefits of standardization - Final report and practical examples, DIN German Institute for Normalization e.V., Beuth Verlag, Berlin

Eaton, J. and S. Kortum (1999), International Technology Diffusion: Theory and Measurement, *International Economic Review*, 40: 537-570.

Eaton, J., S. Kortum and J. Lerner (2004), International patenting and the European patent office: a quantitative assessment, in: OECD, Patents, Innovation, and Economic Performance, Paris, 2004, pp. 27–52.

Ellerman, A.D., P.L. Joskow, R. Schmalensee, J.-P. Montero, and E.M. Bailey (2000), *Markets for Clean Air: the U.S. Acid Rain Program.* Cambridge University Press, New York.

Fischer, Carolyn, and Richard G. Newell (2008), 'Environmental and technology policies for climate mitigation', *Journal of Environmental Economics and Management* 55, 142-162

Fullerton, Don, and Gilbert E. Metcalf (2001), 'Environmental controls, scarcity rents, and pre-existing distortions', *Journal of Public Economics* 80, 249-267

Gerard, David and Lester B. Lave (2005), 'Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advanced automotive emissions controls in the United States', *Technological Forecasting and Social Change* 72, 761-778

Glachant, Matthieu (2007), 'Non-binding voluntary agreements', *Journal of Environmental Economics and Management* 54, 32-48

Goulder, Lawrence H., Ian W.H. Parry, Roberton C. Williams III, and Dallas Burtraw (1999), 'The cost-effectiveness of alternative instruments for environmental protection in a second-best setting', *Journal of Public Economics* 72, 329-360

Hacker, Florian, Ralph Harthan, Felix Matthes and Wiebke Zimmer (2009), *Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe – Critical review of the literature*, ETC/ACC Technical Paper, European Topic Centre on Air and Climate Change

Hackett, S.C. (1995), 'Pollution-controlling innovation in oligopolistic industries: some comparisons between patent races and research joint ventures', *Journal of Environmental Economics and Management* 29, 339-356

Helfand, Gloria E. (1991), 'Standards versus standards: the effects of different pollution restrictions', *American Economic Review* 81(3), 622-634

IEA (2010), *Technology roadmap: electric and plug-in hybrid electric vehicles*, International Energy Agency, France, Paris: OECD Publishing

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins (2002), 'Environmental policy and technological change', *Environmental and Resource Economics* 22, 41-69

Jung, Chulho, Kerry Krutilla, and Roy Boyd (1996), 'Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives', *Journal of Environmental Economics and Management* 30(1), 95-111

Katz, Michael L., and Carl Shapiro (1994), 'Systems competition and network effects', *Journal of Economic Perspectives* 8(2), 93-115

Keller, Wolfgang (2004), 'International technology diffusion', *Journal of Economic Literature* 42, 752-782

Kerr, S. and R.G. Newell (2003), 'Policy-induced technology adoption: Evidence from the U.S. lead phasedown', *Journal of Industrial Economics*, 51(3), 317–343

Kemp, René (1997), *Environmental policy and technical change*, Cheltenham: Edward Elgar

La Pierre, D. Bruce (1977), 'Technology-forcing and federal protection statuses', *Iowa Law Review*, 62, 771-838

Lovely, Mary and David C. Popp (2011), 'Trade, technology, and the environment: does access to technology promote environmental regulation?', *Journal of Environmental Economics and Management* 61, 16-35

Matsuno, Y., T. Terao, Y. Ito, and K. Ueta (2010), *The impact of the* SO_x *charge and related policy instruments on technological innovation in Japan*, OECD

Milliman, Scott R., and Raymond Prince (1989), 'Firm incentives to promote technological change in pollution control', *Journal of Environmental Economics and Management* 17, 247-265

Montero, Juan-Pablo (2002), ‘Permits, standards, and technology innovation’, *Journal of Environmental Economics and Management* 44, 23-44

OECD (2009), *Eco-innovation in industry: enabling green growth*, Paris: OECD Publishing

OECD (2010), *Taxation, Innovation and the Environment*, Paris.

OECD (2011), *Better policies to Support Eco-innovation*, Paris

Popp, David C. (2003), ‘Pollution control innovations and the Clean Air Act of 1990’, *Journal of Policy Analysis and Management* 22(4), 641-660

Popp, David C. (2006), ‘International innovation and diffusion of air pollution control technologies: the effects of NO_x and SO_2 regulation in the US, Japan, and Germany’, *Journal of Environmental Economics and Management* 51, 46-71

Popp, D., R.G. Newell and A.B. Jaffe (2010), ‘Energy, the Environment and Technological Change’, chapter 21 in B.H. Hall and N. Rosenberg, Handbook of the Economics of Innovation, vol. 2, North-Holland.

Puller, Steven L. (2006), ‘The strategic use of innovation to influence regulatory standards’, *Journal of Environmental Economics and Management* 52, 690-706

Requate, T. (2005), ‘Dynamic incentives by environmental policy instruments: a survey’, *Ecological Economics*, **54**, 175–195

Rysman, Marc, and Tim Simcoe (2008), ‘Patents and the performance of voluntary standard setting organizations’, *Management Science* 54(11), 1920-1934

Simcoe, Timothy (2012), ‘Standard setting committees: consensus governance for shared technology platforms’, *American Economic Review* 102(1), 305-336

Sliggers, J. and W. Kakebeeke (eds) (2004), *Clearing the Air, United Nations - 25 years of the Convention on Long-range Transboundary Air Pollution*, United Nations, New York and Geneva

Tassey, Gregory (1982), 'The role of government in supporting measurement standards for high-technology industries', *Research Policy* 11(5), 311-320

Tassey, Gregory (2000), 'Standardization in technology-based markets', *Research Policy* 29(4-5), 587-602

Thompson, George V. (1954), 'Intercompany technical standardization in the early American automobile industry', *Journal of Economic History*, 14(1), 1-20

West, Joel (2007), 'The economic realities of open standards: black, white and many shades of gray', chapter 3 in Shane Greenstein and Victor Stango (eds.), *Standards and Public Policy*, Cambridge University Press: Cambridge