POLICY SHIFT FOR THE LOW-CARBON TRANSITION
IN A GLOBALLY EMBEDDED ECONOMY

Evaluative framework for policymakers to study the potential of (inter)national standards and other instruments for further development and deployment of eco-innovations

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Working paper – Version 26 September 2019

(1) Introduction

Limiting warming to no more than 2°C has become the *de facto* target for global climate policy. To reach this goal with at least 66% probability, net zero carbon dioxide (CO_2) emissions from all anthropogenic sources should be achieved around 2065, with net negative CO_2 emissions thereafter (Rogelj et al., 2015). This requires not only dramatic global emission reductions, for example from the energy sector, but possibly also employment of sources of negative emissions (or 'carbon sinks'; Gasser et al., 2015).

Austria has committed to a transition to a low-carbon society, yet the details of the policies and technology trajectories required to fulfil this commitment are still to be explored. Eco-innovation – innovation that results in a reduction of environmental impact, whether or not that effect is intended (OECD, 2009) – plays a crucial role in this transition as currently deployed technologies will not allow the country to meet its objectives. Indeed, the invention, innovation and diffusion of low- and zero-carbon technologies are crucial for the global community to meet the 2°C target (IPCC, 2018). Still, emission reductions and eco-innovations will be under-supplied by the market due to the underlying market failures (public good characteristics and positive externalities). Government policies can play an important role in the transition process. Which policies should be implemented by the Austrian government to support eco-innovation in the context of the transition to a low-carbon economy is yet to be assessed. In such an assessment it is important to realize that Austria is a small, open economy, in which many technological and economic developments are driven by foreign (including European Union) forces and policies.

The objective of this paper is to develop an evaluative framework which should allow policymakers to assess the potential of (inter)national standards and other instruments for further development and deployment of eco-innovations.. These instruments are necessary because the transition to a low-carbon society suffers from two types of market failures: the negative externalities stemming from the use of greenhouse gas emitting technologies, and positive externalities from spillovers in the process of eco-innovation. Hence, we include both environmental policy instruments and technology policy instruments, and for both we look at the role of standards. Schumpeter (1942) distinguished three different phases of technological change: invention, innovation and diffusion. We take a broader look at eco-innovation than just the innovation phase and include invention and diffusion as well. When describing technology policy instruments, we explicitly look at their role in improving market outcomes during each of the phases of technological change. For this, we distinguish four dynamic spillovers: positive externalities from the generation of new knowledge, learning by doing, network externalities, and diffusion of technology knowledge.

In the next section we briefly explain the dynamics of technological change. We pay attention to the role market factors and policy instruments play in directing technological change. In section 3 we provide a shortlist of instruments that could play a role in addressing the two externalities. We discuss their focus, scope and interaction with other instruments. We also discuss the role of timing. In section 4 we describe the international dimension of instrument choice for eco-innovation. In section 5 we present a framework for the evaluation of policy instruments for eco-innovation and in section 6 we present some preliminary applications. We conclude in section 7.

(2) The dynamics of eco-innovation

The transition towards a low-carbon society suffers from two market failures (Jaffe et al., 2003). The first is the environmental market failure of greenhouse gas emissions. Environmental policy instruments can be used to reduce these emissions. The second market failure is related to technological change. Invention and innovation lead to positive knowledge spillovers as newly created knowledge and technologies have public good characteristics and can be used by others in society as a basis to build new knowledge and products (Romer, 1990). Furthermore, new technologies may benefit from increasing returns in production or consumption or from network externalities (Jaffe et al., 2005) and the diffusion of new technologies may be hampered by imperfections in the diffusion of knowledge about these technologies (Jaffe and Stavins, 1994). As is well-known in the economics of technological change and the environment, a portfolio that combines environmental and technology policy instruments generally reduces emissions at lower costs than a single policy instrument (e.g. Fischer and Newell, 2008).

As noted in the introduction, Schumpeter (1942) distinguishes three phases in the process of technological change. Invention is the first technical implementation of an idea for a new technology, product or process. Since these inventions (which may or may not have been patented) can form the basis of the development of further new ideas and inventions, inventions generate positive spillovers from the inventor to society. Hence, from the perspective of society, too little invention occurs when incentives from invention only come from market developments. Policy support for invention can come in the form of generic policies that support research and development (R&D), but in the case of eco-innovation it could be support for inventions aimed at a specific environmental problem (e.g. R&D support for low-carbon technologies).

The second phase comprises the development of inventions into new technologies or processes that can be sold on the market, which is called innovation. This typically involves the testing of technologies in the laboratory. Policy support for innovation can again come in the form of policies which are generically focused on R&D or are specifically aimed at an environmental problem, but it could also be aimed at a specific technology (technology forcing; Gerard and Lave, 2005). We will discuss technology forcing in section 3.1.2. Profit-maximizing inventors and innovators will aim their R&D efforts at markets in which they can earn back their initial investment. Logically, the larger the market and the higher the relative price of the product for which the new technology or process is developed, the larger the incentive to innovate (Acemoglu, 2002; Acemoglu et al., 2012). As we will see, these market size and price effects play an important role for eco-innovations as well.

Finally, diffusion is the process of adoption by multiple actors of new technologies that have been proven at commercial scale. There are various arguments for support for new technologies in the diffusion process. The first is that there are positive externalities that stem from learning by doing in the production or consumption of a new technology. For example, as has long been known, the production of a new type of airplane becomes cheaper as more units have been produced (Wright, 1936), and the same holds for the production of windmills (McDonald and Schrattenholzer, 2000). It should be noted that recent empirical literature suggests that learning is subject to diminishing returns and quick decay (Bollinger and Gillingham, 2014; Nemet, 2012). The second argument applies to technologies that suffer from network externalities. With network technologies, consumption benefits depend on the number of users of the same network (Katz and Shapiro, 1985). Direct network effects occur when increases in the number of consumers on the same network raise the consumption benefits for everyone on the network, as in a physical network (for example telephone, e-mail). A virtual (or indirect) network effect arises when individuals consume a system that consists of a 'hardware' good (such as a video game console) and complementary software products (games). In such a 'hardware/software' system, the consumption benefits of the hardware good increase with the variety of compatible software (variety of games available), and the indirect network effect occurs when increases in the number of users of compatible hardware increase the demand for compatible software and hence the supply of software varieties (Gandal, 2002). Network effects are relevant for the diffusion of plug-in electric and fuel cell electric vehicles. One risk that is inherent to subsidizing particular technologies for adoption is that it may lead to 'picking winners': subsidizing technologies that are close to market may impede the development and diffusion of superior yet less evolved technologies (David and Steinmueller, 1994). The third argument for support for new technologies in the diffusion process is the availability of knowledge about the new technology by actors in the market (Jaffe and Stavins, 1994). Various studies have found that the probability of adopting a new technology is positively affected by the proximity of agents that have already adopted the new technology. In their review of the literature, Allan et al. (2013) conclude that, although the empirical evidence is only indirect, information does seem to play an important role in the adoption process of new technologies. The size of the market failure of imperfect technology knowledge diffusion, however, is unclear.

Learning by doing, network effects and imperfect markets for information (lack of technology knowledge) are arguments for support for adoption subsidies for new technologies (although these arguments do not each equally apply to each (eco-)innovation). As noted above, the size of the potential market for the new technology has a positive effect on R&D efforts. Diffusion subsidies support the adoption of a new technology (e.g. solar panels or electric vehicles) and thereby increase the size of the market. As a result, these subsidies indirectly increase incentives for invention and innovation.

In sum, R&D is driven by market incentives but is subject to market failures. The same holds for the diffusion phase of technological change. We identified four dynamic spillovers: positive externalities from the generation of new knowledge, learning by doing, network externalities, and diffusion of technology knowledge. For eco-innovations, these market failures come on top of environmental externalities. Hence both environmental and technology policy instruments need to be implemented to mitigate these market failures.

(3) Policy instruments for a low-carbon society

In this section, we describe policy instruments that can be used to counter the two types of market failures that are relevant for eco-innovation: environmental externalities and dynamic spillovers in the process of eco-innovation itself (knowledge spillovers, learning-by-doing, network externalities, and diffusion of technology knowledge). For each instrument, we describe its potential role in mitigating each market failure by discussing the instrument's focus (which market failure is being addressed, and how directly is it being addressed) and scope (to what extent is the market failure covered by the instrument, or how narrow is the instrument; see also Vollebergh, 2018). Where relevant, we also discuss the interaction with other instruments and the role of timing (when to start using it and how should it be phased out) in the use of the instrument. An elaborate overview of the effect of environmental policy on innovation can be found in Popp et al. (2010) and, providing an update of that paper with a focus on empirical studies, Popp (2019).

To allow for a discussion of standards both in the context of emission reductions and in the context of technological change, we follow Vollebergh and Van der Werf (2014, p.231) and define a standard as "a document that specifies characteristics of technical design or rules of behavior". Note that 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. The definition also allows for a distinction between environmental policies that prescribe specific technical standards and policies that prescribe behavorial standards, such as emission limit values. For eco-innovation this distinction accounts for the difference between regulations that simply prescribe certain technologies, like a catalytic converter, versus regulation that prescribes certain emission limits and hence allow for a range of technologies to be applied. Indeed, in the case of technical standards the regulated agents simply have to comply with the regulation by installation of the specified technology. With behavorial standards, like an emission limit value or emission ceiling, the agent has several degrees of freedom to comply with the law, including the installation of new technologies.

Some standards are set by the government through law-making in order to achieve a particular policy objective. We denote such standards as 'policy standards' throughout the paper.

We follow David (1987) by not only distinguishing technical from behavioral standards, but also by making a distinction between standards in relation to the specific role they play in society. The first type of standard guarantees commensurability by setting uniform units of measurement or reference, like currencies and weights. The second type sets explicit targets by requiring minimum quality and safety levels. Finally, the third type of standard focuses on interface compatibility. More information on standards can be found in Appendix A.

It should be noted that the analysis in this section is not comprehensive but intended to supply a sufficient basis. A deeper literature review would be required for a complete overview that then could be used by policymakers for fully fledged innovation analysis. Nevertheless, we believe the analysis in this section provides sufficient basis for the evaluation framework we develop in Section 5, and provides useful insights for some preliminary applications of the framework in Section 6.

(3.1) Environmental policy instruments

Environmental policy instruments are first and foremost aimed at reducing harmful emissions. There is a large literature on the welfare impacts of various environmental policy instruments, for example by analyzing their efficiency in achieving a given environmental target (see e.g. Baumol and Oates, 1988). In this paper, however, we are primarily interested in their impacts on the development and diffusion of eco-innovations.

(3.1.1) Communication instruments: eco-labels

Many consumers are willing to pay a premium for products that cause less harm to the environment than otherwise comparable products (see e.g. Bjørner et al., 2004, Cason and Gangadharan, 2001). However, consumers typically cannot tell whether a firm and its suppliers use ‘green’ production technologies, which makes it hard for green firms to differentiate themselves from their ‘brown’ competitors, while the latter typically can sell their product at lower prices due to lower production costs. This is a problem of asymmetric information (Akerlof, 1970). Eco-labels can be used as an instrument to mitigate this. As is clear from Appendix A, eco-labels labels act as technical quality and safety standards and inform consumers about the ‘green’ properties of products that can subsequently be compared against their ‘brown’ competitors. Eco-labels can be set by a firm or sector, by the government, or by an independent third party, where the latter two are found to be superior in terms of reliability (see e.g. Bjørner et al., 2004, Cason and Gangadharan, 2001). Examples of eco-labels are the FSC and MSC labels for responsible forest and fisheries management, EU Energy Labels that rank the energy performance of consumer durables, and the energy label for houses in The Netherlands.

When an eco-label is considered to be reliable by potential consumers, it can mitigate the problem of asymmetric information and solicit a price premium from consumers who have a higher willingness to pay for green products (Bjørner et al., 2004, Cason and Gangadharan, 2001). In this way, eco-labelling supports the diffusion of an eco-innovation and the development of a market for eco-innovation. This, in turn, gives firms an incentive to further invent and develop eco-innovations, provided that the willingness to pay of green consumers and the number of such consumers is sufficiently large to cover the additional investments.

Clearly, the *focus* of eco-labels is on the adoption of green products and production processes, and hence on the three dynamic spillovers related to adoption (learning-by-doing, network externalities, and diffusion of technology knowledge). The *scope* of an ecolabel is typically rather narrow as it usually focusses on a particular product (e.g. fish products, consumer durables) and one environmental problem (e.g. bycatch, energy savings to mitigate climate change).

(3.1.2) Command and control instruments

The increasing environmental awareness of society in the 1960s and 1970s resulted in the implementation of so-called command and control instruments. These instruments came in the form of regulations that required polluters to implement a prescribed pollution-reducing action or face a fine (Phaneuf and Requate, 2017).

Polluting firms were often required to install a *mandated technology* (a quality and safety standard of technical design – see Appendix A) such as flue gas desulphurisation units for power plants to reduce sulphur dioxide emissions, and catalytic converters for cars to reduce HC, CO and NO_X emissions. Mandated technologies are usually end-of-pipe technologies. An advantage of such a policy is that an environmental objective can be obtained relatively quickly. Such a mandate does support the diffusion or deployment of eco-innovation, but only for the mandated technology. A technology mandate does not differentiate over polluters: relatively clean firms within a sector are treated just the same as their dirty competitors. Such a policy provides little incentive to develop new eco-innovations: unless the innovating firm is able to convince policymakers to make the innovation the new mandated technology, eco-innovations are not rewarded.

The *focus* of a mandated technology is on the diffusion of an existing eco-innovation and hence on the three dynamic spillovers related to adoption (learning-by-doing, network externalities, and diffusion of technology knowledge). The *scope* of a mandated technology is very narrow as only pollution mitigated by the technology, usually only in a particular sector, is covered. In terms of *timing*, a mandated technology can achieve a given target rather quickly. However, since it does not support further invention and diffusion, it should be reconsidered once the target has been achieved, in order to promote further invention and innovation efforts.

Alternatively, regulators can require firms to meet an *emission or emission reduction standard* (a quality and safety standard of behavioural performance – see Appendix A). This behavioural standard could be in absolute terms, e.g. total emissions, or in relative terms, e.g. emissions per unit of output or grams of polluting emissions per m^3 of wastewater release. As illustrated by the higher-than-allowed emissions from diesel vehicles in the Volkswagen diesel scandal, actual emissions by (the product produced by) the firms subject to the standard should be monitored by an independent party and the standard should be enforced. A firm-level emission limit provides full flexibility for a firm as it allows a firm to choose an optimal mix of measures from investment in clean technologies and reducing output. However, it does not give an incentive to reduce emissions beyond the emission limit. An emission standard expressed in grams of polluting emissions per m^3 of smokestack release gives zero incentives to reduce output or smokestack release but does provide incentives to invest in cleaner technologies.

Hence both absolute and relative emissions standards provide incentives for adoption of an existing eco-innovation, yet neither provides an incentive to develop even cleaner technologies.

The empirical evidence on the effect of regulation on R&D is mixed. Popp (2003) showed that before the passage of the U.S. 1990 Clean Air Act (the introduction of sulphur dioxide emissions trading), when firm-level emission limits were in place, innovators focussed on reducing the operating costs of existing abatement technologies (flue gas desulphurisation units) rather than improving the removal efficiency of these technologies. Renewable energy portfolio standards are aimed at increasing the share of renewable energy in total energy production. Such a standard induces firms to adopt renewable energy technologies, yet these technologies are typically the ones that are closest to the market. Johnstone et al. (2010) find that renewable energy standards support innovation for wind energy, which is the technology with lowest costs. Crabb and Johnson (2010) find that fuel economy standards for vehicles do not spur innovation. Aghion et al. (2016) find a positive but limited role for emissions regulation for the global automobile industry. Knittel (2011) finds a positive effect of fuel economy standards for cars but not for trucks. Noailly (2012) and Costantini et al. (2017) find a positive effect of building code stringency on energy efficiency innovations for the residential sector.

The dynamics of environmental policy-setting matter for the incentives for innovation that stem from emission reduction standards. Environmental regulators may let the standard depend on the abatement technologies that are available. If polluting firms are required to use the Best Available Control Technology (BACT) or BACT Not Entailing Excessive Costs (BACTNEEC), or if a relative emission standard is based on the characteristics of a particular (new) technology, then innovators have a potential market for a new, cleaner technology. Indeed, an emission reduction standard may induce eco-innovations if it is announced in advance and cannot be met using existing technologies. An example of such a technology-forcing policy is the 1975 standards in the U.S. for HC and CO emissions from internal combustion engines which was announced in the 1970 Clean Air Act Amendments (Gerard and Lave, 2005). It should be noted, however, that the regulating agency must have a high level of technological knowledge to be able to set a technology-forcing policy that is feasible.

The *focus* of an emission standard or an emission reduction standard is on the diffusion of clean technologies, and hence on the three dynamic spillovers related to adoption (learning-by-doing, network externalities, and diffusion of technology knowledge). However, by increasing the size of the market for an eco-innovation, it also provides incentives for invention and innovation (contrary to mandated technologies), yet adopters do not have an incentive to reduce emissions beyond the standard. The *scope* of an emission or emission reduction standard is rather narrow as the focus is typically on a particular sector and pollutant. Since this type of standard only provides limited incentives for invention and innovation, the *timing* of the instrument (notably phasing out) should take into account effects on and possibilities for eco-innovations that go beyond the objectives of the standard.

(3.1.3) Cap and trade programs

In a cap and trade program, an authority puts a maximum (the cap) on a particular activity, for example emissions of a harmful substance, and makes permits (also called allowances or rights) available where each permit covers a particular amount (say, one unit) of that activity. The number of permits should then cover the level of activity as prescribed by the cap. Agents that want to participate in the activity can only do so if they hand in a number of permits that is at least equal to their level of activity in a particular period (say, a year). As the name suggests, under a cap and trade program these permits can be traded amongst agents. As long as the cap is set at a level below the level of activity under business-as-usual, the program will lead to a reduction in the activity. Since the 1990s, cap and trade programs have become a popular policy instrument, for example to reduce sulphur dioxide (SO_2) emissions in the US and greenhouse gas emissions in the EU. It is a cost-effective policy instrument (achieves a given emission target at lowest costs for society) even when permits are allocated for free to agents rather than auctioned (Dales, 1968, Montgomery, 1972). Note that the activity covered by the cap and trade program need not be harmful emissions. Cap and trade programs have been used in the U.S. refinery sector to phase out lead in gasoline over the period 1982-1987 (Kerr and Newell, 2003) and to put a maximum on the level of milk produced in the EU and Canada. Cap and trade programs can be considered as behavioral quality and safety standards (see Appendix A) as they limit the level of harmful activities.

A cap and trade program for harmful emissions gives agents subject to the program a continuous incentive to assess whether they can find cheap options to reduce emissions, such that they need fewer permits. As such it provides an incentive to adopt existing clean technologies if these are expected to provide more benefits than costs. Theoretical analyses (Milliman and Prince, 1989, Jung et al., 1996, Fischer et al., 2003) find that cap and trade programs perform better on the diffusion of eco-innovations than performance standards. Popp (2003) showed that after the passage of the U.S. 1990 Clean Air Act (the introduction of sulphur dioxide emissions trading), innovators moved from reducing the operating costs of existing abatement technologies (flue gas desulphurisation units) towards improving the removal efficiency of these technologies.

An issue at hand is uncertainty about the development of the emissions price in cap and trade programs. If the price is expected to stay relatively low, there is little incentive to invest in clean technologies. Indeed, this is (or at least, was until recently) a major concern about the EU Emission Trading System (EU ETS; Brink et al., 2016). Indeed, Taylor (2012) argues that prices in cap and trade programs are usually over-estimated ex ante. These high (expected) prices initially induced adoption of clean technologies but led to a drop in adoption and innovation activities a few years after the cap and trade programs for sulphur dioxide and nitrous oxides became active in the U.S. While cap and trade systems are cheered for their cost-effectiveness, the fact that firms can apply low-cost options (such as using low-sulphur coal or fuel switching; Carlson et al., 2000) implies that they will first search for these options before applying more expensive solutions such as innovation or adoption of new technologies.

The *focus* of cap and trade programs is on reducing a particular economic activity relative to a baseline. How directly such a program addresses harmful emissions depends on the program design. For example, the damage caused by SO_2 emissions depends on the location of the emissions (contrary to CO_2 which is a uniformly mixing pollutant). Hence, the U.S. SO_2 trading programme directly addressed emissions but since it did not differentiate by location it did not directly address environmental damages. Clearly, by ensuring a market for clean technologies, these programs provide incentives for invention and innovation of new technologies and the adoption of existing ones. A cap and trade system creates a market for clean technologies and thereby supports the diffusion of existing eco-innovation and hence addresses the three dynamic spillovers related to adoption (learning-by-doing, network externalities, and diffusion of technology knowledge). By increasing the size of the market for an eco-innovation, it also provides incentives for invention and innovation. The size of the incentives for generation of new knowledge and the adoption of new technologies depend on the stringency of the cap. The *scope* of a cap and trade program is clearly program-dependent. The lead phase-out program in the US focussed on refineries in the US (one sector) and the reduction of emissions of lead by internal combustion engines (one pollutant), yet it had a global impact in terms of phasing out leaded gasoline. The EU ETS covers a range of sectors and multiple greenhouse gases and thereby about half of the EUs greenhouse gas emissions. In terms of *timing*, experience with Phase I of the EU ETS has shown that a test phase can be very useful when designing a cap and trade program (Ellerman et al., 2010), and that regularly updating the cap and the announcement of the future development of the cap affect market expectations and thereby the incentives for eco-innovation (Koch et al., 2016).

(3.1.4) Environmental taxes

Taxes as environmental policy instruments vary widely in their focus and in their scope. Although the environmental problem addressed is often clear, such taxes vary in how direct they address it. For example, an electricity tax (a tax per kWh electricity produced or consumed) is much less direct in reducing harmful emissions than a carbon tax. Still, a pollution tax can only directly address a pollutant if emissions can be measured and the tax can be monitored: a waste tax per kilogram is not directly aimed at a particular pollutant, yet when the tax exempts specific types of waste (glass, plastic) it can both reduce harmful emissions (as less waste is being burned) and support recycling of resources.

A carbon tax is cost-effective and at the global level outperforms cap and trade programs as a policy instrument in the case of uncertainty about the marginal abatement costs of firms and the global marginal benefits of emission reductions (Pizer, 2002). Like a cap and trade system, a carbon tax provides continuous incentives for firms to develop and adopt emission reducing technologies as long as their marginal costs are lower than the pollution tax. Theoretical analyses (Milliman and Prince, 1989, Jung et al., 1996, Fischer et al., 2003) find that emission taxes perform better on the diffusion of eco-innovations than performance standards. However, their relative performance vis-à-vis cap and trade schemes is less clear (Requate, 2005). A major advantage of an emissions tax over a cap and trade program is the constant marginal benefits of emission reductions that stem from a tax. This avoids the potential uncertainties for innovators and polluting firms that may stem from low or volatile emissions prices under a cap and trade program. Several studies (e.g. Popp, 2002; Aghion et al., 2016) find a positive effect of oil prices on U.S. energy efficiency patents for the automobile sector, which suggests that fuel taxes induce eco-innovations.

The *focus* of an environmental tax is on reducing emissions. How directly the tax reduces emissions depends on its design (e.g. an electricity tax vs a carbon tax). Also, the *scope* of an environmental tax clearly depends on its design, as well as on its level. It can be very broad, such as a tax on greenhouse gas emissions (expressed in CO_2-equivalents) or very narrow, such as a tax on coal that exempts coal for power plants. A high tax rate obviously has a larger effect than a low tax rate. The extent to which the dynamic spillovers are addressed also depends on the design of the tax. As with a cap and trade system, an environmental tax creates a market for clean technologies and thereby supports the diffusion of existing eco-innovation and hence addresses the three dynamic spillovers related to adoption (learning-by-doing, network externalities, and diffusion of technology knowledge). However, by increasing the size of the market for an eco-innovation, it also provides incentives for invention and innovation. The size of the incentives for invention, innovation and adoption depend on the level and design of the tax.

(3.1.5) Hybrid instruments

A major advantage of a cap and trade program is certainty the environmental outcome (Weitzman, 1974). However, as noted above, uncertainty about the price level of emission permits, and the commonly overestimated prices of permits ex ante, may lead to less investment in innovation and diffusion of eco-innovations. An obvious solution to this would be to introduce price elements, such as a price floor, in a cap and trade program (Roberts and Spence, 1976, Pizer, 2002, Brink et al., 2016). A minimum emissions price gives firms more certainty about the future returns of investments in low-emission technologies as it provides insurance against low carbon prices (Wood and Jotzo, 2011).

Both the Regional Greenhouse Gas Initiative, a cap and trade program for power plants in the North-eastern United States, and the linked California and Quebec emission trading programs have a reserve price or price floor. In both systems this minimum price has been binding at several auctions.

(3.2) Technology policy instruments

In section 2 we identified four dynamic spillovers: positive externalities from the generation of new knowledge, learning by doing, network externalities, and knowledge availability. In this subsection we assess the potential of technology policy instruments to improve market outcomes for these dynamic spillovers.

(3.2.1) Standard setting

Standards are outcomes (products) of standardization processes. Most standards are the outcome of market processes, without government intervention, and are set by firms or standards-writing organizations (e.g. the American National Standards Institute (ANSI) and the German DIN). According to David and Greenstein (1990), various reasons exist for intervention in the standardization process by government. Government may perceive that the result of some standardization process affects important national goals such as domestic employment or defense capabilities, or conclude that voluntary standardization leads to a result that threatens competition, or a lack of internalization of an externality, for example a network externality or environmental externality. Finally, publicly available standards have typical public good characteristics. The setting and writing of a standard involve a sunk cost, while the gains cannot be fully appropriated as the standard can be accessed by other firms. As a consequence, ‘open’ standards tend to be under-supplied by the market.

In the context of eco-innovations and the dynamic spillovers identified in section 2, network externalities may be a motivation for government to intervene in the standardization process. For network technologies, compatibility of devices is an important issue. When multiple specifications for plugs and sockets for plug-in electric vehicles are available, a consumer runs the risk of not being able to charge her car at a given charging station. This reduces the likelihood of adopting the technology. Government intervention may then be necessary to limit the number of available specifications, perhaps even to one, in order to prevent a potentially superior technology (vis-à-vis existing technologies) from failing (Katz and Shapiro, 1985, David, 1987).

The *focus* of government intervention in the standardization process is typically on a network externality and the diffusion of a particular technology. While it directly addresses this dynamic spillover, its *scope* is very narrow as it aims at a particular technology. Still, intervention in the standardization process can be an important *complement* to other policy instruments for eco-innovation.

(3.2.2) R&D Subsidies

The generation of new knowledge through innovation generates positive externalities. Since knowledge has public goods characteristics, others can benefit from a firm's eco-innovation while the latter bears the full cost. As a result, the market provides too little new knowledge from the perspective of society. Government support for R&D through subsidies (either to firms or through funding of universities or through government R&D) can improve market performance. Such subsidies (which can take the form of tax credits) can be general subsidies for basic research, or be dedicated to particular areas, such as energy, or even a specific technology such as solar energy for electricity production. Johnstone et al. (2010) find that, relative to a mandate to provide renewable energy, R&D subsidies for renewable energy induce innovating activities in novel technologies (as reflected in the number of new patents) that are relatively far from being competitive with traditional energy technologies.

An important question is whether the government knows better which technologies to invest in than the market does. As general R&D subsidies support the level of innovation, but not its direction, a subsidy aimed at a particular technology bears the risk of selecting a technology that the government may think is the best bet ('picking winners') but stifles the development of alternative and potentially better technologies.

The *focus* of R&D subsidies is on invention and innovation. The exact design of the subsidy determines its *scope*: a generic R&D subsidy (e.g. a tax credit for labour costs for R&D staff) has a very broad scope, whereas a subsidy for a specific technology (e.g. carbon air capture) has a very narrow scope.

(3.2.3) Diffusion subsidies

A well-known government technology policy in the field of the transition to a low-carbon economy is a subsidy that supports the diffusion of eco-innovations. The renewable energy subsidies that are and have been employed in various countries are a prime example of a diffusion subsidy. Notably the German Renewable Energy Sources Act has been very successful in accelerating the installed capacity of wind power and solar photovoltaics (see e.g. Frondel et al., 2010).[1]

Wind and solar energy are believed to be technologies with learning effects, as costs per unit are observed to be declining with cumulative installed capacity (McDonald and Schrattenholzer, 2000). As such eco-innovations are competing against incumbent, usually mature technologies, eco-innovations may have a cost-disadvantage due to lack of scale. Commercial production decisions for eco-innovations will not take into account the positive dynamic spillover on future production costs, so a subsidy for the adoption of the eco-innovation can improve market performance.

Commercial R&D activities are positively affected by the size of the potential market for the new technology (Acemoglu, 2002, Acemoglu et al., 2012). Diffusion subsidies support the expansion of the market for an eco-innovation. The effect of such subsidies on R&D may depend on whether the technology that is subject to R&D is related to the technology supported by the subsidy. For example, if R&D takes place for a technology that is an improvement of an existing technology (e.g. improved glassing for houses, or improved batteries for electric vehicles), then a diffusion subsidy for the underlying technology (home insulation; electric vehicles) can support commercial R&D activities. However, the R&D activity might be aimed at a rival technology. A non-differentiated diffusion subsidy typically supports the adoption of technologies that are close to market (Johnstone et al., 2010). Hence, a non-differentiated tax advantage for electric vehicles may have a stronger effect on the adoption of PEVs, for which a larger charging network exists, than on the adoption of fuel cell electric vehicles FCEVs. As a consequence, such a subsidy may lead to improved incentives for commercial R&D for plug-in electric vehicles but diminished incentives for R&D aimed at fuel cell electric vehicles.

As noted above, a technology neutral diffusion subsidy will especially support the diffusion of technologies that are closest to market. A neutral diffusion subsidy may lead to the smallest ‘bang for the buck’ in terms of supporting learning effects when it accrues to technologies that have a small learning effect due to the existing scale of deployment. The German subsidies for renewable energy production were differentiated by technology with the largest subsidy per kWh for solar PV, the technology with the largest distance to market.

PEVs and FCEVs are technologies that suffer from network externalities: the utility derived from a vehicle (a piece of software) depends on the availability or expected availability of charging stations for that vehicle’s underlying technology (hardware), yet the availability of charging stations will depend on the number or expected number of vehicles that use that technology. As a result, expectations on both sides of the market will have an important effect on the eventual market equilibrium: a technology may fail to take off or become abandoned, it may become a dominant technology, or it may co-exist with other technologies (Katz and Shapiro, 1985). In the former case, consumers will be stuck with an ‘orphan’ technology (David, 1987). This may happen with one or more of the competing technologies for electric vehicles (PEV, FCEV, EV with battery exchange). The current dominant

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[1] As argued in section 3.1.6, this does not mean that it was successful in reducing global greenhouse gas emissions, or doing so at low costs.

technology in the market for vehicles is the internal combustion engine, which has a global network of charging stations. Large-scale diffusion of alternative fuel technologies will require large investments in a network of charging stations. While a transition to a low-carbon economy will almost certainly lead to widespread support for electric vehicles – and result in phasing out of the internal combustion engine – it is yet unclear whether multiple EV technologies can co-exist or that one technology will become globally dominant. Given the high sunk costs involved in the development of a charging network and given that increased network density induces further adoption of the related EV technology, it might be inefficient for multiple technologies to co-exist. As in the case of renewable energy, a generic diffusion subsidy for electric vehicles may support the technology closest to market, whereas technology-specific subsidies bring the risk of 'picking winners' by the government.

The *focus* of a diffusion subsidy is primarily on learning and network externalities. At the same time, by increasing the scale of the market for eco-innovations, such a subsidy can indirectly support R&D activities and thereby indirectly address positive externalities from the generation of new knowledge. Finally, a diffusion subsidy supports the availability of technology knowledge: as adoption of a new technology increases, knowledge about the technology spreads, which mitigates potential imperfect diffusion of technology knowledge.

The *technological scope* of a diffusion subsidy depends on the design of the subsidy. It can target a very specific technology or it can be designed to be more generic and target a range of technologies. The *environmental scope* is usually rather narrow: typically only a small part of an environmental externality is covered by a diffusion subsidy.

(3.2.4) Government purchases

An alternative way for government to support the diffusion of eco-innovations is by mandating the purchase of such technologies by government agencies. Corts (2010) analysed the response of gas stations to an increase in the number of government flexible fuel vehicles. Such vehicles can operate on E85, a fuel that consists of 85% ethanol. Corts (2010) finds that government purchases of flexible fuel vehicles support the diffusion of a distribution infrastructure for E85 and that one E85 station is added for every 100-170 government FFV vehicles.

The *focus* of mandatory government purchases is on the diffusion of a particular technology and hence on the dynamic spillovers of learning by doing, network effects and the diffusion of technology knowledge. Government purchases address these dynamic spillovers very *directly* by directly supporting the diffusion of the technology. The *technological scope* of the instrument is clearly very narrow. The *environmental scope* is rather narrow as typically only a small part of an environmental externality is covered by mandatory government purchases of a particular technology. Still, the results of Corts (2010) suggest that such alternative fuel vehicle mandates can act as a *complementary* policy instrument to other instruments, if these instruments insufficiently cover the positive externalities from learning by doing, network effects and the diffusion of technology knowledge.

(3.3) Complementarity and interaction of policy instruments

Since eco-innovations suffer from multiple market failures (an environmental externality and at least one of the dynamic spillovers), multiple instruments are needed (Tinbergen, 1956). Hence, a portfolio of instruments can be created in which an environmental policy instrument addresses the environmental externality and at least one technology policy instrument addresses the relevant dynamic spillover(s). Indeed, such an instrument portfolio generally reduces emissions at lower costs than a single policy instrument (e.g. Fischer and Newell, 2008).

The practice of climate change mitigation policy in the EU shows that multiple instruments are being used simultaneously (Helm, 2009). The EU ETS covers about half of the EU's greenhouse gas emissions and focusses on the power sector, industry and non-industrial firms with high emissions (e.g. hospitals with a combined heat and power (CHP) plant). Emissions from other sectors (smaller firms, transport, households) are covered by domestic policies of member states. Although in principle this design is not cost-effective (Helm, 2009), it does not lead to an interaction that mutes the effectiveness of either instrument. However, on top of these environmental policy instruments, member states have domestic policies to meet EU targets for renewable energy generation and energy saving. The main instruments to meet these policies are diffusion subsidies for renewable energy and energy saving technologies. These instruments interact with the EU ETS: an increase in the amount of renewable energy produced implies a reduction in demand for energy from fossil fuels (ceteris paribus) and hence a reduction in the demand for emission allowances by the power sector. These allowances will then be sold and used by other firms, resulting in a lower price for emission allowances but not in a reduction in emissions ('waterbed effect'; see e.g. Böhringer et al., 2009, Van den Bergh et al., 2013). Obviously, when overlapping instruments lead to lower allowance prices, the incentives to invest in innovation and adoption of eco-innovation are mitigated.[2]

This example shows how the introduction of a new policy instrument for eco-innovation (e.g. a subsidy for the adoption of a clean technology such as wind power) can reduce the incentives for R&D and the adoption of clean technologies that come from another instrument (e.g. a cap and trade system).

(4) The international context

In this section we discuss the role of the international environment for the choice of policy instruments in Austria. Austria is a small open economy in which many technological and economic developments are driven by foreign (including European Union) forces and policies.

In terms of environmental policy instruments, Austria should address its domestic environmental problems with domestic environmental instruments. Indeed, the subsidiarity principle of the European Union implies that international environmental problems to which Austria is subject, such as climate

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[2] In February 2018, the European Parliament adopted new rules regarding the EU ETS. In the EU ETS firms are allowed to hold unused allowances for future use (banking). Currently, there are between one and two billion banked allowances (e.g. Brink et al., 2016). Following the new regulations, starting in 2023 some banked allowances will get permanently cancelled (the total number being cancelled is endogenous), reducing the aggregate supply of allowances. As a result, the 'waterbed effect' described above will temporarily disappear but come back gradually over time (Perino, 2018).

change, are addressed at the EU level, whereas domestic problems should be addressed domestically. As is clear from section 3, the environmental policy instruments may affect the dynamic spillovers but should primarily address the environmental externalities.

The fact that Austria is a small open economy affects its scope to deal with each of the dynamic spillovers. A general observation is that such an economy might be more dependent on developments in other countries than large economies would be, due to its potentially limited role in the value chain of a sector. For example, Austria has a strong automotive sector in terms of size and relative export position (Vogel and Geiger, 2019) that exports most of its products to downstream manufacturers in Germany. Hence, the scope for the Austrian automotive sector to develop eco-innovations depends on the demand for such innovations in Germany. If the German automotive sector is more conservative and focussing on the internal combustion engine, the scope for the Austrian automotive sector to develop EV technologies and the scope for the Austrian government to support these is rather limited. Still, being a small open economy also offers opportunities. If, for example, a hydrogen production sector develops in Germany, Austria can benefit by supporting a shift by industry from fossil fuels to electricity by using German hydrogen.

Positive externalities from the generation of new knowledge, the first dynamic spillover identified in section 2, are sufficiently general to warrant a general policy instrument such as a generic national R&D subsidy. Technology- or sector-specific R&D subsidies may be harder to justify from an economic perspective, but could be motivated by industry policy objectives (e.g. supporting Austria’s strong automotive industry).

The benefits from the positive externalities from learning by doing largely accrue to the countries with a large share in the production of the particular technology. As Frondel et al. (2010) point out, the German subsidies for renewable energy production induced a large expansion of the installed capacities of wind and solar photovoltaics (PV) in Germany. However, since Germany is a net importer of these technologies, the benefits of lower per-unit production costs largely accrued to exporting countries such as Japan and China. Hence, it depends on the relative export position of a sector whether policies aimed at diffusion of a particular technology (e.g. subsidies or government purchases) largely benefit domestic or foreign producers. Still, from a global perspective it might be optimal for the Austrian government to provide diffusion subsidies for learning by doing.

The third dynamic spillover concerns network externalities. Network technologies may spread beyond the borders of a small, open economy. To take the example of the EV: if Austria supports the development of a charging network for FCEVs whereas other countries (notably neighbouring Germany) support the development of a charging network for PEVs, Austrian consumers cannot travel by car (much) beyond their national borders. Indeed, since car producers benefit from economies of scale in production, they will produce EVs that possess the dominant EV technology. As a result, Austrian consumers could end up with an orphan technology. Hence, international (policy) developments are especially relevant for domestic policies towards network externalities.

The fourth dynamic spillover concerns the diffusion of technology knowledge. The policy instruments for this spillover could be the same as for the other dynamic spillovers that concern technology diffusion. However, imperfect diffusion of technology knowledge can be a domestic policy issue to a larger extent than the other spillovers as technology knowledge diffusion might largely stop at the border. Hence, even for a small, open economy, policies aimed at the diffusion of technology knowledge can be welfare improving. However, as noted in section, 2, the size of this market failure is unclear.

(5) Instrument design for eco-innovations: an evaluative framework for policymakers

The process of eco-innovation suffers from four dynamic spillovers: positive externalities from the generation of new knowledge, learning by doing, network externalities, and the diffusion of technology knowledge. A range of environmental policy instruments and technology policy instruments exists that can be used by policymakers to support eco-innovation. However, as argued in section 3, each instrument has a different focus, the scope of the instrument depends on its design, instruments can be complements or substitutes, and instruments may require a particular time path of phasing in or out. In addition, the international context matters, especially for the first three dynamic spillovers. Based on the previous sections, we present an evaluative framework for policymakers that should support their decisions regarding the implementation of policy instruments for eco-innovation. This evaluative framework consists of five questions:

1. What should be the *focus* of the instrument?

That is, which dynamic spillover (and environmental problem) should the instrument address, and how directly should it address this spillover? As argued in section 3, both environmental and technology policy instruments can affect some of the dynamic spillovers to some extent, yet the focus of the instruments may differ. Hence, it matters whether the policymaker would like to address the positive externalities from new knowledge through generic R&D support or address the learning externality of a new technology through the support of the diffusion of the technology. Importantly, the focus of the instrument can be affected by the international context, as explained in section 4. Furthermore, if the policymaker has a particular technology in mind, the technology readiness level of that technology and the presence or absence of network externalities will affect the focus of the instrument. Once the policymaker has answered this question, (s)he can assess the pros and cons of each instrument for the desired focus. The preliminary instrument descriptions in section 3 provide some first insights in the focus of existing instruments.

2. What should be the *scope* of the instrument?

Here we distinguish (a) the *technological scope*: and (b) the *environmental scope*. For the technological scope the question to be answered is: should the instrument be generic towards technologies and sectors or should it focus on one specific technology or sector? International value chains and networks should be considered. For the environmental scope the question is: how much of the environmental externality should be covered by the instrument? For example, the environmental scope of the EU ETS is much broader than that of an adoption subsidy for energy efficient appliances, while a scientific research grant for air carbon capture has a more narrow scope than a generic R&D subsidy. In case of a pollution tax, the base of the tax determines its scope: the more exemptions are awarded to particular sectors or goods (e.g. a carbon tax that exempts coal for electricity production), the smaller the tax base and the more narrow the scope of the instrument. Again, once the policymaker has answered this question, (s)he can assess the pros and cons of each instrument for the desired scope using the preliminary instrument descriptions in section 3.

3. What are existing instruments (including international ones) and how do they potentially *interact* with a potential new instrument?

An existing policy instrument may negatively affect the effectiveness of a newly proposed instrument. The best-known example is perhaps the waterbed effect resulting from the interaction between the EU ETS and subsidies for the adoption of renewable energy technologies described in section 3. Furthermore, adjusting or abolishing existing instruments may improve the effectiveness of a new instrument or make it abundant. For example, an instrument that supports the shift from private road transport to public transport may benefit from abolishing subsidies for commuting by car.

4. Can multiple instruments form a portfolio of *complementary* instruments without inefficient interaction?

Since eco-innovations suffer from multiple market failures (an environmental externality and at least one of the dynamic spillovers), multiple instruments are needed (Tinbergen, 1956). The next question, then, is whether the proposed instrument and the existing instruments can form a portfolio of complementary instruments without inefficient interaction. Indeed, answering this question should also answer the question of the necessity of a new policy instrument.

5. What should be the *timing* of the instrument or instrument portfolio?

Finally, if a particular instrument has been decided upon, its time path can be assessed. Should it be announced in advance? Should it have a testing phase? Or should it be implemented as soon as possible? And should the instrument be assessed on a regular basis, or, in the extreme: should the law that introduces the instrument have a sunset clause? As noted in section 3, spillovers from learning by doing appear to decay quickly, hence an instrument aimed at this dynamic spillover should be used temporarily, both to protect the government budget and to create a level playing field for competing technologies.

(6) Applications of evaluative framework

In this section we present two case studies as initial tests of the evaluative framework developed in section 5. We first apply our framework to the buildings sector in Austria. We subsequently apply it to the Austrian transport sector. The objective is to develop (preliminary) policy packages, based on the framework presented in section 5 and the information in earlier sections. It is important to note that a full application of the framework requires much more detailed knowledge about the sectors and technologies involved.

(6.1) Buildings sector

Austria's buildings sector emitted 10.1% of the country's greenhouse gas emissions in 2016 (Anderl et al., 2018). The main sources of final energy use in the sector are electricity (30%), biomass (19%), natural gas (18%), district heating (16%) and mineral oil (13%). Note that energy from electricity and district heating do not cause emissions in the buildings sector, but rather in the energy sector and industry, respectively. Energy consumption from electricity and district heating is still growing.

Sporer (2019) provides an overview of both the environmental policy instruments that are relevant for energy use by and greenhouse gas emissions from the buildings sector and of the technology policy instruments that are specific for the buildings sector. We discuss the ones that appear to be the most relevant, as presented in Sporer (2019), below.

Perhaps the most important policy instruments for eco-innovation for the buildings sector are building codes. Part of these building codes are aimed at energy savings and thermal insulation and can be considered emission reduction standards (a command and control instrument). Building codes are the responsibility of the federal states. However, since 2007, state-level thermal insulation standards (that define minimum standards for the level of insulation of building components) have been surpassed by national OIB (Österreichisches Institut für Bautechnik) guideline 6. Since then state-level building codes have focussed more on energy performance standards. These define maximum values for energy demand of an entire building for new buildings and buildings that are subject to comprehensive renovation. By their design, both the thermal insulation standards and the energy performance standards support the diffusion of existing technologies. The extent to which they support new innovations depends on the dynamics of standards-setting by the government. It should be noted that the OIB guidelines largely follow from EU directives.

The Wohnbauförderung (Housing Support Scheme) is a state-level policy that subsidizes construction of new buildings. It co-funded about 75% of housing permitted for construction in the early 2000's (Streimelweger, 2010). The scheme combines the subsidy with a standard as it puts the subsidy conditional on (among other things) minimum energy performance standards. In recent years, subsidized gross floor space has declined while the main measures are aimed at refurbishment and support for energy systems. Like the OIB guidelines, the Wohnbauförderung supports the diffusion of existing technologies, while the extent to which they support new innovations depends on the dynamics of standards-setting within the scheme.

The Domestic Environmental Support (Umweltförderung im Inland) is aimed at increasing energy efficiency and reducing emissions (not only for the buildings sector). It provides adoption subsidies, for example for biomass heating projects, and for renovation activities of private households.

Austria has several environmental taxes that are relevant for the buildings sector. Taxes are imposed on the supply of electricity, natural gas, and mineral oils and are (partly or fully) passed on to consumers. These taxes are indirect taxes. The electricity tax incentivizes consumers to reduce their electricity consumption. The other taxes may induce a shift from dirty to cleaner fuels, depending on the exact rates. Figure 12 in Sporer (2019) suggests that rates per kilogram of CO_2 are higher for mineral oils than for natural gas.

The Green Electricity Subsidy is aimed at increasing the share of electricity from renewable sources. Most relevant for the buildings sector are subsidies for CHP plants that provide public district heating (and ensure energy savings and emission reductions as compared to separate heat and electricity production) and subsidies for solar PV panels. The subsidy has an environmental objective and effectively supports the diffusion of existing technologies.

Whereas Austria is a small open economy, the buildings sector is typically a domestic and rather sheltered sector. Components and technologies used in construction and renovation may be imported. The extent to which this is the case, may affect the effectiveness of diffusion policies. Most importantly, many policies implemented in Austria (e.g. OIB-guideline 6) are derived from EU directives.

With this information, we now answer the questions posed in the evaluative framework in section 5.

1. What should be the *focus* of the instrument?

The first dynamic spillover concerns positive externalities from the generation of new knowledge. This is a general market failure that is presumably covered by general technology policy instruments. The relevance of the spillover of learning by doing will depend on the technology at hand and policy instruments that address this spillover focus on diffusion. Austria has several policies available that support diffusion of technologies. Some of these policies, e.g. building codes, will require regular updates to allow for the inclusion of recent technologies. Network externalities, the third spillover, seem to be relevant for the electricity network as network owners may need to upgrade local electricity networks to facilitate local fluctuations in supply of (e.g. through solar PV) and demand for (e.g. through electric vehicles) electricity. This issue appears not to be covered by existing instruments. Finally, the diffusion of technology knowledge seems to have relevance for two groups. First, firms in the construction and installation sectors who build, offer and install buildings and technologies that are subject to technological change. These firms should be informed about the latest available technologies and their pros and cons, including technologies that have been invented abroad. Whereas knowledge diffusion within the sector will typically occur through trade journals, government may still want to organize technology seminars or use other information instruments to inform key stakeholders about the latest (international) technologies. The second group concerns home owners and tenants. As this group is very diffuse and typically does not have its own specific information sources for new technologies in the buildings sector, an information instrument, such as public advertisement via TV and social media, might be useful.

This brief discussion of the first question in the evaluative framework suggests that, for the buildings sector, the dynamic spillovers discussed in this document are largely covered by existing policy instruments. Points of attention might be the existing electricity network (especially at the local level), regular updating of command and control instruments (e.g. building codes) with the latest technological insights, and availability of information about the latest technologies for firms and households.

In the remainder of this subsection, we focus on the hypothetical arrival of a new thermal insulation technology.

2. What should be the *scope* of the instrument?

In case of a new thermal insulation technology, the *technological scope* of the instrument could be the particular technology itself, or it could be aimed at the broader set of technologies for thermal insulation. The *environmental scope* in this case would be determined by the technology itself: energy use by buildings. The answer to the first question has shown that instrument design can focus on existing instruments. Indeed, existing instruments (notably OIB guidelines, the Wohnbauförderung and Umweltförderung im Inland) could be adjusted such that they support the adoption of the new technology. Such adjustments could involve the reduction of U-values (which would not be feasible, or not feasible at reasonable costs, without the new technology) or the extension of the list of technologies that qualify for a subsidy with the new technology. Furthermore, information programs for the sector and/or households might need to be developed or adjusted.

3. What are existing instruments (including international ones) and how do they potentially *interact* with a potential new instrument?

The texts above provide an overview of relevant instruments: OIB-guidelines, the Wohnbauförderung, Umweltförderung im Inland and information programs. The answers to the first two questions suggest that the only new instrument that may be needed is an information program for firms and households. In addition, existing instruments may need adjustment. Existing instruments need to be checked for their interaction. For example, both the OIB-guidelines and the Wohnbauförderung aim at new buildings. To what extent is there inefficient overlap of instruments?

4. Can multiple instruments form a portfolio of *complementary* instruments without inefficient interaction?

Above, multiple instruments were identified as relevant: OIB-guidelines, the Wohnbauförderung, Umweltförderung im Inland and information programs. These instruments need to be scanned for their complementarity: to what extent do they target different user groups (e.g. firms vs household; renovation vs new construction)? If the answer to the previous question suggests that there is partial inefficient overlap between OIB-guidelines and the Wohnbauförderung, can these instruments be redesigned in such a way that they target different user groups?

5. What should be the *timing* of the instrument or instrument portfolio?

The policy instruments proposed are existing instruments, except possibly for information instruments. Since an information instrument is neither novel nor complicated, a test phase is not required: all instruments can be implemented as soon as they are available. However, all instruments would need to be regularly assessed as newer, better technologies may arrive over time.

In sum, the existing policy instruments for diffusion of eco-innovations in the buildings sector seem to be well-designed and probably only need updating with the latest technologies. Perhaps the introduction of an information instrument, insofar it does not yet exist, may be required.

(6.2) Transport sector

The transport sector has a large share in Austrian greenhouse gas emissions. A modal shift from road transport (which is largely based on the internal combustion engine, probably for at least another decade) to rail transport (which is largely electrified) could, given the large share of hydro-energy-based electricity production in Austria, contribute to a reduction in emissions from the transport sector. This modal shift could apply to both transport of passengers and transport of goods. Based on Williges and Dugan (2019), three technologies were identified at a SHIFT project meeting in May 2019 that could contribute to this modal shift. The first one was the use of light-weight material, which would reduce both energy consumption and noise and thereby make rail transport more attractive. The second was electrification of the last mile by using hydrogen- or battery-driven locomotives: in many areas in Austria, diesel trains are used on the last part of the railroad track as electric trains cannot be used due to the absence of overhead lines. The third one was digital technologies for position detection of freight wagons.

Williges and Dugan (2019) provide an overview of existing policies for the Austrian rail transport sector. The Anschlussbahnförderung provides subsidies for investments in initiatives that strengthen transport of goods and materials via rail. “Subsidies are granted for new construction, extension and renovation of connections (industry rail sidings) and freight terminals, as well as necessary loading / handling equipment used in freight terminals” (Williges and Dugan, 2019, p.3). This policy is relevant for the last mile. The Ordinance on Protection from Railway Traffic Noise imposes binding noise limit values on rolling stock. Here it should be noted that, being a small country, a considerable amount of rolling stock comes from outside Austria, passing through to other countries. Finally, rail routes in Austria have stipulated weight limits for varying line classifications and speeds. For lines with speeds under 120 km/h, weight limits range between 5 tons per meter and 8 tons per meter, with the vast majority of the country being serviced by lines with a maximum of 8 tons per meter.

With this information, we now answer the questions posed in the evaluative framework in section 5.

1. What should be the *focus* of the instrument?

The case for the rail transport sector outlined above focuses on three existing technologies with relatively high technology readiness levels (TRLs). Hence, positive externalities from the generation of new knowledge are not particularly relevant for this case. The dynamic spillover of learning by doing could be relevant for all three technologies. Hydrogen- and battery-driven locomotives can be considered to be network technologies: the use of such engines requires the availability of charging points, while the availability of these points will be positively affected by the use of these types of engines. Note that the two technologies (hydrogen and battery) might be competing network technologies, and there might be scope for only one technology on the market due to the high investment costs for the network of charging stations. The diffusion of technology knowledge about each of the technologies amongst rail transport companies might be an issue as well.

The three relevant dynamic spillovers identified all point towards technology diffusion instruments as a possible solution for the spillovers.

2. What should be the *scope* of the instrument?

The *technological scope* is the three technologies identified above: light-weight material, battery- or hydrogen locomotives for the last mile, and position-detection systems for wagons. Austria is considered to be a major producer of rail transport equipment (Williges and Dugan, 2019). Since in addition 'the last mile' is by definition a local issue, international policies and value chains might be less relevant, except that economies of scale will occur for producers when the domestic technology is the same as the technology used abroad. The question about the *environmental scope* is less relevant here, as the policy question regards pre-identified technologies. Given that technology diffusion instruments were identified as the relevant set of instruments, rather technology-specific diffusion instruments may be required.

3. What are existing instruments (including international ones) and how do they potentially *interact* with a potential new instrument?

The Anschlussbahnförderung provides subsidies for investments in initiatives that strengthen freight transport via rail, notably for the last mile. The instrument could be adjusted to allow for subsidies for battery- or hydrogen-powered locomotives. In addition, existing noise and weight regulations could be adjusted to limit the weight of the rolling stock and the noise produced. However, direct regulation may be problematic considering the large amounts of foreign rail transport through Austria. Additionally, the EU has developed an intricate set of regulations for passenger and freight railways, the Technical Specifications for Interoperability (TSIs), which could lead to conflicting regulation between the two governance levels.

Alternatively, heavy transport vehicles can be considered as causing a negative externality to society (as it requires more energy generation than lighter vehicles). Existing rail pricing schemes could be adjusted to more closely reflect a Pigovian pricing system, where rail use is priced by a charge per ton per kilometre. Such a system would not only induce both foreign and domestic wagon owners to switch to lighter wagons, it would also generate income for the owner of the railway network instead of requiring tax money for the subsidy.

4. Can multiple instruments form a portfolio of *complementary* instruments without inefficient interaction?

The relevant dynamic spillovers identified under question 1 all point towards diffusion of the technology as the major bottleneck. A single instrument, for each technology, that supports this diffusion would then be sufficient. For hydrogen- or battery-powered locomotives on the last mile this could be an adjusted version of the subsidies provided via the Anschlussbahnfördering. For light-weight vehicles, the policy instrument could be the Pigovian pricing system outlined under 3. For digital technologies for position detection of freight wagons a new instrument (e.g. an adoption subsidy) might be needed.

5. What should be the *timing* of the instrument or instrument portfolio?

The Anschlussbahnförderung is an existing instrument that would only require adjustment to account for locomotives. The Pigovian pricing system would be novel and require careful design and implementation. An adoption subsidy for digital technologies for position detection could be developed and implemented rather quickly. The subsidy instruments would need to be regularly assessed as the dynamic spillovers identified tend to be only temporary.

In sum, support for a modal shift to rail transport via support for light-weight vehicles, position-detection systems and electrification of the last mile (battery- or hydrogen-based locomotives) could be realised by adjusting the existing Anschlussbahnförderung to support the diffusion of zero-emission locomotives. For light-weight vehicles, an alternative instrument would be a Pigovian pricing system for rail use by charging per weight-kilometre, while for digital technologies for position detection of freight wagons a new instrument (e.g. an adoption subsidy) might be needed

(7) Conclusion

New technologies and processes that mitigate an environmental problem suffer from at least two market failures. The first one is the environmental externality, the second comes from the process of technological change. Here, we identified four dynamic spillovers: positive externalities from the generation of new knowledge, learning by doing, network externalities, and the diffusion of technology knowledge. Hence, for eco-innovations, at least two policy instruments are needed.

In this paper, we have presented a wide array of environmental and technology policy instruments. We have sketched their contribution to each stage in the process of technological change and concluded that, for most instruments, this will depend on the exact design of the instrument. We have then looked into four characteristics of the instruments: the focus of the instrument, its scope, its timing, and interaction with other instruments. From this overview, we then derived an evaluative framework for policymakers for designing a policy instrument for an eco-innovation.

There are two logical follow-up steps that can be taken. The first one is a more complete and deeper overview and understanding of the policy instruments – one that goes deeper than what is presented in section 3. This more elaborate overview can then be used by policymakers when using the evaluative framework to design policy instruments. The second follow-up step is to test the evaluative framework using one or two concrete policy problems.

Acknowledgments

This project is supported with funds from the Climate and Energy Fund and implemented in line with the ACRP (Austrian Climate Research Program).

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Appendix A: A classification of standards

As noted in section 3, we follow David (1987) by not only distinguishing technical from behavioral standards, but also by making a distinction between standards in relation to the specific role they play in society. The first type of standards guarantees commensurability by setting uniform units of measurement or reference, like currencies and weights. The second type sets explicit targets by requiring minimum quality and safety levels. Finally, the third type of standards focuses on interface compatibility. We summarize the different types in Table 1. Note that many standards have multiple functions and that most standards also convey information (see Tassey, 2000). In the next subsections we discuss each row of Table A1.

Table A1: A taxonomy of standards

	Standards of technical design	*Standards of behavioral performance*
Standards for measurement, reference, and definition ensuring commensurability of data	- currencies, weights, measures - chemical properties - dimensions of materials and products	- professional licensing - accreditation of institutions - precedents in law - audit standards - Environmental Technology Verification systems
Minimum quality and safety standards	- safety levels (system) - safety features (component product) - product quality - environmental technology standards	- legal codes - job qualifications - certification of competence - emission (intensity) limits
Standards for interface compatibility	- physical design of interfaces - screw threads - signal frequencies - A4- and letter-sized paper - freight containers - GSM - data formats (e.g. MP3)	- contractual forms - diplomatic protocols - vernacular languages

Source: David (1987)

A.1 Standards for measurement and reference

Standards for measurement and reference are established for use as rule or basis of comparison. Indeed, 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).

Measurement and reference standards can also come in the form of behavioral standards. For example, (local) governments can require firms to obtain a license before being allowed to work with particular hazardous goods such as particular toxics. This also informs the firms' neighbors and customers that the firm is able to handle the toxics in a safe way. Obviously, this requirement also serves as a minimum safety standard (see below), which reflects the fact that standards often fulfil multiple functions. The accreditation of an institute is another example of a behavioral standard, since it guarantees commensurability across different institutes with certain qualities and characteristics of the (employees of the) organization.

For eco-innovators, measurement and reference standards help to signal the superiority of their innovation. As an eco-innovation results in a reduction of environmental impact, this improvement needs to be measurable and demonstrable. If an innovator claims that it has developed a car engine that requires less fuel, it needs to be shown that it can deliver the same qualities (horsepower, acceleration power, noise level, etc.) with lower energy use. Similarly, governments can use information standards as an environmental policy tool, such as the labels of the Energy Star program in the US, or the EU Energy Labels which rank the energy performance of consumer durables like refrigerators based on their energy use. The lack of relevant and rigorous metrics for comparison of the performance of electric vehicles was until recently seen as an obstacle to mass deployment of electric vehicles (OECD, 2011).

A.2 (Minimum) quality and safety standards

Minimum quality and safety standards specify some (minimum) level or target for one or more attributes. By specifying some yardstick level for performance comparisons, these standards also convey information to the users of products that satisfy a particular standard. In doing so, quality and safety standards not only reduce transaction and search costs but, if sufficiently enforced, also damage costs by protecting third parties from negative externalities in the production or consumption of goods. In particular, regulatory standards often take this particular form irrespective of whether they apply to technical designs or behavior. For example, safety standards on technical design of children's toys make sure that toxic inputs do not exceed certain levels. In this way children's health is protected because parents usually do not know which (chemical) materials are used in the production process. The use of some products might even be forbidden altogether (e.g. DDT). Traffic rules are a clear example of a behavioral safety standard that protects traffic participants from the negative externalities from other persons' behavior.

Environmental policy standards belong to the category of (minimum) quality and safety standards. Environmental technology and product standards require that particular industrial equipment processes be employed in production or that a good satisfies particular technological requirements to reduce negative impacts from consumption. In contrast, behavioral environmental policy standards usually come in the form of performance standards. These specify maximum or minimum input or output or emission levels for particular pollutants, possibly specified in emissions per unit of (flue) gas (e.g. emission limit values like 400 S $\mu g/Nm^3$) or units per economic activity (e.g. a minimum share of biofuels). Such constraints still leave agents free to select their best option to comply with the standard and do not prescribe one specific technology. In the European Union, many environmental performance standards are accompanied with a list of technologies that meet the standard. In this way, the policy standard not only serves as a safety standard, but also as a source of information. Alternatively, the performance standard can be defined as an aggregate ceiling on the amount of emissions for a particular region, as for example with the EU Emission Trading System for greenhouse gases or the trading system for SO_2 under Title IV of the 1990 Clean Air Act Amendments in the US.

A.3 Compatibility and interface standards

The type of standards most commonly studied in the field of technological change are standards that facilitate compatibility and interfaces ('interoperability') between technical appliances (e.g. Farrell and Saloner, 1986, David and Steinmueller, 1994, Tassey, 2000, West, 2007). 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, gas or telecom network. Here delivery of the good requires a physical system of hardware that connects participants who therefore have to use technical devices that are interoperable. This interoperability is also essential for virtual networks where producers and consumers are connected using the same hardware/software system. For example, for consumers to play a video game on a game console, the games producers must provide a product that meets the requirements of the particular console. However, without a variety of games offered, the console itself is not of much use to the consumer.

As indicated in the columns of Table A1, compatibility and interface standards can apply to both technical and behavioral standards. Technical compatibility standards can be found for nearly any part of a multi-part product and any device that needs to communicate with other devices, and the benefits of these standards are not restricted to network industries. Many industries are not network industries based on the nature of their product, but still have designed their production process as a network. For example, many firms in manufacturing sectors have outsourced the production of parts of their final good to other firms, possibly in other countries. Outsourcing may bring lower production costs due to increased specialization. In order for the several parts to be compatible, the outsourcing firm must provide clear technical production standards to the producing firms. DIN (2000) reports that firms perceive that standards considerably reduce transaction costs, as standards make information available and are accessible to all interested parties.

Behavioral compatibility and interface standards often facilitate inter-personal or inter-institutional communication. This is obvious for something like a common language that facilitates communication between different groups within a community. Interface compatibility is also guaranteed, however, if legal codes follow certain standards. For instance, the contents of a contract, such as an insurance contract, often follow such a behavioral standard. The standard applies to the terms and conditions in the contract under which the insurance company is supposed to behave when, for instance, liability claims apply.

Obviously, both technical compatibility standards (e.g. the plugs and sockets used for charging the batteries of an electric vehicle) and behavioral standards (e.g. the conditions under which an investment vehicle is allowed to label itself as ‘green’) can apply to eco-innovations and serve to facilitate applications of a specific eco-innovation in particular circumstances.