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Policy for environmental innovation: a comparative review of empirical evidence from two sectors

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Abstract

Since the 1960s, governments have sought to encourage technological development to reduce pollution. These efforts now include global greenhouse emissions, especially in sectors such as transport and energy generation. A variety of means are applied: general taxes and trading systems, subsidies and technology-forcing standards. At the macro-level, economists argue that general economic instruments are a more efficient way to regulate emissions than administrative or technology-specific measures. The effectiveness of general economic instruments needs to be examined in relation to their innovation impact in different (sub-) sectors, however. This paper builds on research in the automotive and energy sectors to compare general and specific, economic and administrative, means in terms of their impact on different types of innovation. The review shows that the effectiveness of policy instruments is conditioned by the type of innovation needed (incremental, modular, architectural or radical) and the responding industrial context. General instruments ? economic and administrative ? encourage development and diffusion of incremental and modular innovation, whereas technology-specific instruments are needed to support the development and diffusion of architectural and radical low-carbon innovations. However, in order to have an effect, instruments have to be connected to a responding industrial context, i.e. networks of firms with requisite resources and capabilities to deploy. Key challenges for policy makers when choosing instruments include issues of selection, stringency, scale and stability.

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Key words: Environmental policy, innovation, energy, automotive

1. The controversies regarding general versus specific policy instruments

Government policies, from administrative standards to economic incentives, play a vital role for innovations not directly related to customer benefits, such as various types of emissions reduction. Since the 1960s, authorities in the OECD-countries and emerging economies have sought ways to encourage technological development to reduce pollution from production plants and mobile sources. More recently, global greenhouse emissions have come into focus, especially for high-emitting sectors, such as transport and energy generation. A variety of means have been applied, from technology-forcing standards or market incentives for the introduction of specific technologies, to general economic means, such as CO_2 taxes and emissions trading systems.

Economists tend to argue that economic instruments are superior to administrative, “command-and-control” measures (e.g. regulation of the emissions level for specific products or plants), and that general measures (e. g. taxes) are preferable to technology-specific ones, such as subsidies to targeted technologies (Jaffe et al., 2002). The argument is that with general, market-conforming means economic actors will make rational decisions to invest where the cost of pollution abatement is lowest, thus maintaining economic efficiency. By contrast, support of specific technologies or industries may lead to inefficient resource allocation, and to lock-in effects, as the support of one technology, which once seemed promising, crowds out other more potent technologies not envisaged at the time of the decision (OECD, 2005).

With few exceptions this debate has been concerned with economic efficiency in static (allocative) terms. The impact of different types of instruments on technology development and innovation has received far less attention. Policies that focus on achieving targets at the currently lowest possible cost tend to neglect the dynamic interplay between market formation, learning and cost reductions. They are seldom designed to compensate for the technical and commercial uncertainties related to new technology and, thus, do not support its development and diffusion.

Moreover, there is a lack of empirical studies comparing the effects of different types of policy instruments on innovation (Popp et al., 2009; Taylor, 2008). The papers referred to above are primarily based on theoretical reasoning and economic modelling and the empirical studies of policies for sustainable innovation that do exist tend to focus on one or a few instruments and are often limited to one specific sector or industry. In order to draw more general conclusions about the pros and cons of various instruments, comparisons between sectors as well as instruments are needed. In a recent broad review of empirical studies of environmental policy, Kemp and Pontoglio (2011) concluded that the context in which policy instruments are applied is important for their outcomes. This implies that a focused review comparing the effects of the same types of instruments in two different sectors would provide important input for more informed decision-making processes and policy debates.

Against this background, the purpose of this paper is to present a systematic review of empirical studies of the effects of four main types of policy instruments in two high-emitting sectors: the automotive sector and the energy sector. By comparing the outcomes of various policy instruments in different contexts, we can arrive at a richer understanding of the impact, applicability and limits of different types of policies outcomes across sectors and instruments.

2. Previous literature on the impact of different types of environmental policy on innovation

2.1 Technology-specific vs. general instruments

General policy instruments aim at increasing sustainability throughout the economy without pinpointing any particular technology (Sandén and Azar, 2005). These include taxes and cap-and-trade systems, such as the European Union Emissions Trading System (EU ETS). General instruments can also be found on lower levels of aggregation; some are aimed at a particular group of technologies (e.g. renewable energy technologies), but do not distinguish between technologies within that group. In this paper, we will treat them as general instruments.

Technology-specific instruments directly support or regulate specific technologies. They include technology-specific standards and requirements as well as various types of support to innovation: R&D funding, public procurement, and demonstration and market support.

The proponents of general instruments tend to use the efficiency argument: general instruments will achieve rapid diffusion of technology in a cost efficient way. Moreover, they argue that supporting specific technologies comes at the expense of other, potentially better technologies and implies a risk of postponing their development (cf. Popp et al., 2009).[1] Proponents of technology-specific instruments argue that general policy instruments mainly benefit close to commercial technologies that can be picked "from the shelf," whereas technology-specific policies are needed to "put technologies on the shelf" for later selection within the frame of more general policy instruments (Sandén and Azar, 2005).

2.2 Economic vs. administrative policy instruments

Economic instruments aim at providing actors with economic incentives to adopt low-emission technologies. The main principle is that investors in sustainable solutions should receive an economic compensation corresponding to the avoided social cost of pollution, or conversely be economically punished if they invest in a polluting technology. Firms are then expected to undertake pollution control efforts in their own interest (Stavins, 2003). The most commonly

[1] E.g. technology standards provide incentives to adopt the prescribed solution, but no incentives to invest further in technological innovation, in contrast to performance standards (Lee et al., 2011).

used economic instruments are emission taxes, subsidies on abatement of emissions, pollution charges, investment subsidies and tradable permits (Jaffe et al., 2002; Requate, 2005).

Administrative instruments aim at controlling the actions of firms, mainly through regulation. The most prevalent administrative instruments are different types of standards e.g. technological standards (i.e. prescription of a certain method, equipment or technology, emission standards (an absolute upper emission level), and performance standards, such as a cap on emissions per unit of output. There are also other types of administrative instruments, for example bans or prescribed use of certain solutions and permits for building and operation of plants. Whereas some of these regulations are compulsory, others are optional, i.e. firms can choose whether or not to comply, but non-compliance comes with a penalty or other negative consequences.

According to Requate (2005), most economists tend to favour "… instruments which provide incentives through the price mechanism", since this, it is argued, makes it attractive for firms to clean up more than mandated, if there are feasible technologies available (Jaffe et al., 2002; Stavins, 2003), and offers incentives for private actors to develop new and improved technologies (Sandén and Azar, 2005). On the other hand, critics argue, many markets are characterized by differentiated set of actors whose behaviours are less influenced by market prices than is presumed in general theories, for example when buyers are not the actual users or when the life-time value of a more efficient utility is much greater than the perceived value for the first customer.[2]

As for administrative instruments, it has been shown that performance and technology standards can create a pressure on firms to improve products and processes and develop new technologies to meet the requirements (Grubb and Ulph, 2002), if the standards mandate performance levels that cannot be achieved with current technologies (Jaffe et al., 2002; Popp et al., 2009). On the other hand, it can be costly for firms to develop technologies to meet regulatory standards (Lee et al., 2010), and this, it is argued, might reduce the overall means available for innovation and limit the firms to seek for 'optimal' solutions (cf. Chappin et al., 2009; Jaffe et al., 2002).

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[2] An example of the former is multi-tenant buildings, where landlords can choose inexpensive building solutions, since the tenants carry the costs of poor insulation. An example of the former is fuel-saving technologies for cars, where consumers tend to include only the savings during the first 2-3 years at the time of their buying decisions (Greene, 2010).

2.3 A combined framework

If we combine the two categorizations discussed above four main types of policy instruments can be distinguished: general economic instruments, general administrative instruments, technology-specific economic instruments and technology-specific administrative instruments (see Figure 1). The aim of this paper is to scrutinize available empirical evidence of the impact on innovation of these four policy types. As will be described in the following section, we will use a two-sector comparative approach to achieve this.

	Economic	**Administrative**
General	General economic	General administrative
Technology-Specific	Technology-specific economic	Technology-specific administrative

Figure 1: Four types of policy instruments

Kemp and Pontoglio (2011) and Demirel and Kesidou (2011) argue that there is a need to qualify the concept of innovation further when studying the effects of policy. We therefore use an innovation typology developed by Henderson and Clark (1990), which includes four types of innovations: (1) incremental innovation implies small improvements in individual components, (2) modular innovation implies substantial changes on component level (i.e. replacement of, or substantial changes in the core design concept of, one or more component/-s), (3) architectural innovation implies a reconfiguration of existing components in a new way and (4) radical innovation implies substantial changes in the set of components as well as in the product architecture.[3]

[3] Although this typology was originally developed to describe product innovations, we suggest that it can also be applied to process innovations.

3. A two-sector comparative approach

3.1 Case selection and sector characteristics

The paper builds on published research related the automotive and energy sectors, complemented with findings from the authors' current studies of innovation in the two sectors. As mentioned above, we have chosen a sector-level comparative approach because previous research has shown that the context in which policy instruments are applied is important for their outcomes (Kemp and Pontoglio, 2011).

We chose these specific sectors for three reasons. First, both are capital-intensive, high-emitting sectors, and therefore have been subject of a broad range of policies. There are, thus, plenty of examples of all four types of policy instruments in both sectors. Second, both sectors are dominated by a limited number of incumbent actors that, according to traditional economic thinking, have few incentives apart from government policies to accelerate the introduction of sustainable innovations, considering that the production and distribution of their current technologies are closely connected to existing, large-scale (and mostly paid for) infrastructures (Weyant, 2011). Third, both sectors are based on complex products which integrate a number of different components and sub-systems, some of which are complex products in themselves. Innovation can therefore take place on several different levels: on component/sub-system level, on system (architectural) level or on both.

The two sectors also differ in several important aspects, e.g. product life cycles, turnover of existing equipment, scale of production and unit costs. The energy sector is characterized by long product life cycles, slow turnover of existing equipment, low volume production of new equipment, and low operating costs per unit in existing large-scale systems. Reduction of CO_2 emissions in this sector requires technological leaps, either in the form of expensive and complex auxiliary equipment, such as the addition of carbon capture and storage (CCS) technology to existing coal burning power plants, or a switch to renewable energy technologies (the exception being the substitution of biomass for fossil fuels, a realistic option only in some countries). In the automotive industry, product life cycles are shorter, the stock of products is turned over more rapidly and mass production is the norm. Modular innovations are continuously introduced, which makes it possible to use policy means to relatively rapidly enforce new standards regarding e.g. safety or emissions. We assume that such differences can result in different patterns of innovation and policy interventions. The cases therefore complement each other, and similar patterns across sectors will strengthen the value of the observations.

3.2 Identification of empirical evidence of innovation impacts

We first searched a number of relevant journals (e.g. *Energy Policy*, *Environmental Economics, Energy Economics, Technology Analysis & Strategic Management*, *Technological Forecasting and Social Change*, *Research Policy* and *Technovation*) for papers on sustainability, innovation and policy. Based on title and abstract we sampled papers that we read in their entirety. Using references in these papers we identified other sources, using a snowballing method until no more relevant references with significant new information could be found. We also consulted recent review articles, e.g. Kemp and Pontoglio (2011) and Popp et al. (2009). To be included, papers had to be based on empirical studies of the innovation impact of some type of government policy instrument. Here we defined innovation as the stages leading up to and including commercialization of new-to-the-market inventions, new products and systems as well as refinement and addition to existing ones.[4] We included studies of innovation processes that resulted in new solutions being brought to one market, even if similar solutions were already present in other markets, but not studies of large-scale diffusion of already existing products and processes. Due to the general shortage of relevant studies, we also included some studies that use patent data, although patents are an indicator of invention than of innovation as defined above.

After categorizing the remaining studies according to our policy instruments typology, we noticed that studies of technology-specific administrative instruments in the energy field were missing entirely. We therefore made more specific key words searches in available full text databases (e.g. “BAT and innovation”), but still did not manage to identify any relevant studies. Although there are plenty of examples of, e.g., best available technology standards, there does not seem to be any evaluation of their impact on innovation.

[4] The scope of this paper is limited to *technological* product and process innovations, which means that we did not search for studies of organizational innovation without any technological component.

4. Experiences of policy influence on environmental innovation in the energy and automotive sectors

As mentioned briefly in the previous section, both the automotive and the energy sectors have a long history of policy intervention to improve sustainability. In the *automotive* sector, the US in the 1960s was the birthplace of administrative regulation to reduce emissions**.** After a period of escalating criticism of automotive pollution, and mounting political pressure (Tao et al., 2010), US Congress introduced the path-breaking Clean Air Amendment Act (CAAA) in 1970. EU started later, but in the 1990s it introduced a comprehensive framework for eliminating noxious emissions from gasoline and diesel engines, starting with the EU I level in 1992, followed by gradually tightened standards through Euro II (1996), Euro III (2000), Euro IV4 (2005), Euro V (2009) and Euro VI in 2014.[5] Similar efforts are in place or being implemented to reduce greenhouse gas emissions; in the US, the means chosen is a new Corporate Average Fuel Economy (CAFE) standard, whereas EU standards directly target CO_2-emissions from new cars. In addition, there are also a multitude of technology-specific subsidies for so-called 'clean' vehicles and fuels, such as ethanol and electric cars.

The *energy* sector has been influenced by government policies for a very long time. In this paper, we focus on the period after the oil crises in the 1970s, when public energy policy in the OECD-countries shifted focus from fossil fuels to renewable energy technologies (and nuclear power). In this period, a multitude of different policy measures have been applied to increase sustainability and energy security (cf. Norberg-Bohm, 2000). In the last two decades, two main policy trajectories have emerged. One the one hand, specific attempts to support the development and diffusion of new "low-carbon" technologies with the potential to replace fossil fuels have continued. On the other hand, general environmental policy measures, such as the European Emissions Trading Scheme (EU ETS) to reduce greenhouse gas emissions have been implemented.

In both sectors, all four types of policy instruments identified in Section 2 have been applied. Table 1 provides some examples with a focus on instruments with an ambition to support the entire innovation process from R&D, prototypes and demonstration units to more large-scale

[5] European Council Directive 98/69 relating to measures to be taken against air pollution by emissions from motor vehicles, and European Council Regulation No 715/2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles.

implementation in supported or commercial markets (Foxon et al., 2005). As described in Section 3, we have not been able to find empirical studies of the innovation impact of all these different instruments. The instruments written in italics are therefore *not* analyzed further in this section.

Table 1: Examples of environmental economic and administrative policy instruments in the automotive and energy sectors

	Economic		**Administrative**	
	Automotive	Energy	Automotive	Energy
General	▪ CO_2 tax on transport fuels ▪ *Investment subsidies, public procurement of 'environmental' vehicles*	▪ Emissions trading schemes ▪ Tradable renewable certificate (TGC) systems ▪ *CO_2 tax on energy generation*	▪ Emissions regulation (NO_x, SO and CO_2) ▪ *Renewable fuel mandates (requiring blending of renewable fuels into gasoline)*	▪ Emissions regulation for power plants (SO, NO_x) ▪ Energy performance regulation for buildings ▪ *Feed-in laws and quotas for renewable electricity*
Technology-specific	▪ Subsidies for specific alternative fuels ▪ Public procurement of specific technologies ▪ *Investment subsidies for specific technologies*	▪ Fixed tariffs for renewable electricity ▪ *Investment subsidies for specific RETs*	▪ Californian zero-emissions vehicle (ZEV) mandate	▪ *Identification of Best Available Techniques (BAT)* ▪ *Technology-specific rules for permits, land-use etc.*

4.1 *Effects of general economic instruments on innovation*

Examples of general economic instruments from the *automotive sector* include CO_2 levies and other taxes related to transport fuels. Studies of such instruments tend to focus on overall efficiency improvements rather than development and diffusion of specific technologies. In broad comparisons, the significant tax and price differences between the US and the EU have been noted, and their consequences in terms of smaller and more fuel-efficient cars in Europe. The price difference has also contributed to the refinement and a much higher penetration of diesel cars in Europe: more than 50% of the market compared to 3% in the US (cf. Berggren et al., 2009). However, price instruments have not been very effective in driving the development and diffusion of more advanced fuel-saving technologies (Greene, 2010). Based on a broad comparison of the effects of regulatory standards versus prices on automobile fuel economy, Clerides and Zachariadis (2008, p. 268) argue that: "Fuel prices do play a role in reducing fuel consumption but the price elasticity is quite small even in the long run, so that it becomes difficult to improve fuel efficiency considerably relying on prices increases alone". One problem is the issue of volatility: taxes tend to rise and fall with different administrations, which makes decision-makers inclined to discount the information provided by taxes when making purchasing or investment decisions.

In the *energy sector*, the dominant general economic instruments are CO_2 taxes on energy generation and emissions trading schemes (ETS). There are also various quasi-general instruments supporting the development and diffusion of renewable energy technology, such as tradable green certificate (TGC) systems. With regards to the impact on innovation, we will focus on the EU ETS and the TGC systems in Sweden, Belgium (Flanders) and the UK.

Emissions trading have become a favourite instrument among many macro economists on the basis of their assumed successes in cleaning up coal-fired power plants in North-eastern US in the 1980s. However, Taylor et al. (2005) found little evidence that the trading program established by the 1990 Clean Air Act Amendments induced innovation in SO_2 emissions control technologies. In Europe, the EU ETS from 2005 is currently the key instrument for reducing greenhouse emissions from power generation plants and big energy-intensive industries. It puts a cap on the allowed emissions from large, stationary greenhouse gas emitters in EU's energy and heavy industry sectors and distributes a corresponding number of allowances to the emitters. Companies that emit less than they are allowed can sell allowances to other companies. Studies of the impact of the EU ETS on innovation in power generation technologies in Germany have found that "the largest impact occurs among the most carbon-intensive technologies and among incumbents with large-scale coal power generation technologies in their portfolios. In contrast, the innovation impact of the EU ETS on low or zero-carbon mitigation options tends to be very limited" (Rogge et al., 2011, p. 520).[6] Their studies show that the EU ETS resulted in a significant increase in R&D and demonstration projects on efficiency improvements at large fossil fuel plants, focusing on new materials and components (e.g. boilers). The system also stimulated R&D and

[6] In addition the EU ETS has been criticized for being production-based rather than consumption-based, which implies a risk for carbon leakage since regulated agents can comply with the regulation either by buying allowances in the ETS or by reducing their direct emissions by, for example, outsourcing production (and in effect emissions) outside Europe (Cló, 2010).

demonstration projects on carbon capture and storage (CCS) but was not enough for encouraging market introduction. The effect on RD&D on renewables was limited and indirect, especially with regards to wind power; the EU ETS complements the existing favourable framework conditions for renewables, but did not drive e.g. wind turbine development (Rogge and Hoffmann, 2010).

Our second example of general economic policy instruments is TGC systems. These are based on a production-dependent allocation of tradable certificates to renewable electricity producers, usually combined with an obligation for power consumers or suppliers to buy certificates corresponding to a certain share ("quota") of their electricity consumption/sales (i.e. an administrative instrument). Here we will focus on experiences of TGCs in the UK, Sweden and Flanders.[7] The UK Renewables Obligation (RO) came into effect in 2002. Several studies show that the system primarily promotes land-based wind power, biomass, landfill gas and sewage gas, i.e. technologies that in the UK context can be considered "near-market technologies" (cf. do Valle Costa et al., 2008; Foxon et al., 2005). The effects on innovation in these technologies are limited and mainly in the form of learning-by-doing by global manufacturers (Foxon et al., 2005). The system does not encourage development of technologies such as offshore wind, solar photovoltaic cells and wave/tidal power, which in the UK context are seen as promising options for the future, since they are too expensive and/or too risky (Butler and Neuhoff, 2008). The Swedish electricity certificate system came into force in 2003 and, similar to the UK system, primarily benefit actors who invest in mature technologies;[8] in 2008, for example, 70% of the renewable production in the system consisted of biomass-based electricity production in industrial back-pressure plants and combined heat and power (CHP) plants, thus supporting the diffusion of established technologies, whereas novel technologies find it hard to compete with these within the TGC regime (Bergek and Jacobsson, 2010). The TGC system in Flanders was set up in 2002, and the outcome is similar: Although Verbruggen's (2009) performance assessment shows that some projects were more innovative, in that they took advantage of waste flows in agriculture and industry, the author concluded that from a dynamic efficiency perspective "[t]he

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[7] For detailed descriptions of the systems, see Mitchell et al. (2006) (UK), Wood and Dow (2011) (UK), Bergek and Jacobsson (2010) (Sweden) and Verbruggen (2009) (Flanders).
[8] This part is based on Bergek and Jacobsson (2010).

predominance of bio-waste conversion and of the role played by incumbent companies is rather worrying” (p. 1392).

4.2 Effects of general administrative instruments on innovation

Examples of general administrative instruments in the *automotive sector* include regulation of various types of tailpipe emissions (e.g. NO_x, SO and CO_2) and legislation forcing fuel suppliers to blend a certain share of renewable fuels into gasoline (e.g. the European Commission’s 10% mandate[9] and the US Renewable Fuels Standard). Here, we will focus on the innovation impact of the US Clean Air Act Amendment (CAAA) of 1970 and subsequent legislation.

As a consequence of CAAA, the Environmental Protection Agency (EPA) required industry to achieve a 90% reduction in HC and CO emissions by 1975 compared to the levels in 1970, and in the following year to cut also the allowed NO_x emissions by 90%. In 1990, the Congress took this one step further by introducing the Tier I-standard, followed in 1999 by the Tier II-level to be phased in between 2004-2009. Compared to the levels before the first CAAA, this standard mandated a reduction of HC and CO emissions of 98% and 95%, respectively. As Lee et al. (2010) show, the industry after an initial period of resistance responded by increasing its innovative efforts: overall patenting in emissions control technologies increased from virtually no patents in 1970 to almost 100 annual US patents granted in the mid-1970s. Their analysis also shows that when the stringency level was unchanged in the 1980s, the industry’s patenting efforts quickly subsided, but when more stringent standards were introduced or announced, the industry’s innovative activities increased to new heights in the 1990s. The US approach has driven a series of modular innovations that could be added to conventional vehicles without changing their basic architectures, e.g. catalyst technologies, but also generic innovations in electronic controls which laid the basis for modern engine management systems.[10]

In 2008, EU legislated restrictions for vehicular CO_2 emissions**,** with the first step (amounting to on average of 130 g CO_2 /km) to be legally implemented 2012-15. This regulation has been efficient in driving rapid development and diffusion of existing (on-the-shelf-)technologies, such as turbo charging, direct ignition, dual clutch transmission, start/stop systems and more advanced

[9] Directive 2009/28/EC.
[10] Similarly designed standards were implemented for diesel engines in the EU. This resulted in advances in combustion diagnostics, sensors, electronic control, and engine management systems (Bauner, 2007; Knecht, 2008).

valve management systems (cf. Berggren and Magnusson, 2012). In anticipation of the impending regulation, car makers already in 2008 made more rapid progress in improving fuel efficiency and reducing emissions than in the previous ten years. This was followed in 2009-10 by an average reduction of almost 10% to an average of 140 g CO_2 /km, not far from the target for 2015 (Dings, 2010, 2011).

In the *energy sector,* SO/NO_x emissions are regulated, just as in the automotive sector; the US Clean Air Act applies to power plants as well as to cars (but in this case it is also connected to an emissions trading system).[11] The innovation effects of this emissions regulation for US coal power plants are analyzed by Bañales-López and Norberg-Bohm (2002). According to this study CAAA 1990 was explicitly expected to provide a "pull" for advanced clean coal technologies, but largely failed to do so. The main reason was that cheaper, modular options were available, for example by switching to low-sulphur fuels and installing scrubbers. Thus this regulation stimulated diffusion of modular, mature technologies rather than development and diffusion of less mature innovations.[12]

A somewhat earlier administrative measure was the Public Utilities Regulatory Policy Act of 1978 which deregulated electricity markets in the US (followed by similar legislation in the UK). By mandating utilities to buy the power produced by qualified plants at the avoided cost, this change opened up for new independent power producers. For a brief period, the new regime created opportunities for the diffusion of the fluidized bed combustion technology, but conventional boiler manufacturers responded by improving their technologies for emission control, and then a new contender arrived, combined cycle gas turbines (CCGT). This soon became the technology of choice among independents due to favourable costs and short constructions times (Watson, 2004). Advanced gas turbines had developed according to their own trajectory closely related to advances in jet engine technologies, but regulatory changes such as PURPA stimulated the diffusion of the latest vintages.

[11] So far, CO_2 emissions have not been regulated in the same way, but regulation is being implemented in the US (starting in 2012) (van Alphen et al., 2010).
[12] Considering this, it is interesting to note that the US recently adopted the ACES act, which sets strict CO_2emissions standards for coal plants from 2012. Some claim that these standards can only be met by CCS technology (van Alphen et al., 2010).

The supply and use of renewable electricity have also been subjected to various types of administrative regulation. On the supply side, feed-in systems implemented in, e.g., Germany require electricity distributors by law to accept (and pay for) renewable electricity delivered to the grid by independent producers. On the user side, quota systems used in, e.g., Sweden and the UK oblige electricity users (or distributors) to include a certain share of renewable electricity in their total use (sales). As these are normally combined with economic instruments (e.g. tradable certificates or fixed price tariffs), which we discuss in other sections, the administrative aspects are not considered further here.

On the user side, there are also policy instruments aimed at reducing the use of energy, e.g. the EU Buildings Directive from 2003 that obliges all EU member states to implement energy performance regulation for buildings. Such regulation was introduced in the Netherlands already in 1996. This regulation is based on an energy performance coefficient (EPC), which provides a generalized measure of the energy efficiency of a building. The first EPC was set at a level corresponding to standard building practice in 1996 (defined as 1.4) and has then been tightened three times: to 1.2 in 1998, to 1.0 in 2000 and to 0.8 in 2006 (Noailly and Batrakova, 2010). Beerepoot and Bereepoot (2007) analyze the impact of this regulation on energy-efficiency innovations in the Netherlands, with a focus on hot water production technologies. They conclude that the performance regulation contributed somewhat to improved efficiency in conventional water heating technologies, such as gas condensing boilers and district heating, but did not result in the development or diffusion of "really new innovation", such as solar hot water boilers or heat pumps.[13]

4.3 Effects of technology-specific economic instruments on innovation

Technology-specific economic instruments in the *automotive sector* include subsidies to specific fuels and investment subsidies or public procurement directed at specific solutions, such as electric vehicles.

[13] These findings primarily concern the user side of innovation, but they are largely consistent with the supply-side patent analysis performed by Noailly and Batrakova (2010) They show that although the number of energy-efficiency patents applied for by Dutch firms increased in the mid-1990s, most technologies only showed a slight increase in the number of patents to the late 1990s and a steady decline or stabilization afterwards. The main exception was lighting technology, which showed a sharp increase in the number of patents applications after 1997, probably due to the dominance of Phillips in this area.

With regards to subsidies, Sweden has been highly committed to support the use of biofuels, especially ethanol in the transportation sector. This has included economic support for ethanol production, tax rebates on the fuels, and various subsidies to the vehicle owners, from sales incentives to free parking. Taken as a whole, these measures have resulted in considerable expenditure for very meagre results in terms of climate gas reductions, according to a critical report from the Swedish National Audit Office (2011), the key reason being that the policy failed to encourage any technological development or power train innovations. To be eligible for ethanol subsidies, firms implemented minimal adaptations in the cars, which made them even less fuel-efficient than when driving on gasoline. Ethanol production from crops (wheat, corn or sugar canes) did not make the leap to so-called second generation biofuels based on forest materials, and so the system subsidized a mature technology both in fuel production and use.

An example of public procurement is a Transport for London (TfL) project initiated in 2006 to trial diesel electric hybrid bus technology from a number of suppliers, which would be put in service by several different operators in order to assess the suitability of different types of technology in an urban environment. This expanded into a five-year evaluation program, covering eight different technology types applied in 200 hybrid buses by 2011. The long term goal was that 300 hybrid buses would have been introduced by 2012 and that all new buses delivered after that date would be hybrid vehicles. In addition to the original intention of evaluating and refining various technological solutions, the expansion of the program envisaged a reduction in line with the volume increases of the initial price premium of 50% for a hybrid bus compared to conventional diesel buses.

Our own research shows that in terms of scale, public visibility and timing this was a very important project for bus manufacturers in Europe, since it helped them to focus their efforts, compare and choose between alternative solutions and start series production. For example, the Volvo Group had just presented prototypes of hybrid electric buses when the TfL program started and it was very important for the company’s decision to commercialize this technology. In the words of the technical director at Volvo Powertrain, Anders Kroon: “Until then, we had only built demonstration vehicles. We were now going to develop an entirely new driveline for vehicles on the market” (Hanssen, 2011). At the time of writing, the TfL program cannot be conclusively evaluated, but according to industry sources, it has been a key initiative to accelerate market introduction of this architectural innovation to cities around the world.

In the *energy sector*, various types of investment subsidies have been applied for renewable energy technologies, e.g. wind power and solar cells. In some countries, such as Germany, these have been used together with feed-in systems with different tariffs for different technologies (small-scale hydro, landfill gas, biomass, geothermal, onshore and offshore wind and solar PV cells). The German electricity feed-in law (EFL) of 1990 required electricity distributors to buy power from producers of a selection of renewable electricity and pay them a fixed price corresponding to 60-95% of the average consumer price for electricity (Lauber and Mez, 2004), which was guaranteed for 20 years (Wüstenhagen and Bilharz, 2006).[14] The different percentages referred to different technologies; more developed and cheaper technologies received a lower price than less developed and more expensive technologies (Mitchell et al., 2006).[15] In 2005 the European Commission concluded both that feed-in laws so far had been more effective than quota systems to promote renewable electricity deployment and that they had been more cost-efficient than the quota systems.[16] With regards to its effect on innovation, studies of the development and diffusion of wind turbines, solar cells and biomass digestion technology show that the EFL has been a major contributing factor to Germany's industrial success in these areas (cf. Bergek and Jacobsson, 2003; Büsgen and Dürrschmidt, 2009; Jacobsson and Lauber, 2006; Negro and Hekkert, 2008).[17] By scaling up previous development and demonstration efforts, EFL led to a professionalization of the emerging industries supplying the capital goods and to the development of complete innovation systems around each technology. The rapid diffusion enabled capital goods suppliers to exploit economies of scale and experience and, thus, to reduce costs and improve performance of the technologies. In the case of wind power, it has also been shown that the German feed-in system created strong competition among turbine producers and constructors, which decreased costs and increased diffusion even further (Butler and Neuhoff, 2008).

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[14] In the EEG, the costs of the feed-in mechanism are shared by all end customers (Mitchell et al., 2006).
[15] The EFL was replaced in 2000 by the Erneuerbare Energien Gesetz (EEG), in which more renewables were included and in which prices for new plants were reduced annually (Mitchell et al., 2006).
[16] COM(2005) 627 final: The support of electricity from renewable energy sources.
[17] Obviously, the effects of learning and competition not only benefitted German firms, but also others active in the German market.

Spain implemented another feed-in systems in 1997, when the Law of the Electricity Sector provided producers of renewable electricity grid access, and a price premium of 80-90% of the average electricity price, guaranteed for the whole lifetime of each plant and descending for new plants, different for different technologies (del Río González, 2008).[18] According to evaluation studies, the system has primarily stimulated the diffusion of wind power in Spain there is also some evidence that manufacturing costs for wind turbines and PV cells have been reduced more in Spain than in countries without feed-in tariffs. Similar to those who have studied the German case, these researchers argue that the feed-in law has "led to the emergence of a … techno-institutional complex made up of learning networks between RES-E producers, RES-E equipment suppliers, local communities, policy makers and NGOs" (del Río and Gual, 2007, p. 1009).

4.4 Effects of technology-specific administrative instruments on innovation

Examples of technology-specific administrative instruments in *the automotive sector* include the well-known zero emission vehicle-rule from 1990, mandated by Californian authorities who were encouraged by the success of previous emissions regulation, and the apparent availability of pollutions-free electrical vehicles demonstrated by GM (Shnayerson, 1996). This regulation demanded an elimination of all hazardous tailpipe emissions, requiring automotive majors to introduce emission-free vehicles for a rapidly increasing part of their sales, 2% in 1998, 5% in 2001, and 10% in 2003 (Sperling and Gordon, 2009). Thus, the ZEV mandate tried to enforce the market diffusion of an entirely new vehicle architecture, which implied the replacing of all existing power-train technologies. The new vehicles could not be developed and tested in any gradual way, but had to be introduced in one single package competing on cost, reliability and performance with conventional cars.

The ZEV-rule inspired some startup firms in the electrical vehicle field and new collaborative networks to develop battery technologies (Pilkington et al., 2002), where developments in nickel cadmium and nickel metal hydride technologies created expectations of a breakthrough for EVs. The major automakers did launch battery electric cars in small quantities, such as GM EV1,

[18] Since 1998, producers have been able to choose between a fixed total price and a fixed price premium. Since 2007, the support is tied to the consumer price index instead of the electricity price (del Río González, 2008).

Honda EV Plus, Ford Ranger EV, and Toyota RAV4 EV (Sperling and Gordon, 2009), but the fundamental intention with the legislation – to enforce the conversion of the Californian vehicle fleet to zero-emitting vehicles – failed. In 2002, when company lawyers had succeeded in fighting back the ZEV-legislation, EV-production ceased at all automotive majors and the electric cars were physically destroyed, with the exception of Toyota who agreed sell 300 RAV4 EV, after being pressured by lobbyists and customers. Citing unfavourable cost and range issues, no incumbent made efforts to continue electric vehicles as a commercial operation, and the new entrants were equally unsuccessful. Norwegian Think did develop a first production model but then went bankrupt in 1998.Taken over by Ford, Think produced 1,000 cars, before Ford sold out, and production ceased for a long period (Roste, 2009). Other firms never made it to any of developed markets.

In the *energy sector*, examples of administrative regulation include the European level identification of Best Available Techniques (BAT) for energy efficiency in industry under the IPPC Directive,[19] which prescribes very specific solutions for different applications, such as replacing conventional electric motors with variable speed drives in energy-using systems, processes activities or equipment (European IPPC Bureau, 2009). Specific technologies are also often subjected to administrative rules in terms of permits and land-use, for example, regarding the erection of wind turbines (Bergek and Jacobsson, 2003). As mentioned in Section 3, we have not been able to find any empirical studies of the innovation effects of such instruments.

4.5 Synthesis and comparison

The experiences of the four main types of policy instruments in our two sectors are summarized in Table 2. In both sectors, *general economic instruments* have primarily induced incremental innovation related to conventional technologies as well as diffusion of relatively mature technologies, as the various trading and certificate examples indicate. However, it also seems like they can encourage research and demonstration of complex modular innovation, as the case of

[19] Directive 2008/1/EC on integrated pollution prevention and control. This directive has recently been replaced by the Industrial Emissions Directive (2010/75/EU). In the directive, BAT is defined as "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole" (p. xii) In this context, available means that the techniques should be "developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions".

CCS-technology shows. However, there is a vast difference between stimulating initial interest and development of a new technology and achieving widespread diffusion of it, and this gap is not bridged by the general instruments, again demonstrated by the CCS example, where general economic instruments seem insufficient to stimulate commercial application due to the scale of the required investments (Hoffmann, 2007; van Alphen et al., 2009). In addition, general economic instruments seem to provide too limited incentives to stimulate investments in promising architectural innovations (e.g. renewables).

As evidenced by examples from both sectors, *general administrative instruments* can be highly effective in driving development and diffusion of incremental and modular innovations, especially if they contain stepwise increasing stringencies. This is especially clear for the mass-production oriented automotive sector, where penetration is critical for success. It is very difficult to envisage economic means which would accomplish the same innovation and emissions reduction effect as the CAAA-legislation or the corresponding Euro 1- 6 framework (and the same applies for the recent fuel efficiency regulation in the US and the EU). However, this type of regulation seems to be difficult to apply if architectural or radical innovation is needed.

Finally, *technology-specific instruments* – both economic and administrative – seem to be necessary to support architectural and radical innovations, from their early development, via market introduction and to the critical diffusion stages when learning curves are still steep. However, the review also shows that technology-specific measures may fail to promote further development and diffusion of such technologies, either because they are designed to target essentially mature technologies (such as the Swedish or US ethanol subsidies), and thus have little or no innovation effect, or because they support technologies or industries which are too immature for any meaningful market introduction to take place, such as the Norwegian support for an electrical vehicle industry in the 1990s. We will return to these issues in the next section.

Table 2: Innovation effects of four types of policy instruments in two sectors

Type of means	Sector	Example	Positive impact on:	Limited or no impact on:
General economic	Automotive	Fuel taxes	Development and diffusion of incremental innovations in conventional technologies; diffusion of modular technology (diesel engines)	Development and diffusion of fuel saving modular innovations.
	Energy	EU ETS	Development and diffusion of incremental innovations in conventional technologies; development of complex modular innovation (CCS)	Market introduction and diffusion of complex modular innovations (CCS); development of renewable energy technologies.
		TGC	Diffusion (and some cases of incremental improvements) of relatively mature renewable energy technologies.	Development and diffusion of modular, architectural or radical innovations (especially more immature renewable energy technologies).
General administrative	Automotive	CAAA and similar European emissions regulations	Development and diffusion of modular innovations (catalytic converters, clean diesel technologies, fuel-saving modules) and improvements in existing on-the-shelf technologies.	Development and diffusion of architectural or radical innovation.
	Energy	CAAA	Diffusion of existing modular innovations (scrubbers); development and diffusion of modular innovation (CCGT)	Diffusion of new architectural innovation (PFBC) for clean coal.
		Dutch building regulations	Incremental innovation in conventional water heating technologies.	Development and diffusion of architectural innovations (solar how water boilers, heat pumps)
Technology-specific economic	Automotive	Subsidies to specific fuels	Incremental adaptations of existing engines + increased use of first-generation ethanol.	Development and diffusion of (architectural) power train innovations; development and diffusion of second-generation biofuels.
		Public procurement	Development and market introduction of architectural innovation (hybrid-electric buses)	Broader development and diffusion and of electric cars (various schemes in Europe)
	Energy	Feed in tariffs	Development and diffusion of architectural and radical innovations (e.g. wind turbines, solar PV cells)	Development and diffusion of technologies not included in the tariffs.
Technology-specific administrative	Automotive	ZEV	Development and market introduction of architectural innovation (electric cars)	Further development and diffusion of electric cars.
	Energy	n.a.		

5. Conclusions and discussion

In the theoretical debate, general economic means are contrasted and perceived as generally superior to other means, technology-specific and/or administrative. The comparisons of actual outcomes above display a much more differentiated and nuanced picture (cf. Kemp and Pontoglio, 2011) and a number of similar lessons emerge across sectors.

First, there is no generally effective policy route. Although the experiences from the two sectors in focus in this paper are largely similar, which probably is due to their similarities in terms of technology complexity, the evidence still shows that context matters for the effectiveness of different types of instruments. In particular two types of contextual factors seem to be of importance: (i) the type of innovation needed to achieve policy goals (incremental, modular, architectural or radical) and (ii) the responding industrial context. With regards to innovation type, general instruments are clearly effective in achieving rapid diffusion of already existing solutions and modular add-ons to existing technology. In contrast, the development of entirely new architectural or radical solutions requires a higher degree of uncertainty reduction and protection from market competition (although fostering upgrades and cost reductions is necessary as well). Depending on the goal of policy, different types of instrument can, therefore, be relevant.

This is, in part, related to the responding industrial context. In order to have effect, policy instruments have to be connected to a responding industrial context, i.e. networks of firms with requisite resources and capabilities to deploy. This is usually quite easy to achieve for incremental and modular innovations, which tend to be driven by incumbent actors. In contrast, architectural and radical innovations are often introduced by new entrants (Henderson and Clark, 1990) and can, indeed, require the building up of entirely new innovation systems. More wide-reaching, “systemic” innovation policies (Smits and Kuhlmann, 2004) might then be needed to stimulate actor entry, network formation and institutional change before policies more targeted at achieving specific targets of performance or diffusion can be successful.

Second, the need for a strong industrial base implies that various instruments need to be combined in larger policy packages, extended over longer periods of time and changing as the context changes. Especially technology-specific support is usually pursued in long-term programmes, including not only the types of instruments discussed in this paper (e.g. public procurement, investment subsidies and differentiated fixed tariffs), but also support for R&D and network building. The incumbent actors and structures in sectors such as the automotive and energy sectors have benefitted from this kind of long-term support in the past and that similar programmes might be needed to induce more radical changes to the current energy and transport systems in the future.

Third, for all types of policy instruments, there are challenges related to design issues and implementation. Here, we would like to highlight four such challenges:

- *Selection*. For technology-specific policies, the dangers involved in trying to pick winners have been discussed at some length. However, it is clear from the empirical studies referred to above that also general instruments lead to selection, for example the selection of mature rather than immature technologies over immature or modular rather than architectural innovations. In some cases, this selection seems to have been unintended, as for example in the case of the Swedish support to ethanol. However, such implicit selection can often be predicted beforehand, based on performance and cost comparisons between technologies, and such information should be taken into account when choosing between different instruments.

- *Stringency*. Stringency is a critical issue for both economic and administrative instruments (cf. Kemp and Pontoglio, 2011). Initial stringency tends to be the result of an uncertain search process and therefore needs to be followed up by increasing levels of stringencies over an extended period of time, otherwise innovative efforts will tend to fade out. The significance of this is illustrated both in the power sector (the German feed-in system) and in the automotive sector (the Euro 1- 6 framework with significant tightening of standards five times over a 20-year period of time) and applies both to economic and to administrative means; to have any lasting innovation impact allocations in trading systems need to be tightened, and so do fuel taxes or administrative standards.

- *Scale*. To be effective, technology-specific economic instruments for mass-production industries have to be significant enough for relevant industrial decision-makers, which implies that they tend to require heavy resource commitments. The various European public procurement schemes for electric cars in the 1990s fell far short of this scale criterion and thus failed to really accelerate the intended innovations. The program for procurement and evaluation of hybrid electric buses in London represents an opposite case, where the number of purchased vehicles represents a significant volume in relation to total UK sales. However, successful large-scale programmes can lead to legitimacy problems over time. In spite of its success in terms of both industry development and diffusion of renewables – or rather because of this success – the consumer cost the German feed-in law is now being questioned.

- *Stability*. In capital-intensive sectors, such as the automotive and energy sectors, stability of policy instruments is of particular importance. The exact level of economic support or regulation limits is usually much less important than their predictability. Administrative instruments have an advantage here compared with economic instruments, especially when, they are implemented at an international level, such as the Euro 1-6 framework.

In the end, several other factors influence the final outcome of interventions, such as political competence and credibility (cf. Jacobsson and Bergek, 2004; Kemp and Pontoglio, 2011). One important reason for the success of the original US CAAA legislation, with its stringent technology-forcing character, was the political support, and the competence and credibility of the new Environment Protection Agency (Gerard and Lave, 2005). Successful policy-making needs to bring issues of public education and institution-building into the regulatory context, but that is the subject of a different paper.

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