Environmental Policies and Directed Technological Change

Klaus Gugler, Florian Szücs
and Thomas Wiedenhofer [*]

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Abstract We evaluate if and to which extent policy can steer innovation towards eco-friendly technologies. We construct a comprehensive dataset on sectoral green innovation and complement it with data on policies designed to address environmental market failures: environmental taxes, regulation, and R&D subsidies. All of these policy tools exert a positive effect on green innovation on average, however we document substantial heterogeneities across regions and sectors. While we are unable to directly compare the cost-effectiveness of policies, we find that green innovation reacts most strongly to R&D subsidies.

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[*] Klaus Gugler, Wirtschaftsuniversität Wien, klaus.gugler@wu.ac.at; Florian Szücs, Wirtschaftsuniversität Wien, florian.szuecs@wu.ac.at; Thomas Wiedenhofer, Wirtschaftsuniversität Wien,thomas.wiedenhofer@wu.ac.at.

1 Introduction

There is now an almost universal consensus that climate change is anthropogenic, i.e. that it is caused by an enormous increase in greenhouse gas (GHG) emissions due to human industrial activity. In order to comply with the goals set forth in the Paris Agreement and to limit the increase in average temperatures to 1.5°C, policy makers need to guide the behaviour of consumers and companies towards a zero net-emission economy. Unfortunately, current technologies and mere behavioral changes will likely not be sufficient to achieve this task.[1] New technologies will be decisive in attaining the required reductions in emissions and therefore, it is crucial to introduce efficient policies and research incentives as soon as possible. This paper studies which measures can steer innovation towards a greener path.

It is common knowledge among economists that the optimal policy to combat climate change is a combination of a carbon tax (or price) and research subsidies for green technologies (Acemoglu et al., 2012). A carbon tax/price alone would not achieve the first best outcome (i.e. it does not minimize total consumption costs over the horizon of the policy), since the private value of an innovation tends to be more short-sighted than its social value.[2] Since a larger fraction of the social value of "dirty"[3] innovation is realized in the short-run than is the case for green innovation, the optimal policy also includes a research subsidy specifically devoted to steering innovation towards clean technologies. Intuitively, the incumbent, dirty technologies enjoy a productivity advantage over the more recent, clean technologies and an intervention is necessary to set the economy on a new innovation path. Such a policy mix would internalize both the environmental externality, by putting a price on emissions, and the R&D externality, by subsidizing R&D as an optimal response to the public good nature of knowledge. Most importantly, such a policy would direct technological change in an optimal way towards green innovation. However, due to reasons of political feasibility, this optimal policy mix is not implemented by the majority of countries around the world.

Most countries either do not collect carbon taxes/prices at all or do not set them sufficiently high.[4] While nearly all countries grant research subsidies specifically for clean/green technolo-

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[1] See e.g. https://www.iea.org/reports/clean-energy-innovation

[2] Reasons include finite-lived patents, creative destruction, imitation, and building-on-the-shoulders-of-giants externalities (Hémous and Olsen, 2021).

[3] Aghion et al. (2016) distinguish i) "dirty" patents, which are based upon fossil fuel combustion, ii) "grey" patents, which improve the efficiency of "dirty" technologies and iii) "green" or "clean" patents, related to zero-emission technologies.

[4] For example, the Economist (2021) estimates that only 20% of global emissions are currently subject to a pricing scheme. In existing schemes, the median tonne of carbon emissions is priced at only 15$, way below all estimates of the social costs of carbon (SCC), most of which are beyond 50$. In February 2021, China's carbon trading market went live, however, coverage and price are still insufficient. In the USA, there is no carbon tax/price on a country wide basis, and only some states (e.g. California and the Regional Greenhouse

gies, the subsidies are currently not high enough.[5] Instead, essentially all countries revert to regulating CO2 emitting technologies and activities.[6]

In theory, there might be opposing forces at work. If fossil fuel use and green energy are gross substitutes, regulatory restrictions on fossil fuel use (e.g. via outright prohibition or portfolio requirements for green energy) increase the marginal product of green energy and demand for complementary technologies. This increases the returns to innovating in technologies that augment green energy relative to returns to fossil fuel augmenting technologies. Regulation in this case directs innovation towards green innovation (Acemoglu et al., 2016). If fossil fuel use and green energy are less substitutable, however, the overall scale of production in the economy may fall, reducing the demand for all capital goods that complement energy. In this case, green regulation might reduce incentives for clean innovation (Gans, 2012). Which effect dominates can only be determined empirically.

Moreover, the effects of regulation may depend on its specific political implementation. For example, a limit on fleet emissions or a green portfolio standard may induce efforts by companies until the limit is reached, but not beyond. Thus, effects could be non-linear, i.e. increasing innovation up to a point but then - e.g. when a specific target is achieved - tapering off.[7] Likewise, regulation punishes polluters but it does not (directly) reward emission efficient actors. Thus, effects may depend on how exactly regulation is implemented (e.g. CC or MB). Environmental regulation, such as stipulating renewable energy quota or subsidies for green technologies, may also have unintended consequences. For example, subsidies for renewables may reduce the electricity price via increased supply of electricity, leading to more consumption of energy. On the positive side, environmental regulations may convey a stronger signal to markets and firms that this policy is here to stay, reducing adoption uncertainty.

Our knowledge about which policy instruments are successful in directing technological change towards green innovation is limited. The fact that essentially all countries use environmental

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Gas Initiative (RGGI)) have implemented carbon pricing schemes. In the EU, the carbon price surpassed €50, for the first time in history in May 2021, however, it remained below €10, for the largest part of the existence of the European Trading System. The most notable exceptions with respect to insufficient carbon pricing are Sweden, Switzerland, and Norway, charging more than 100€ per tonne of CO2.

[5] For example, Acemoglu et al. (2016, p.91) state that the (relative) research subsidy of 43% in the US is "insufficient to redirect technological change toward clean with no carbon taxes".

[6] Regulations on carbon emissions can take many forms. One useful distinction is between command-and-control (CC) and market-based (MB) regulations. CC regulations are characterized by specific state-imposed targets, limits or performance standards, which must be reached by producers or consumers within a certain time period. An example is the fleet regulation in the EU to reduce CO2 emissions from new passenger cars. MB regulations are characterized by using market-based mechanisms to reduce CO2 emissions. An example is the EU ETS restricting the emissions of included sectors. Sometimes specific regulations can take a hybrid form with some elements of CC and some elements of MB. In the empirical analysis we therefore employ a three way classification.

[7] See Aghion et al. (2021) for recent evidence of a threshold effect of labor regulation on innovation for French small companies.

policy tools – taxation/pricing, regulation and subsidies – to curb climate change without really knowing their effects on directed technical change is worrying. This paper aims to fill this void by analyzing the effects of environmental taxes, clean research subsidies, and environmental regulations on green patenting activity in a cross-country, cross-industry panel setup.

Our research project focuses particularly on technological innovation concerning decarbonization technologies across sectors and countries. Specifically, we construct a sector/country/year panel dataset, which includes details about green patenting behavior at that level of observation. We evaluate whether and how sectors react to different policies (carbon prices/taxes, regulations, subsidies) in terms of emission reducing innovation. We use newly defined categories of innovation, allowing us to identify green patents (Veefkind et al., 2012) and link these technologies to different sectors of the economy (Dorner and Harhoff, 2018). We employ a comprehensive dataset on green patents filed in Europe, America and Asia from the European Patent Office (EPO). We complement the innovation data with data on carbon prices and carbon taxes from the European Commission (EC) and data on environmental regulation and research subsidies from the International Energy Agency (IEA) and the OECD.

Our main results are encouraging. All three possible policies to direct innovation towards green technologies do so. Environmental taxes, environmental regulation and state-subsidized R&D in green technologies significantly direct innovation towards green patenting. Doubling the environmental taxes in an industry, on average increases green patenting activity by around 2.6%. The presence of an environmental regulation in a NACE2 industry sparks a 17% increase in green patenting. Doubling direct state R&D subsidies leads to a 9.2% increase in green patent applications. An increase of R&D tax subsidies by 1 percentage point increases green patent applications by 1.5%.

These clear-cut results, however, mask important heterogeneous effects across regions and industries. While in Asia command-and-control type regulations successfully increase green innovation, in Europe and America market-based regulations have a stronger effect. Hybrid regulations appear to be even negatively associated with green patenting, particularly in America. Similarly, the effect of R&D subsidies differ by region. While in the EU and America, R&D subsidies for fossil fuels increase green innovation, they do not in Asia.

Energy taxes increase green patents predominantly in non-manufacturing industries as do CC regulations. This should come as no surprise since the transport sector is part of non-manufacturing and in transport the mineral oil tax (the largest component of environmental taxes) as well as CC regulations (e.g. automobile fleet regulation) are very important. In contrast, in manufacturing substitutability between fossil and non-fossil inputs (e.g. in steel, cement etc) may be limited, and taxes/carbon prices may not (yet) induce patenting.

The literature contains some studies on directed technological change, which are, however, limited in their scope in one or several dimensions. Most importantly, there is no paper that applies a comprehensive set of policy tools in a cross-sector, cross-country and cross-time dimension. Given the cross-industry and worldwide dimension of climate change, this appears to be a severe limitation.

Aghion et al. (2016) use patents to estimate the effects of fuel prices on innovation in the car sector. They distinguish between "green" (e.g. electric and hybrid vehicles), "grey" (e.g. energy efficiency increasing) and "dirty" (e.g. internal combustion) patents. Two main channels influence innovation activities: (1) market size and (2) (relative) prices. Innovation is directed to larger markets and to markets with higher prices. As the market for fossil fuels is one of the largest sectors, it attracts innovation over-proportionally. Green innovation is more expensive and therefore the gap between dirty and green innovation is not closed. Increasing fuel prices leads to more innovation in green technology, with an estimated elasticity of 0.98. Only small effects are found for other policies, such as emission regulation or R&D subsidies.

Yet, as innovation is path-dependent in the automobile sector, the optimal policy mix includes carbon taxes as well as R&D subsidies for green innovation. We can improve upon this approach by using a more accurate classification of patents (Veefkind et al., 2012), looking also on more recent technological advances (until 2016, whereas Aghion et al. (2016) stop in 2005), and using a comprehensive set of policy instruments and not only fuel prices. Moreover, our primary interests are the effects across sectors and countries while Aghion et al. (2016) is confined to the automobile industry.

Most studies find that market-based policies are more effective for innovation than other policy instruments (Magat, 1978, 1979; Milliman and Prince, 1989). Command-and-control regulations penalize polluters but they do not reward emission efficient actors. However, Baumann and Lee (2008) show that under certain scenarios command-and-control could lead to more innovation. Market-based policies may be more efficient if technologies are 'close to the market'. Wind energy, for example, is almost competitive with fossil fuel energy, since costs are already relatively low. Therefore, firms may be induced to invest in technologies which are relatively close to the market if a carbon price or tax additionally tips relative prices in their favor. Innovation in solar power, in contrast, may be further 'away from the market', therefore direct investment incentives may be more effective (Johnstone et al., 2010).

On the micro level, Fischer and Newell (2008) and Gerlagh and Van der Zwaan (2006) are important studies which evaluate a broader set of policies. Fischer and Newell (2008) evaluate emission-reducing policies in the energy sector and rank them in order of cost effectiveness: (1) emission price (cheapest), (2) emission performance standard, (3) fossil power tax, (4) renewable share requirement, (5) renewable subsidy and (6) R&D subsidy. They show that a combination of emission pricing and R&D subsidies achieve significantly lower costs than any other policy. Gerlagh and Van der Zwaan (2006) in contrast, find that an emission performance standard is the cheapest policy to reach different carbon stabilization goals. Compared to a carbon tax, emissions performance standards directly address the environmental externality. Calel and Dechezlepretre (2016) address the effect of EU ETS on directed technological change. The authors show (1) that innovation increases if the EU ETS price rises and (2) innovation by firms not covered by the ETS is not influenced by the cap-and-trade system.

One of the first empirical papers dealing with innovation in the automobile sector is Crabb and Johnson (2010). It includes the effects of expected oil prices and fuel economy regulations on energy efficient automotive patents from 1980-1999 in the United States. They found an elasticity of 0.24 between oil prices and patents, but no effects of fuel economy standards on innovation.

While the papers mentioned before use patents as a measure of technological change, Knittel (2011) uses a model of vehicle's fuel economy as a function of weight, horsepower, and torque. He has found an increase of only 6.5 percent of the fuel economy of new US automobile vehicles but an increase by 80 percent of the average horsepower during the last decades. His main findings are (1) holding weight, horsepower, and torque constant at the level of 1980, efficiency could have increased by 60 percent, and (2) fastest technological change happens in years with high gasoline prices.

Lee et al. (2011) show different effects of regulations for automobile emissions control technology on innovation. They use US data and ask whether performance-based technology-forcing regulations increase innovation. Command-and-Control regulations are often criticized for inducing less innovation, but their advantage is that they are flexible in how the performance standards are met. This paper offers no welfare analysis but it shows that CC regulation can inspire firms to comply with ambitious targets and therefore increase innovation.

Recently, Palage et al. (2019) find that renewable energy support policies for solar photovoltaics (PV) technology increase patenting. For 13 countries over the period 1978–2008, the analysis addresses one technology-push instrument, public R&D support, and two demand-pull instruments, feed-in tariffs (FIT) and renewable energy certificate (REC) schemes. The results indicate that: (a) both FIT and REC schemes induce solar PV patenting activity, but the impact of the former policy appears to be more profound; and (b) public R&D support has overall been more influential than FIT and REC schemes in encouraging solar PV innovation. A comprehensive survey of the empirical literature in this field is provided by Popp (2019).

Summarizing, the evidence on whether environmental policies direct technological change towards green innovation is encouraging. However, the literature so far did not provide for a comprehensive tackling of the broad picture of the effectiveness of a comprehensive set of policies. Most papers only analyze specific aspects of policies, e.g. only the EU ETS carbon pricing system, only specific regulations (e.g. renewable portfolio requirements) or supply subsidies (e.g. feed in tariffs), in specific sectors (e.g. the automobile industry).

The rest of this paper is organized as follows. In section 2 we briefly discuss the sources of externalities and the channels through which policy can influence the path of innovation. Section 3 describes the construction of the dataset, while the empirical strategy is detailed in section 4. Results of the empirical analysis are discussed in section 5 and section 6 concludes.

2 Theory and channels for directing technological change

Economists have identified two market failures leading to the excessive emission of greenhouse gases and the sub-optimal level of technical change towards green inventions. The first market failure concerns the *environmental externality.* Consumers and firms do not pay the full social cost of the pollution of the atmosphere, leading to overconsumption, similar to a 'tragedy of the commons'-type situation. Moreover, since historically it has been cheap to use this resource, polluting technologies are usually cheaper to operate than technologies not causing environmental pollution. Therefore, in the absence of policy intervention dirty technologies are favoured over green technologies.

The second market failure is due to the *public goods nature of knowledge* (see Geroski (1995)). If a company innovates, the created knowledge may spill over to other, competing companies for free. That is, the investing company may not be able to appropriate the returns of its innovation and will therefore underinvest in new technologies. A fortiori, it will also underinvest in green technologies.[8]

As a first best solution to the first market failure, economists would suggest to put a price on these negative externalities, leading households and firms to internalize them. This would reduce the common goods problem or eliminate it altogether. This can be achieved through carbon pricing e.g. by an emission trading system or by direct taxation. Additional pros of

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[8] Studies on the public-good-nature of knowledge are cited in Popp (2010), p. 5 f.

market based solutions are a lower need for information acquisition by the state than with specific regulatory limits, and the continuous nature of pricing/taxation.[9]

The second market failure may best be tackled through R&D subsidies or other R&D promoting policies such as patent protection or direct state funding of basic research. As mentioned in the introduction, these "first best" solutions are essentially not followed by the majority of countries. Instead, most countries adopt environmental regulation to achieve their climate change goals.

Which effects are to be expected from the policies mentioned above? It is useful to follow the schematic framework of Nordhaus (1969) arguing that investments into the discovery of innovation rise with the profits expected from successful discovery, i.e. there is a monotonic relationship between innovative investments and the probability of successful discovery.[10] Define I as the total level of investment into innovative activity, and $p(I)$ as the probability of a successful discovery, where $p'(I) > 0$ and $p''(I) < 0$. Define G as the state of the world in which a discovery in green technologies occurs, and D as the state in which no discovery occurs (i.e. the dirty technology prevails). $E(\pi|G)$ is the innovator's expected profit in case of green invention, and similarly for $E(\pi|D)$ for staying with dirty technology. Green innovation investments will be undertaken if and only if $E(\pi|G) > E(\pi|D)$. Firms may get subsidies so that they do not have to bear all the cost of innovation - define $\phi(I) \leq I$ as the firm's private cost of investment, I. Finally, define r as the cost of capital. Then, the privately optimal level of innovation is given by the solution to:

$$\max_I \; p(I)\, E(\pi|G) + (1 - p(I))\, E(\pi|D) - (1 + r)\, \phi(I)$$

Thus, policies can affect the decision to invest in new technologies via four channels. They can

1. increase the probability of successful innovation, $p(I)$,
2. increase the expected profits from green innovation, $E(\pi|G)$,
3. decrease the expected profits from dirty technologies, $E(\pi|D)$, and/or

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[9] On the negative side of taxation/pricing, Hepburn et al. (2020) enumerates four reasons why carbon pricing alone might not be sufficient. Carbon pricing may not achieve the task on the necessary timescale and the necessary scale of structural change. Moreover, regulation (e.g. a prohibition) may eliminate the burning of fossil fuels altogether, eliminating all deaths associated with it, whereas taxation/pricing may not. Further, regulation may give (more) confidence in new technologies such as solar, wind, or battery technologies characterized by large learning-by-doing effects and increasing returns to scale, than carbon pricing. Another drawback may be the lower political acceptance of carbon pricing than of regulatory intervention.

[10] The theory of Hicks (1963) stating that profit-motivated investment in innovation (R&D) is more attractive in sectors that can command higher relative prices is closely related to Nordhaus (1969).

4. reduce the private costs of investment, $\phi(I)$.

In the empirical analysis, we try to capture all four channels. Concerning channel (1), we expect the probability of successful innovation, $p(I)$, to be affected by the stock of knowledge amassed up to a specific point in time (Scotchmer, 1991). Channels (2) and (3) can be jointly examined by considering the expected profits from green innovation, relative to those from dirty innovation, $\frac{E(\pi|G)}{E(\pi|D)}$. This ratio is increased if the expected profits from dirty technologies, $E(\pi|D)$, are decreased by carbon taxes/pricing. Regulation could also affect both types of profits, since the implicit cost ratio between dirty and green inputs is increased. A green portfolio standard will increase expected profits from green innovation, a ban on oil heating will decrease the expected profits from dirty technologies. However, there may be non-linear effects (as e.g. with a regulatory limit) and possibly perverse effects (as e.g. with endogenous supply side responses) of regulation. Moreover, the general equilibrium effects of regulation depend on the gross substitutability between fossil fuel use and green energy.[11] Finally, related to channel (4), policies can reduce the private costs of investment. Policies can reduce $\phi(I)$ directly (via direct subsidization or direct state R&D) or indirectly (via the tax system), thereby subsidizing green R&D. This would help internalize the public goods nature of knowledge externality.

Figure 1: Policy channels for Directed Technological Change

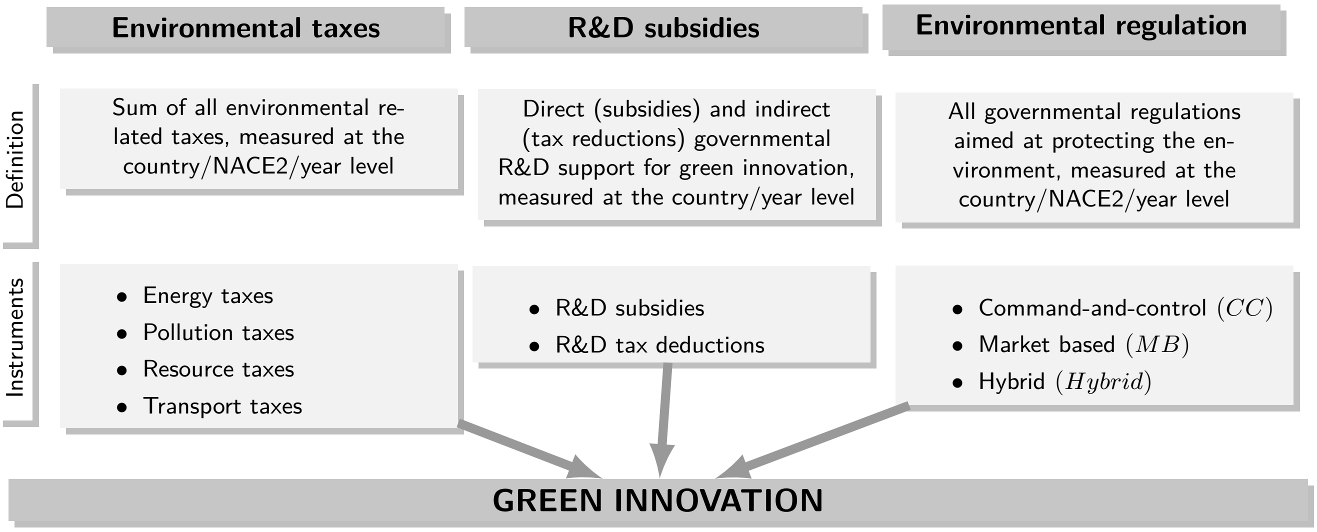

Figure 1 defines and summarizes the policy channels potentially leading to green innovation. It also lists the different types of environmental taxes, R&D subsidies and regulatory measures included in the empirical analysis. Ultimately, the impact of policies on green innovation is an empirical question. In the following sections we econometrically analyse the effects of the

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[11] See the discussions of Acemoglu et al. (2016) and Gans (2012).

three main policy instruments, carbon pricing/taxation, regulation, and subsidization of green patenting.

3 Data

In the following section, we briefly summarize the construction of the dataset. The main data are drawn from the European Patent Office ($PATSTAT$) where we use data from the $PATSTAT$ Global spring version 2020. Based on the Veefkind et al. (2012) classification, we select all Y02 ("green") patents in all available countries. We use this classification to identify emission reducing or zero emission innovations over time. Additionally, data from *EuroStat* on environmental taxes are used, as well as data from the $OECD$ on R&D subsidies and R&D tax deductions. Finally, we complement the dataset with data on environmental regulations from IEA.

3.1 Green patents (*Y02*)

Three different types of green patents are included in our dataset: (i) zero emission, (ii) emission reducing technologies[12] and (iii) negative emission technologies. Our search strategy in $PATSTAT$ follows Haščič and Migotto (2015) and selects all $Y02$ patents. These include climate change mitigation technologies related to energy, transporation and buildings as well as capture, storage, sequestration or disposal of greenhouse gases. Examples of zero emission technologies are patents for renewable energy generation. Emission reducing technologies include those improving the fuel-efficiency of vehicles or the input/output efficiency of power plants. Finally, negative emission technologies comprise, for example, carbon capture and storage through biological or chemical separation.

We assign green patents to countries based on the country of the patent owner. Thus, patents filed by Siemens AG are counted towards German innovation, but patents filed by a Spanish subsidiary of Siemens are counted in Spain. The year of first filing is used as the application date of the patent. In order to attribute patents to sectors, we follow the procedure developed by Dorner and Harhoff (2018), who exploit a large dataset of linked inventor-employee data to create detailed and fine-grained concordance tables of patent technology classes (4-digit International Patent Classification (IPC) class) and industry sectors (2-digit NACE codes).

Thus, every green (according to the $Y02$ classification) patent is assigned to 2-digit industries based on its 4-digit IPC codes. As many patents have multiple IPC codes and the link between

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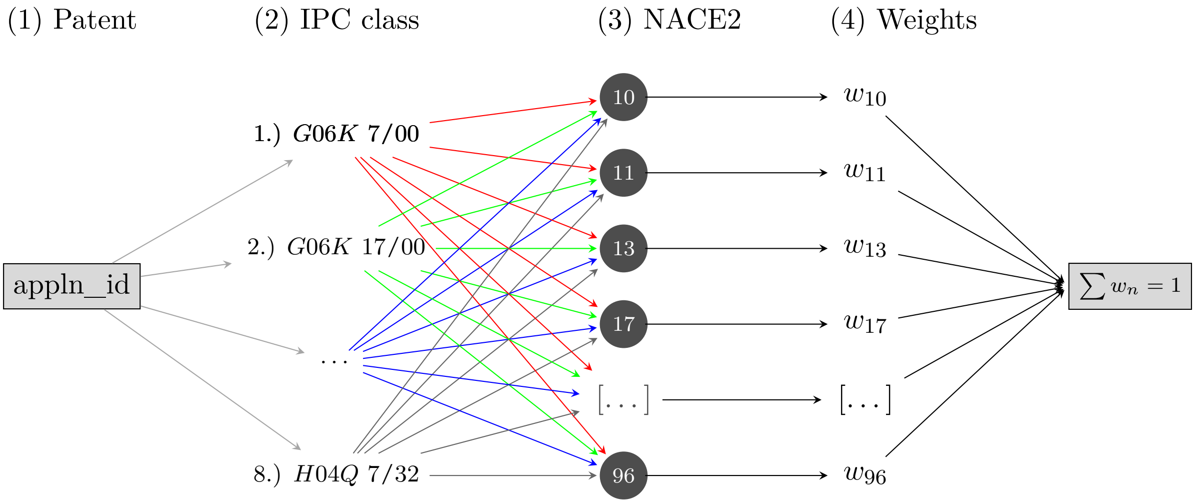
[12] Based on Aghion et al. (2016) we include "green" and "grey" patents in our dataset but do not consider "dirty" patents.

technology and industry classes is $n : n$, we weigh each patent such that i) it is counted in all applicable industries and ii) the overall weight of every green patent is one.

The procedure of assigning green patents to industries is illustrated in Figure 2. For a given patent we collect all relevant *IPC* classes (step (2) in figure 2); use the Dorner and Harhoff (2018) mapping to identify the corresponding NACE2 codes (3); and adjust the weights (4) such that the sum of a patents' weights across all industries is equal to one.

Figure 2: Mapping of IPC classes into NACE2 sectors based on Dorner and Harhoff (2018)



3.2 Environmental taxes

An environmentally related tax is a tax on a physical unit of something that has a proven, specific negative impact on the environment (Eurostat Environmental taxes - A statistical guide). We collect data on environmentally related taxes for all European countries (including Iceland, Lichtenstein and Norway) from Eurostat. Tax revenues are allocated to their respective NACE sectors and available for the XXXX-YYYY period.

Additionally, all variables for environmental related tax revenues are classified into energy, transport, pollution and resource taxes. Energy taxes include all taxes on energy production. This category covers tax revenues from emission trading systems, mineral oil tax and emission taxes of CO2 and SO2. Therefore revenues of permission permits (e.g. carbon taxes) are part of this class. It accounts for the major share in environmental related taxes across Europe. Transport taxes include taxes related to the ownership of motor vehicles, e.g. transport equipment and services. Pollution taxes are measured or estimated values of emissions to water or air, management of solid waste and noise belong to this category. Resource taxes include all taxes for the extraction or use of natural resources are included here (e.g. deforestation).

3.3 R&D subsidies and tax deductions

The IEA database for government funding of energy-related R&D includes all relevant research subsidies in the field of energy. We can split those budgets in subgroups pertaining to R&D in fossil fuels, renewables, as well as energy efficiency & others. Fossil fuel (oil, gas and coal) subsidies refer to all methods which try to increase the amount of oil and/or gas extraction from underground. Renewable energy include public investments regarding solar, wind, biofuels and others for cooling and heating. Energy efficiency and others captures all activities which increase output with less or equal energy input. As with the tax variables, we allocate research subsidies to NACE groups, countries and years. Thus, we observe the amount of R&D subsidies received by a sector in a country during a year.

Data on R&D tax deductability is collected from the OECD and include data of all OECD (and eleven non-member economies) between 2000-2016. In the regressions, we use the tax subsidy rate (1 minus $B - index$, which is a measure of the required before-tax income to spend USD 1 on R&D). This measure captures the relative support for private sector investment in R&D delivered through a tax system and is available at the country/year level.

3.4 Environmental regulations

We scrapped data on environmentally related, regulatory policies (around 6,000 different regulations) from the International Energy Agency (IEA) and mapped them into NACE sectors. To this end, we exploit three classifications, which are available in the IEA database: policy types, sectors and technologies.

Based on a regulations' policy type, we classify polices as either market based (MB, 41% of all regulations), command-and-control (CC, 35% of all regulations) or hybrid (HB, 19% of all regulations) CC regulations are characterized by specific state-imposed targets, limits or performance standards, which must be reached by producers or consumers within a certain time period. An example is the fleet regulation in the EU to reduce CO2 emissions from new passenger cars. MB regulations are characterized by using market-based mechanisms to reduce CO2 emissions. An example is the EU ETS restricting the emissions of included sectors. The hybrid category is applied when a regulation exhibits both MB and CC characteristics.

Similar to our approach of mapping patents to industries, the 'sectors' (e.g. transport) and 'technologies' (e.g. passenger vehicles) field of a regulation allows us to assign regulation to industry sectors. In around 75% of cases, the sectors could be directly mapped to the corresponding NACE2 industries, while in some cases (around 20%) we used our best judgment to find the most appropriate NACE2. Around 5% of policies could not be reliably allocated and were dropped from the data. This procedure enables us to identify the prevalence of each policy type within clusters of country, sector and year.

3.5 Control variables

Additionally we control for different variables which are likely to influence green innovation. Control variables include GDP per capita, a CO2 emission index, fuel prices and the knowledge stock. GDP per capita and the CO2 emission index (base 1990) are taken from OECD. We expect that richer economies will invest more in green technologies as well as that more CO2 emissions in a country – ceteris paribus – induce more green patenting.

We use energy prices from OECD and focus on oil and natural gas prices. In our regressions we lag both variables for two years due to temporal lags between price changes and patent applications. Oil comprises light distillate fuel oils, which can be used for heating purposes. Natural gas price are based on average prices for industry and/or households. Both fuel prices increase the cost of using carbon technologies and are expected to increase green patent applications.

To control for the knowledge stock within a given country and sector, we apply the perpetual inventory method with starting year 1995:

$$KS_{cst} = P_{cst} + (1 - \delta) * KS_{cst-1} \tag{1}$$

where KS_{cst} and P_{cst} denote the knowledge stock of patents and the flow of new patent applications in country c, sector s and year t. We discount patents with a rate of $\delta = .20$ by year as in Aghion et al. (2016). We conjecture that sectors with high knowledge stock in emission reducing or zero emission innovation will continue innovating in these patent classes.

3.6 Summary statistics

Table 2 presents descriptive statistics on our main variables, while detailed definitions are provided in Table 1. Figure 3 provides time series plots on our main variables. On average, 7.3% of patents in the European Union are green (Y02) as defined by Veefkind et al. (2012), while the respective shares are slightly lower in Asia (4.9%) and in America (6.7%). In Europe, environmental taxes on a country/NACE2/year level are nearly 100 Mio € on average, the bulk of which is comprised of energy taxes.[13] While transport taxes (around 15% of environmental tax revenues in the EU; around 10% in Asia) are important, the two other types of taxes, pollution and resource taxes, are of lesser importance. On a per capita basis, environmental taxes are approximately twice as high in the EU as compared to Asia. Unfortunately, we lack data on environmental taxes for the US and Canada.

In 7% of European country/NACE2/year observations, there is at least one active regulation (6.4% in Asia and 12.3% in America). Conditional on the presence of regulation, there are multiple regulations per sector on average as witnessed by the sub-categorizations of regulation into Command-and-Control, Market-Based and Hybrid. The most prevalent type of regulation is CC. It should be noted that we cannot measure the stringency of regulation since we merely record the presence or absence of regulation.[14]

While in Europe the R&D tax deduction rate is around 5%, American firms can save nearly ten cents in taxes on each dollar spent on R&D. In Asia, the R&D subsidy rate is only 2.4%. European countries spend around 200 mio. € yearly on green research subsidies. The absolute number is much larger for Asia and America, mainly due to the inclusion of China and the US in the sample. On a per-capita basis, however, subsidies are quite comparable across regions, with Europe and Asia subsidizing green research at around 12 € p.c. versus 14 € p.c. in the US. Light fuel prices (natural gas prices) are nearly 50% (100%) higher in Europe than in America. The CO2 emission index is around 20% higher in America than in Europe. It is largest in Asia (around 50% higher than in Europe).

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[13] The largest part of energy taxes, in turn, is comprised of the mineral oil tax.

[14] In the appendix, however, we employ the OECD Environmental Policy Stringency Index with corroborating results.

Table 1: Variable description

Variable	Definition	Source	Unit	Frequ.
	Dependent variable			
Y02	For all our analysis we use the `PATSTAT global spring 2020` version from the *European Patent Office*. We use *earliest_filing_year* and map each patent based on the $IPC4$ class to a specific industry sector (see 2). Dorner and Harhoff (2018) enables us to assign each patent to a given sector.	EPO	Weighted count	$c/s/y$
	Independent variables			
Environmental taxes	Environmental specific tax revenues in each country and year, separated by NACE2 code. We use all available observations until 2016 of all European countries, incl. Iceland, Liechtenstein and Norway. Enviromental taxes are classified into four main categories (mentioned in order of importance): Energy, Transport, Pollution and Resource taxes.	EuroStat	mio. €	$c/s/y$
Environmental regulations	Environmental related regulations for each country, sector and year worldwide. Using the IEA policy database and counting each regulation by start and end date. We calculate a cumulated time sequence for each regulation in each country and year. In our regressions we transform all assigned policies into dummy variables and control if one sector in a given country and year do have a CC, MB or $Hybrid$ regulation.	IEA	mio. €	$c/s/y$
R&D subsidies	The IEA database for government funding of energy *RD&D*[a] includes all relevant funding in the field of energy across multiple countries. Seperated in *Fossil Fuels, Renewables, and Energy Efficiency & oth.*	IEA	mio. €	c/y
R&D tax deductions	This variable is defined as a tax subsidy rate. The tax subsidy rate is calculated as 1 minus $B-index$, which is a measure of needed before-tax income to break even on USD 1 of *R&D* outlays.	$OECD$	%	c/y
	Control variables			
CO2 emissions	The carbon emission index presents trends in man-made emissions of $CO2$ (emissions from energy use and industrial processes, e.g. cement production). CO2 Fuel Combustion emissions expressed as an index, where the reference $year = 100$. 1990 is used as the reference year.	$OECD$	%	c/y
GDP per capita	Gross domestic product per capita by country and year.	$OECD$	thou.	c/y
Oil price	Oil (light fuel) price exclusive taxes for light fuel oil.	$OECD$	$/ton	c/y
Natural gas price	Natural gas prices exclusive taxes for natural gas.	$OECD$	$/MWh	c/y
Knowledge stock	Depreciated sum of all patents (base 1995) with a yearly discount rate δ of .20. (perpetual invention method)	$OECD$	count	$c/s/y$

Notes: IEA: International Energy Agency; EPO: European Patent Office; $OECD$: Organization for Economic Co-operation and Development; c: country; s: sector; y: year;

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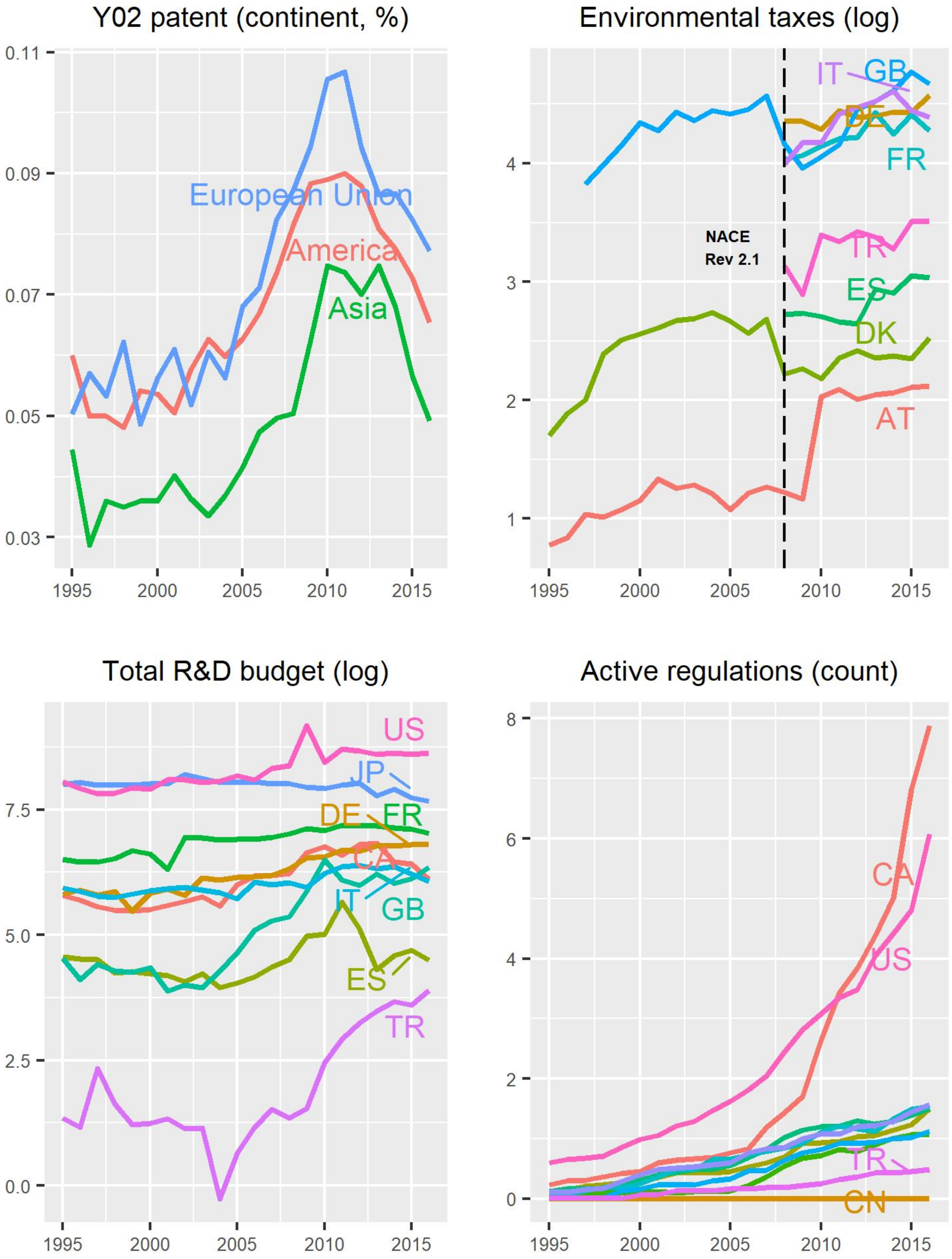
[a] For further details please read the RDD manual at the IEA homepage.

Table 2: Descriptive statistics

		Total			**European Union**			**Asia**			***America***		
	Unit	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs
1. Patents													
Number of Y02 patents	count	25.245	153.420	54783	12.548	73.909	45327	59.304	224.858	5672	126.286	430.956	3784
Number of total patents	count	375.709	2182.400	54783	171.060	914.820	45327	987.062	3345.351	5672	1910.733	6224.829	3784
Share of YO2 patents	share	0.070	0.032	54783	0.073	0.033	45327	0.049	0.024	5672	0.067	0.015	3784
2. Environmental taxes													
Total environmental taxes	mio. €	98.545	280.006	27015	95.149	269.481	26241	213.693	511.044	774	.	.	0
Energy Taxes	mio. €	78.863	245.816	26641	75.574	234.447	25867	188.800	480.359	774	.	.	0
Pollution Taxes	mio. €	3.870	18.972	30483	3.953	19.198	29709	0.700	4.305	774	.	.	0
Resource Taxes	mio. €	1.425	20.389	33730	1.397	20.568	32956	2.615	10.084	774	.	.	0
Transport Taxes	mio. €	14.664	56.755	27483	14.464	56.921	26709	21.578	50.245	774	.	.	0
3. Environmental regulations													
Sectoral regulation	count	0.443	3.295	54783	0.318	1.753	45327	0.311	1.711	5672	2.140	10.628	3784
Total NACE2 reg.	share	0.073	0.260	54783	0.070	0.255	45327	0.064	0.245	5672	0.123	0.329	3784
Command-and-Control	share	0.060	0.238	54783	0.056	0.229	45327	0.061	0.240	5672	0.113	0.317	3784
Market based	share	0.054	0.226	54783	0.052	0.223	45327	0.031	0.174	5672	0.107	0.310	3784
Hybrid	share	0.042	0.201	54783	0.040	0.196	45327	0.027	0.163	5672	0.093	0.291	3784
4. R&D subsidies													
R&D tax deductions	rate	4.868	13.230	53753	4.773	13.593	44985	2.407	8.484	4984	9.227	12.960	3784
Total budget R&D	mio. €	511.583	1084.136	41425	199.036	259.453	33861	1474.115	1478.745	3780	2346.887	2216.735	3784
Fossil fuel	mio. €	58.391	181.430	41597	19.420	40.056	34033	126.341	133.267	3780	341.013	481.236	3784
Renewables	mio. €	71.650	171.851	43219	38.027	48.637	35655	125.432	186.996	3780	334.741	444.278	3784
Energy eff. & oth. R&D	mio. €	112.876	242.608	41597	52.814	60.748	34033	220.646	228.461	3780	545.415	575.015	3784
Control variables													
Oil price	$/ton	595.980	313.482	54783	613.658	317.900	45327	557.779	277.263	5672	441.483	259.168	3784
Natural gas price	$/MWh	29.829	15.408	54783	30.603	15.425	45327	33.327	14.333	5672	15.305	6.551	3784
Knowledge stock	count	2096.419	11889.002	54783	1022.919	5607.084	45327	5035.606	16452.585	5672	10549.770	34149.228	3784
CO2 emission index	number	100.590	30.138	52891	95.440	25.216	45327	146.212	48.744	3780	116.714	6.995	3784

Notes: Data are reported at the country/sector/year level; Environmental regulations are dummies and equal to one if we observe a regulation in a given $c/s/y$; No tax data are available for US, CA, CN and JP. The following nations are contained in the data. **EU**: AT,BE,CA,CH,CZ,DE,DK,EE,ES,FI,FR,GB,GR,HU,IE,IT,LU,LV,NL,NO,PL,PT,SE,SI,SK; **Asia**: JP,CN,TR,CY; **America**: US, CA.

Figure 3: Main variables over time



4 Empirical strategy

We estimate the impact of environmental policies on green innovation in a panel dataset at the country/sector/year level of observation using the following estimation equation:

$$ln(Y02)_{cst} = \alpha_{cs} + \beta_{cs} \times year + \tau ln(Tax_{cst}) + \rho Reg_{cst} + \sigma Sub_{ct} + \gamma \mathbf{X}_{ct} + \varepsilon_{cst}. \qquad (2)$$

The dependent variable is the natural logarithm of the count of Y02 patents, allocated to country c, NACE2 s, in year t. All regressions include fixed-effects at the country/sector level (α_{cs}), as well as time trends at the country/sector level ($\beta_{cs} \times year$). Thus, every time-series in the panel dataset is de-meaned and de-trended before being used for estimation.

The main variables of interest on the right hand side are (i) the log of environmental tax revenues ($ln(Tax_{cst})$), in total as well as classified into four subcategories (energy taxes, transport taxes, pollution taxes and resource taxes), (ii) the presence of environmental regulation in a sector, country and year (Reg_{cst}), which are later divided into command-and-control, market based and hybrid regulations, and (iii) R&D subsidies (Sub_{ct}), which we capture on the one hand by the log of state-level R&D budgets devoted to green innovation (direct subsidies), in total as well as classified into fossil fuel, renewables, and energy efficiency & others, and on the other hand by the R&D tax subsidy rate (indirect subsidies), i.e. the percentage reduction of R&D costs granted to companies by the tax system.

Additional control variables are collected in $\mathbf{X}_{ct}$; it includes the log of GDP per capita, a CO2 emission index, the logs of the two year lagged prices of light fuel and natural gas, and the log of the knowledge stock (which varies at the country/sector/year level). ε_{cst} is the error term.

The identification of the causal impact of environmental policies on green innovation thus relies on panel econometrics, using a comprehensive set of fixed effects and time trends as well as additional control variables. The fixed-effects at the country/sector level account for size differences in green innovation and make large countries and innovative sectors more comparable to small countries and low-tech sectors. Additionally, the time trends at the country/sector level account for different rates of (exogenous) technological change across countries and sectors. We hope to capture other factors driving green innovation through the set of control variables described above. Thus, the variation we employ to identify the impact of environmental policies is the time-series variation of de-meaned and de-trended green innovation trajectories at the country/sector level, conditional on the controls.

5 Results

5.1 Main results

This section presents our main results on how environmental policies impact green patenting. Table 3 contains the estimation results for equation 2. Column (1) presents the results for the main categories of environmental taxes, regulation and R&D subsidies, column (2) distinguishes between different types of environmental taxes, while column (3) also looks at the sub-categories of regulatory measures. The most comprehensive specification, column (4), additionally analyzes the sub-categories of direct R&D subsidies. Before we turn to the main results, a few words about the coefficients of control variables are in order. Richer economies as measured by GDP per capita apply for more green patents: a one percent increase in GDP per capita leads to an around 0.3% increase in green patenting. Consistent with the existing literature (Aghion et al., 2016), the lagged, worldwide prices of oil and natural gas have positive and significant effects on green patenting. Thus, increasing relative prices of carbon via resource prices makes green innovation more attractive. The level of a countries' CO2 emissions - as measured by the CO2 emission index - increases green patents as well. An important variable is the stock of knowledge measured by the initial and updated stock of patents in an industry. Its coefficients of around 0.9 indicates a near proportional effect of the stock of knowledge on green patenting (Scotchmer, 1991; Aghion et al., 2016). The comprehensive set of controls and fixed effects leads to an R^2 of around 97% in all regressions.

Environmental taxes significantly direct innovation towards green patenting. The coefficient indicates that doubling the environmental taxes in an industry on average increases green patenting activity by around 2.8%. Column (2) reveals that energy taxes are responsible for the positive effect, while the other categories (pollution, resource and transport taxes) are not significant. This can be explained by the overwhelming importance of energy taxes in total environmental taxes (more than 3/4 of environmental taxes are energy taxes) and the relative unimportance of the other categories of taxes.

Environmental regulation also has the potential to direct technological change towards green. The presence of an environmental regulation in a NACE2 industry is associated with a 15.8% increase in green patenting compared to a sector without environmental regulation. Since results differ across geographical regions, we defer the discussion of CC versus MB regulation to the next section.

State subsidization of R&D in green technologies – irrespective of subsidizing by direct R&D subsidies or indirectly by tax benefits – significantly increases the number of green patents.

Table 3: Effects of policy instruments on green innovation (Y02 patents)

	(1)	(2)	(3)	(4)
1. Environmental taxes				
Env. Taxes	0.028***			
	(0.007)			
Energy Taxes		0.026***	0.027***	0.025***
		(0.007)	(0.007)	(0.007)
Pollution Taxes		0.000	0.000	-0.001
		(0.005)	(0.005)	(0.005)
Resource Taxes		-0.002	-0.001	-0.001
		(0.006)	(0.006)	(0.006)
Transport Taxes		0.003	0.002	-0.001
		(0.005)	(0.005)	(0.005)
2. Environmental regulations				
Total NACE2 reg.	0.158**	0.156**		
	(0.075)	(0.074)		
Command-and-Control			0.138*	0.143*
			(0.073)	(0.075)
Market based			0.064	0.064
			(0.077)	(0.078)
Hybrid			0.027	0.042
			(0.073)	(0.075)
3. R&D subsidies				
Total Budget	0.101***	0.101***	0.101***	
	(0.009)	(0.009)	(0.009)	
Fossil fuels				0.059***
				(0.008)
Renewables				0.052***
				(0.011)
Energy eff. & oth.				0.012*
				(0.007)
R&D tax deductions	0.015***	0.015***	0.015***	0.016***
	(0.001)	(0.001)	(0.001)	(0.001)
Control variables				
CO2 emission index	0.006***	0.006***	0.006***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)
GDP p.c.	0.307***	0.306***	0.300***	0.429***
	(0.111)	(0.111)	(0.111)	(0.118)
Oil price	0.160***	0.164***	0.163***	0.191***
	(0.021)	(0.021)	(0.021)	(0.022)
Natural gas price	0.352***	0.352***	0.352***	0.320***
	(0.024)	(0.025)	(0.025)	(0.026)
Knowledge stock	0.922***	0.913***	0.916***	0.884***
	(0.057)	(0.057)	(0.057)	(0.059)
Observations	20875	20774	20774	19400
R^2	0.970	0.970	0.970	0.971

Notes: Standard errors in parentheses, * p<0.1, ** p<0.05, *** p<0.01. The dependent variable is the log of Y02 patents allocated to an country/industry/year cluster. All regressions include fixed-effects and linear trends at the country/industry/year level.

Doubling direct state R&D subsidies leads to a 10% increase in green patent applications. From column (4) it is apparent, that fossil fuels and renewable subsidies are the main drivers of this effect. Reducing R&D costs for companies indirectly via more generous tax deductions of R&D costs also increases green patenting. An increase of the R&D subsidy rate by 1 percentage point increases green patent applications by 1.5%.

5.2 Geography

Table 4 differentiates effects by geographic regions. Since we lack data on environmental taxes in North America, we focus on regulation and R&D subsidies.

Table 4: Effects of policy instruments on green innovation by continents

	Total	EU	Asia	America
Environmental regulation				
Command-and-Control	0.144^{***}	0.096^{*}	0.343^{**}	0.107
	(0.047)	(0.054)	(0.144)	(0.073)
Market based	0.127^{**}	0.127^{*}	-0.027	0.229^{*}
	(0.056)	(0.066)	(0.147)	(0.121)
Hybrid	-0.059	-0.051	-0.036	-0.185^{**}
	(0.054)	(0.062)	(0.156)	(0.089)
R&D subsidies				
Fossil fuels	0.058^{***}	0.066^{***}	-0.074^{**}	0.069^{***}
	(0.005)	(0.006)	(0.031)	(0.013)
Renewables	0.033^{***}	0.021^{**}	0.201^{***}	0.291^{***}
	(0.008)	(0.009)	(0.030)	(0.020)
Energy eff. & oth.	-0.023^{***}	-0.030^{***}	-0.104^{***}	-0.104^{***}
	(0.005)	(0.006)	(0.026)	(0.027)
R&D tax deductions	0.006^{***}	0.004^{***}	0.045^{***}	0.004^{***}
	(0.001)	(0.001)	(0.004)	(0.001)
Control variables				
CO2 emission index	0.010^{***}	0.010^{***}	-0.016^{***}	0.029^{***}
	(0.001)	(0.001)	(0.003)	(0.002)
GDP p.c.	0.813^{***}	0.973^{***}	1.561^{***}	0.245
	(0.076)	(0.088)	(0.250)	(0.333)
Oil price	0.270^{***}	0.304^{***}	0.055	0.087^{***}
	(0.016)	(0.019)	(0.051)	(0.023)
Natural gas price	0.256^{***}	0.318^{***}	0.264^{***}	0.072^{***}
	(0.016)	(0.021)	(0.080)	(0.023)
Knowledge stock	0.860^{***}	0.771^{***}	0.832^{***}	0.517^{***}
	(0.029)	(0.041)	(0.057)	(0.080)
Observations	34458	28332	2687	3439
R^2	0.969	0.963	0.983	0.991

Notes: Standard errors in parentheses, * p<0.1, ** p<0.05, *** p<0.01. The dependent variable is the log of Y02 patents allocated to an country/industry/year cluster. All regressions include fixed-effects and linear trends at the country/industry/year level.

The impact of environmental regulation is rather heterogeneous across regions. While in Asia command-and-control type regulations successfully increase green innovation, in Europe and America market-based regulations have a stronger effect. Hybrid regulations appear to be even negatively associated with green patenting, particularly in America.

Similarly, the effect of R&D subsidies differ by region. While in the EU and America, R&D subsidies for fossil fuels increase green innovation, they do not in Asia. Conversely, R&D subsidies for renewables lead to green innovation predominantly in Asia and America, but less so in the EU. Interestingly, energy efficiency R&D subsidies exhibit negative effects on patenting behaviour in all three geographic areas. This is likely due to substitution effects, such as an increase in the efficiency of a conventional technology leading to less incentives for alternative green technologies. While R&D tax deductions increase green innovation in all regions, companies react strongest to R&D tax deductions in Asia.

5.3 Industries

Table 5 differentiates between manufacturing and non-manufacturing industries. Energy taxes increase green patents predominantly in non-manufacturing industries, as do CC regulations. This is not surprising since the transport sector is not part of manufacturing, but is strongly affected by mineral oil taxes (the largest component of environmental taxes) as well as CC regulations (e.g. automobile fleet regulation). In contrast, in manufacturing substitutability between fossil and non-fossil inputs (e.g. in steel, cement etc) may be limited, and taxes/carbon prices do not seem to induce patenting (except for pollution taxes, which are weakly significant). Direct and indirect R&D subsidies induce green patenting in both manufacturing and non-manufacturing industries alike.

Table 6 further differentiates non-manufacturing industries into the most important polluting industries, construction, transport and Others.[15] Environmental taxes display a particularly large directing effect towards green patents in the transport sector consistent with the findings above. Again, the finer classification of non-manufacturing industries does not render the conclusion obsolete that all forms of R&D subsidies successfully induce green patenting. Environmental regulations play a very large role in construction, however there is also a lot of heterogeneity rendering the coefficient insignificant.

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[15] Others includes electricity generation, however the small number of observation does not allow us to estimate effects separately for electricity.

Table 5: Effects of policy instruments on emission reduced innovations - manufacturing

	Manufacturing		Other industries	
Environmental taxes				
Energy Taxes	0.014	(0.014)	0.034^{***}	(0.009)
Pollution Taxes	0.017^{*}	(0.009)	-0.011^{*}	(0.006)
Resource Taxes	-0.007	(0.012)	0.002	(0.007)
Transport Taxes	-0.012	(0.012)	0.004	(0.006)
R&D subsidies				
Fossil fuels	0.042^{***}	(0.015)	0.066^{***}	(0.009)
Renewables	0.051^{**}	(0.022)	0.051^{***}	(0.013)
Energy eff. & oth.	0.022^{*}	(0.013)	0.009	(0.008)
R&D tax deductions	0.013^{***}	(0.002)	0.017^{***}	(0.001)
Environmental regulations				
Command-and-Control	0.082	(0.101)	0.231^{**}	(0.116)
Market based	0.119	(0.110)	0.016	(0.113)
Hybrid	0.048	(0.111)	0.049	(0.104)
Control variables				
CO2 emission index	0.005^{***}	(0.002)	0.005^{***}	(0.001)
GDP p.c.	0.665^{***}	(0.235)	0.329^{**}	(0.137)
Oil price	0.209^{***}	(0.044)	0.185^{***}	(0.026)
Natural gas price	0.289^{***}	(0.051)	0.329^{***}	(0.030)
Knowledge stock	0.770^{***}	(0.116)	0.929^{***}	(0.068)
Observations	5458		13942	
R^2	0.970		0.967	

Notes: Standard errors in parentheses, * p<0.1, ** p<0.05, *** p<0.01. The dependent variable is the log of Y02 patents allocated to an country/industry/year cluster. All regressions include fixed-effects and linear trends at the country/industry/year level.

5.4 A comparison of policies

From the point of view of policy the question of the cost-effectiveness of the different measures is of prime interest. Unfortunately, we are unable to directly calculate and compare the economic costs or effectiveness associated with individual policies. While R&D subsidies and environmental tax revenues per induced patent may give an impression on how large program costs are, these are not the economic costs for society associated with these policies. For example, R&D subsidies must be financed by tax revenues and environmental taxes may be passed on to consumers via higher prices, introducing deadweight-losses we cannot measure. Moreover, estimating the economic costs of highly-heterogeneous regulatory measures is not possible from our data sources. We therefore resort to estimating standardized (beta) coefficients, indicating by how many percent the outcome changes, when a regressor changes by one standard deviation.

Table 6: Effects of policy instruments on selected NACE groups

	NACE groups	
1. Environmental taxes		
Construction	-0.110	(0.078)
Transport	0.109^{**}	(0.050)
Manufacturing	0.013	(0.012)
Others	0.035^{***}	(0.009)
2. R&D subsidies		
Construction	0.091^{**}	(0.042)
Transport	0.091^{***}	(0.032)
Manufacturing	0.114^{***}	(0.015)
Others	0.095^{***}	(0.011)
3. R&D tax deductions		
Construction	0.019^{***}	(0.006)
Transport	0.011^{***}	(0.004)
Manufacturing	0.014^{***}	(0.002)
Others	0.016^{***}	(0.001)
4. Environmental regulations		
Construction	0.257	(0.255)
Transport	0.118	(0.293)
Manufacturing	0.167^{*}	(0.088)
Others	0.045	(0.203)
Control variables		
CO2 emission index	0.006^{***}	(0.001)
GDP p.c.	0.308^{***}	(0.111)
Oil price	0.160^{***}	(0.021)
Natural gas price	0.351^{***}	(0.024)
Knowledge stock	0.913^{***}	(0.057)
Observations	20875	
R^2	0.970	

Notes: Standard errors in parentheses, * p<0.1, ** p<0.05, *** p<0.01. The dependent variable is the log of Y02 patents allocated to an country/industry/year cluster. All regressions include fixed-effects and linear trends at the country/industry/year level.

This achieves comparability in the increment of the policy analyzed (one standard deviation) judging from the history of such variation. Thus, if it is comparably difficult (e.g. due to political economy constraints) or costly (direct and indirect costs of a policy) to increase policy intensity by one historical standard deviation, we can compare the effectiveness in inducing green patenting of the three policies.

Table 7 displays the results on the whole sample (Total) as well as the three geographic groups, EU, Asia and America, and four industry groupings, Construction, Transport, Manufacturing and Others. The highest policy effectiveness in inducing green patenting can be attributed to R&D subsidies (direct and indirect). A one standard deviation increase of R&D tax deductions induce a nearly 20% increase, while a one s.d. increase in subsidies increases green patents by around 15%. The second most efficient policy are environmental taxes (where a one s.d. increase raises green patents by 7.4%), followed by environmental regulations (4.6%). Broadly, this pattern is also observed in the depicted subgroups, although with slightly differing degrees.

Our theoretical reasoning from section 2 can explain these findings. As outlined, economists have identified two market failures leading to the excessive emission of greenhouse gases and the sub-optimal level of technical change towards green inventions, the environmental externality and the public goods nature of knowledge. The most direct mechanism to internalize the second externality is through R&D subsidies or other R&D promoting policies such as patent protection or direct state funding of basic research. Accordingly, we find that this mechanism is most effective in inducing green patents. While environmental taxes and regulation tackle predominantly the first externality, they can only indirectly rectify the knowledge externality (via increasing the relative – explicit or implicit – prices of carbon on the market). Thus, while carbon taxes/pricing and possibly regulation may be best suited to internalize the current environmental externality, R&D subsidies are most effective in inventing the new green technologies needed in the future to combat climate change.

Table 7: Beta coefficients in percentage

	Continents				**NACE groups**			
	Total	EU	Asia	America	Constr.	Transp.	Manuf.	Others
Environmental taxes	0.074	0.055	0.056	0.000	-0.095	0.119	0.021	0.085
R&D subsidies	0.153	0.192	0.087	0.215	0.080	0.100	0.247	0.234
R&D tax deductions	0.197	0.069	0.083	0.041	0.059	0.045	0.121	0.182
Environmetal regulations	0.046	0.038	0.018	0.012	0.038	0.012	0.033	0.006

6 Conclusion

Although it is common knowledge among economists that the optimal policy to combat climate change is a combination of a (sufficiently high and potentially increasing) carbon tax and R&D subsidies, we see few (or no) examples of such a 'first-best' approach. The reluctance to adopt such costly policies is likely owed to the dearth of empirical evidence on their effectiveness. This paper aims to fill this gap by providing empirical estimates of the effectiveness of environmental policies in a comprehensive dataset.

We construct a panel dataset, comprising detailed information on green patening at the sector/country/year level of observation, and evaluate whether and how sectors react to three different environmental policies (carbon prices/taxes, regulation, and subsidies). We use the classification system of Veefkind et al. (2012) to identify green patents and link these technologies to different sectors of the economy using the mapping of Dorner and Harhoff (2018). We complement the innovation data with data on carbon prices and carbon taxes, data on environmental regulation, as well as data on R&D subsidies.

Our main results are encouraging. All three policies direct innovation towards green patenting. Environmental taxes, environmental regulation and state subsidization of R&D in green technologies significantly increase the number of Y02 patents in the affected countries and sectors.

These clear-cut results, however, mask important heterogeneous effects across regions and industries. While in Asia command-and-control type regulations successfully increase green innovation, market-based regulation has a stronger effect in Europe and America. Hybrid regulations even appear to be negatively associated with green patenting, particularly in America. Similarly, the effect of R&D subsidies differs by region. Further, the type of economic activity plays a role. Energy taxes increase green patents predominantly in non-manufacturing industries (e.g. the mineral oil tax in transport) as do CC regulations (e.g. the automobile fleet regulation). In contrast, in manufacturing substitutability between fossil and non-fossil inputs (e.g. in steel, cement etc) may be limited, and taxes/carbon prices may not (yet) induce patenting. R&D subsidies (both direct and indirect) appear to "work" irrespective of type of economic activity.

Finally, from the point of view of policy the question of the cost-effectiveness of the different measures is of prime interest. While our approach does not allow to calculate economic costs of the three broad policies, we calculate standardized coefficients. Consistent with theory, we find that a one standard deviation increase of R&D subsidies induces the largest increase in patents (nearly 20%) compared to environmental taxes (7.4%) and environmental regulations (4.6%). Thus, while carbon taxes/pricing and possibly regulation may be best suited to internalize the current environmental externality, R&D subsidies are most effective in inventing the new green technologies needed in the future to combat climate change.

Our paper holds important results but also some caveats. It is important to know that environmental policies do not only have short-run effects but can spark longer-run green innovation.

Thus, the long-run cost-benefit balance of these policies is more favourable than when only considering short-run costs and benefits. We have to mention, however, that we are not yet able to compare the economic costs nor calculate the economy wide, general equilibrium costs of the policies under consideration. Moreover, there may be interaction effects between environmental policies. Future research should tackle these important questions to guide policy which policies combat climate change at the lowest cost.

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