ISSN 1825-0211

# LEARNING CURVE AND WIND POWER

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Quaderno n. 81 — Dicembre 2010

QUADERNI DEL DIPARTIMENTO
DI ECONOMIA, FINANZA
E STATISTICA

# Learning Curve and Wind Power

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**Abstract**

This study explores the reasons why countries have chosen subsidies to green electricity instead of implementing the more common Pigouvian tax on polluting emissions. I focus on the learning by doing effects from the production of wind power on the cost of future production as a justification for the observed policies. In doing so, I present two models that differ in the way I introduce learning. Under reasonable parameter values, the price paid to a firm for the energy produced from wind power is heterogeneous, and varies among the firms that produce energy from wind power according to the index of productivity of the firm itself. The suggested strategies of this research differ from the main price-driven schemes adopted by EU members; by comparing such results with European Union policy, the paper show that EU policy is not optimal.

Keywords: learning by doing, environmental policy, Pigouvian taxes, subsidies.
JEL classification: H23, Q48

## 1. Introduction

How to control climate change and to spur green energy are among the most important challenges facing the world today. This research attempt to study the reason why governments subsidize green electricity. We know that the regulator can charge a Pigouvian tax on emissions that internalizes all damage from pollution. Nevertheless, countries have chosen subsidies to green electricity. The reasons often put forward are the learning by doing effects from the production of energy from renewable resources on the cost of future production. The main idea is that a critical mass of production has to be reached first, and then costs will be reduced thanks to R&D activities.
The objective of this research is thus to study whether this is indeed a justification to the observed schemes. In particular, I analyze the optimal use of policy instruments such as taxes and subsidies when investment and production of green electricity generates learning externalities that help reduce costs of future production.
Among renewable energies, I take into account wind power, that is growing at a rapid pace not only in Europe, but at a global level.
There is a long history of economic incentives in the European Union aimed at promoting the use of renewable resources. Different schemes have been implemented to make renewable energy competitive.
Policy instruments are usually divided into two classes: they can be either price-oriented or quantity-oriented. Countries among Europe differ in the scheme they adopt, but most of them rely basically on price-driven strategies. Subsidies are directed to wind power and not to turbine producers. The intuition of subsidizing wind energy is essentially that higher demand of wind electricity stimulates the turbine producer industry and it can be a spur to learning and reducing production costs.
In this study I investigate mainly three reasons why an environmental policy of taxes and subsidies to wind power should be implemented by the government.
First I discuss the feasibility of charging firms that produce polluting emissions with a Pigouvian tax. There are some problems for the government to levy a Pigouvian tax both for difficulties in evaluating quantitatively the marginal damage from pollution to society and also due to lobbying activities by firms that use fossil fuel and attempt to achieve less regulation.
When Pigouvian taxes are not feasible, I consider instruments such as emission taxes and subsidies that may lead to Pareto-efficient levels of pollution.
Second, I consider for an environmental policy to be implemented comes from the "big push" literature, as in the paper by Murphy et al (1989). They focus on the contribution of one firm to the market size in a setting with imperfect competition and demand spillovers. One of the models presented in that paper takes into

account investments in infrastructure; the example they consider is the possibility of building a railroad, which is particularly important for industrialization.

The link I find between the model presented by Murphy et al. and environmental policy may be understood if one thinks of "building a railroad" as "achieving a level of investment in wind power that will make green energy as competitive as fossil fuel due to investment and learning-by-doing spillovers." In the renewable energy sector, and more specifically in wind power, every firm benefits both from its own investment and from the spillovers that come from the industry. With coordination of investment by the government, such as taxes and subsidies, it is possible to reach the 'good equilibrium' that is, to achieve an environmental big push through the large-scale adoption of energy from renewable resources.

Thirdly, I then turn to the central purpose of the research: studying learning by doing effects from the production of wind power on the cost of future production. I consider an arbitrarily large number of firms operating in a competitive energy market. Firms produce energy both from non renewable resources and wind power. I present two models that differ in the manner I introduce learning.

In the first model, total learning for a firm is the sum of the private levels of investment in research made by the firm itself and spillovers that comes from the level of investment in research made by the other firms in the sector. I show that if a regulator can observe the level of investment in research made by firms, he will charge an emission tax equal to the marginal damage and he will give a subsidy to research activity. If instead the level of investment in research is not observable, the social planner has two instruments to correct externalities: an emission tax equal to the marginal damage and a subsidy to the quantity of energy produced from wind power.

The main result I find in this setting is that the price paid to a firm for the energy produced from wind power is heterogeneous, and varies among the firms that produce energy from wind power according to the index of productivity of the firm itself. This optimal scheme thus differs from what is observed, i.e. a uniform subsidy to wind electricity.

In the second model, total learning for a representative firm is given by the sum of the quantity of wind energy produced by the firm itself and spillovers that come from the quantity of wind energy produced by the other firms in the industry. In this case, the regulator can charge an emission tax equal to the marginal damage caused by pollution, and a subsidy to the quantity of wind energy produced.

The same result obtains.

Both models deal with a strategy to implement the use of wind power based on the quantity of energy produced. In our setting, depending on the variables observable, the social optimal allocation can be reached by charging an environmental tax and paying subsidies to investment in research or to the quantity of energy produced.

The suggested strategies of this research differ from the main price-driven schemes adopted by EU members; by comparing such results with European Union policy, it seems that this latter one is not optimal.

## 2. Wind energy in the European Union

The European Union policy with regard to the implementation of energy from renewable resources among member states is getting impressive results.

In 2005 renewable energy accounted for 6.7 per cent of total primary energy consumption in the EU-27, compared to a share of 4.4 per cent in 1990. The share of renewable resources in the final energy consumption varies across countries from 25% in Sweden to less than 2% in United Kingdom (European Union).

From 1990 to 2005, electricity production from renewable resources has increased on average of 2.7% per year, even if the simultaneous growth in electricity consumption partially offset the positive growth of the production of energy from renewables.

It has to be noted that the promotion in the European Union of the electricity production based on renewable energy sources takes place in an energy market that is more and more competitive. The United Kingdom was the first European country to pursue liberalization and in 1996 the Council of Ministers reached an agreement on the Directive specifying the rules for electricity liberalization in EU.

On the basis of the experience from electricity liberalization around the world, the goal of the European Union is to achieve higher efficiency and lower consumption prices by introducing conditions of intensified commercial competition, but it is quite hard for firms that produce energy from renewable resources to compete within the energy industry that produce energy mainly from fossil fuel.

Energy from renewable resources is capital intensive and more costly compared with conventional fossil fuel technologies.

Let consider for instance the case of wind power, that is growing at a rapid rate at both European and global level.

The following table shows the cumulative installation of wind power in Europe.

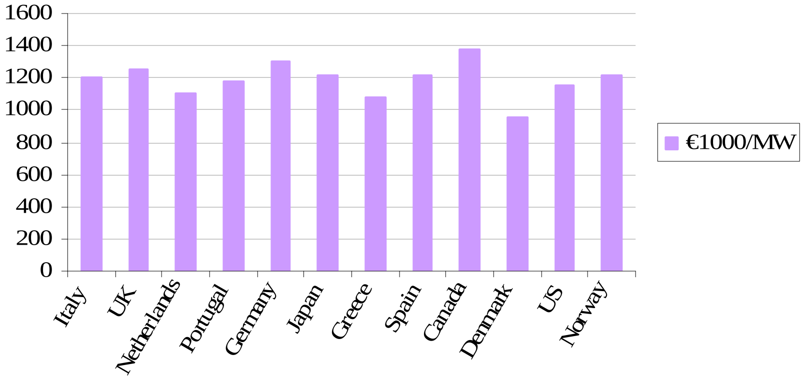
Table 2.1: Cumulative installation of wind power in the EU (MW)

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| Germany | 6,113 | 8,754 | 11,994 | 14,609 | 16,629 | 18,415 | 20,622 | 22,247 | 25,624 |
| Spain | 2,235 | 3,337 | 4,825 | 6,203 | 8,264 | 10,028 | 11,623 | 15,145 | 20,000 |
| France | 66 | 93 | 148 | 257 | 390 | 757 | 1,567 | 2,454 | 5,300 |
| Italy | 427 | 682 | 788 | 905 | 1,266 | 1,718 | 2,123 | 2,726 | 3,736 |
| EU | 12,887 | 17,315 | 23,098 | 28,491 | 34,372 | 40,500 | 48,031 | 56,535 | 64,357 |

Source: EWEA, 2009

On average, a turbine installed in Europe has an investment cost of around 1.23 €million/MW, and this amount is shared between the turbine itself, the grid connection, the foundations and the land.

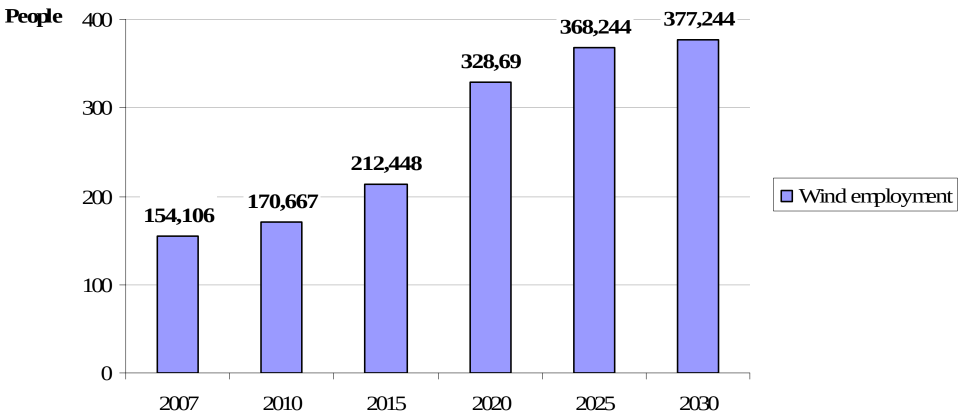
Figure 2.1: Total investment costs of installed wind power capacity shown for different countries (2006)




Source: IEA,2009

In recent years, employment related to wind energy in the EU has grew up as the amount of wind energy capacity installed. The EU wind energy sector employed around 154,000 people in 2007. According to the European Wind Energy Association, wind energy employment in the EU will more than double from 154,000 in 2007 to 330,000 in 2020. Over that period, onshore wind energy will continue to be the largest contributor to the employment, and the share of offshore installations will increase over time.

Figure 2.2: Wind energy sector employment in the EU




Source: EWEA, 2009

Wind turbine and component manufacturers employ approximately half of wind energy direct employment. Germany, Spain, France and Denmark are the countries with the most wind-related jobs. The situation in the new member States varies a lot, with Poland in a leading position.

Regarding the total per unit cost per kWh produced, in the study “Wind Energy – The Facts” by Morthorst et al. (2008) the authors calculate it by discounting and leveling investment and the operation and maintenance costs over the lifetime of the turbine and then dividing them by the annual electricity production.

The assumptions considered to calculate the cost of energy produced by on-land wind power are essentially the following: calculations are related to new land-based, the turbines is a medium size, the average investment cost based on data from International Energy Agency and stated in 2006 prices is at around €1,225/kW, the lifetime of a turbine is set at 20 years, and the discount rate is assumed to range from 5 to 10 per cent annum.

Given the statements above, the calculated costs per kWh of wind-generated power, as a function of the wind regime at the chosen sites, vary in a range from 7-10cEur/kWh at sites with low average wind speeds, to approximately 5-6.5cEur/kWh at windy coastal sites, with an average of approximately 7cEur/kWh at a wind site with average wind speeds (Morthorst et al., 2008). This means that costs for producing electricity from wind power are still higher with respect to the production costs of energy from fossil fuel.

## 2.1 The current status of the Italian wind energy market

The European Union’s climate change package currently in force it’s a scheme that is supposed to lead the EU to its climate targets by 2020. The plan called for a 20% increase in energy efficiency, 20% reduction in greenhouse gas emissions, 20% share of renewables in overall EU energy consumption by 2020, and 10% biofuel[1] component in vehicle fuel by 2020 (European Commission, MEMO/08/33). Implementing the package requires high investments in renewable energy. The European Commission has estimated the direct costs of the energy and climate package at around 0,6% of GDP in 2020.

Italy has experienced a drop in primary energy consumption: in 2008 it has reached 192.1 Mtoe, a 4.8 Mtoe decrease in consumption compared to 2004. The fall in energy consumption it’s part due to the low economic growth, part related to the improvements in energy efficiency[2] on the whole.

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[1] The 10% biofuel target is set at the same level for each member State and the ones that are not able to produce enough biofuel may buy it from elsewhere. Biofuels used in the EU must be produced in a sustainable way, that is they are constrained to biodiversity issues and they must reach at least a minimum level of greenhouse gas savings (European Commission, MEMO/08/33).

[2] Energy efficiency refers to the product or activity that can be produced with a given amount of energy (US Department of Energy). Another important indicator to evaluate efficiency improvements in energy processes is the energy intensity that is a measure of the

Italian energy demand is basically met by fossil fuels imported from abroad, since Italy is not self sufficient in energy production[3]. The share of the oil and gas industry in the Italian energy consumption is at around 80%; the market for oil is mature and steady, while the supply of natural gas is increasing as a result of the growth in consumption both in the civil and thermoelectric sectors. In order to facilitate the supply of natural gas, new pipelines under construction will connect Italy with Libya, Algeria and the Caspian region.

Coal covers 9% of the Italian energy consumption. The limited use of coal is related to its high environmental impact[4]; nevertheless, power companies attempt to recover coal use since it is cheaper than oil or gas. In Italy, in a site close to Rome the energy company ENEL has replaced an old oil fired plant with a coal fired power plant provided with carbon storage technologies to reduce $CO_2$ emissions.

The European energy scheme related to Italy (*Clima-Energia 20-20-20*) states that Italy has to increase its share of renewable energy to 17% by 2020 and to cut the level of polluting emissions at 14% with respect to the level of 2005.

Italy is still a long way from meeting its renewable energy targets, even if both the lack of domestic fossil fuels and environmental concerns spur the promotion of clean energies. Hydro and geothermal power are quite widespread, but they have limited potential for further expansion because of environmental impacts[5]. The photovoltaic market is developing fast thanks to the subsidies' system but its development costs are still high compared to the other technologies among renewables.

In the electricity sector, the share of renewables gains in importance by increasing by 19.9% in 2008 compared to the previous year: besides the growth of the hydroelectric power generation (+21.8%), a strong growth of wind power has been recorded in wind power (+59.6%) and photovoltaic (increasing fivefold from 40 GWh in 2007 to 200 GWh in 2008).

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energy consumption per GDP; it would be more proper to evaluate energy consumption per work unit (instead of GDP), but it is difficult to evaluate the amount of work of the whole country as a physical quantity (Suehiro, 2007).

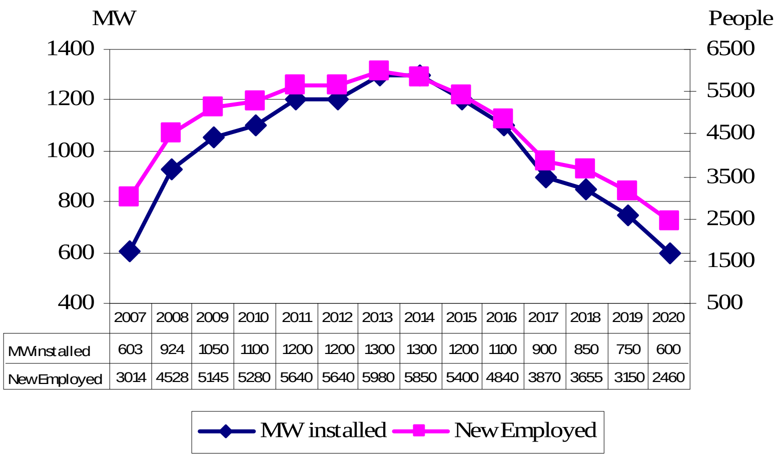
[3] The energy requirements' cut and the weakness of the international markets have cutted 1,2% off hydrocarbons imports in 2008 compared to the previous year (Autorità per l'energia elettrica e il gas, 2009).

[4] The process by which it is possible the partial decarbonization of fossil fuels it's represented by carbon capture and sequestration technologies (CCS), that consist in separating the carbon capture dioxide from other gases during the energy production. The drawback of such a process is that CCS is expensive and it leads to an increase of the energy cost in the 25-45% range (Grimaud et al., 2008).

[5] Electricity generated from hydropower is relatively emission free, but a large amount of methane is produced by the decomposition of plants in the flood areas. Moreover, hydropower has environmental impacts such as fish injury and effect on downstream water quality (Canadian Energy Research Institute, 2004).

Wind power plays an important role in the Italian energy market from renewable resources. Having a cumulative capacity at around 3,736 MW by 2008, Italy is the fourth country as wind power capacity in Europe.
The Italian territory, especially in the southern regions, is characterized by climate and landscape quite suitable for a further diffusion of this technology. The regions that contribute strongly to the Italian growth of the wind sector are basically Apulia (685 MW), Sicily (584 MW), Campania (519 MW) and Sardinia (367 MW). In Central Italy wind power is not well developed and basically the provinces of Pisa and Bologna make the main contribution to wind energy production (Italian Wind Energy Association, 2008). Wind power has a positive impact also on the job market. In Italy, around 3,000 people are directly employed in the wind energy sector; straightforwardly, the employment trend is strictly related to the development of the market, as it is shown in the following figure.

Figure 2.3: Energizing Italy's employment (2009)




| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MW installed | 603 | 924 | 1050 | 1100 | 1200 | 1200 | 1300 | 1300 | 1200 | 1100 | 900 | 850 | 750 | 600 |
| New Employed | 3014 | 4528 | 5145 | 5280 | 5640 | 5640 | 5980 | 5850 | 5400 | 4840 | 3870 | 3655 | 3150 | 2460 |

Source: Italian Wind Energy Association (ANEV), 2008

The steady growth of the Italian wind market has encouraged several turbine manufacturers to locate and expand operations in Italy. The main producers of wind turbine in Italy are Vestas, set up in 2000, that accounts for around 23% of total yearly installation, Gamesa and Leitner.
There are also local wind turbine manufacturers specialized in small-scale and off-grid applications, as the companies Blu Mini Power and Ropatec; the latter is a leading brand of small wind turbines for offshore use.

Concerning the power generation company, despite the energy market is becoming more and more competitive, Enel plays the leading role among the electricity utilities. The other companies active on the market are International Power, Edison Energie Speciali and Italian Vento Power Corporation.

### 2.2. European schemes for promoting green energy

There is a longer history of the use of economic incentives in the EU than in most other parts of the world.

There are different schemes implemented by the European Union in order to use renewable energies and make them competitive on the energy market.

The fundamental distinction that can be made among the European support mechanisms is between direct and indirect policy instruments. Basically, direct instruments stimulate the installation of energy from renewable resources immediately, while indirect policy measures focus on improving long-term framework conditions.

There exist also voluntary approaches; this type of strategy is based on the consumers' willingness to pay premium rates for renewable energy, like donation projects and share-holder programs.

The important classification criteria are whether policy instruments are price-oriented or quantity-oriented.

With the regulatory price-driven strategies, financial support is given by investment subsidies, soft loans or tax credits. Economic support is also given as a fixed regulated feed-in tariff (FIT) or a fixed premium that governments or utilities are legally obliged to pay for renewable energy produced by eligible firms.

Among the price-oriented policy, the most used within the European members is the Feed-in Tariff.

The Feed-in Tariff is a price-driven incentive in which the supplier or grid operators are obliged to buy electricity produced from renewable sources at a higher price compared to the price they pay for energy from fossil fuel.

This higher price is paid in order to compensate the high cost present in the green sector. The level of the feed-in tariff varies between 7.7 and 9.3 eurocents per kWh (Meyer, 2002). This instrument is mainly used in the wind power sector.

The criticisms made to the feed-in tariff scheme underline that a system of fixed price level is not compatible with a free market. Moreover, these favorable tariffs generally do not decrease with the improvements of the efficiency of the technologies that produce green energy.

A particular kind of feed-in tariff model used in Spain consist in a fixed premium, in addition to the market price for electricity, given to the producers relying on renewable energy sources.

Also in this case, premiums should be adjusted in accordance with the performance of the different technologies.

With regard to the regulatory quantity-driven strategies, the desired level of energy generated from renewable resources or market penetration is defined by governments.

The most important are the tender system and the tradable certificate system.
In the tender system, calls for tender for defined amounts of capacity are made at regular interval, and the contract is given to the provider that offer the lowest price.
The winners of the tenders are getting a fixed price per kWh for the period of the contract and the contract offers winner several favorable investment conditions; this system is in a sense quite close to the feed-in tariff model.
In the tradable certificate system, firms that produce energy are obliged to supply or purchase a certain percentage of electricity from renewable resources. Then, at the date of settlement, they have to submit the required number of certificates to demonstrate compliance. The firms involved in the tradable certificate system can obtain certificate from their own renewable electricity generation; they may as well purchase renewable electricity and associated certificates from another generator, or they can purchase certificates that have been traded independently of the power itself.
The economic incentives for renewable resources differ among the EU members, anyway, the support schemes are more based on price-driven strategies than on quantity driven strategies across Europe.
Let us consider some representative countries. The following analysis regarding the schemes adopted in EU is based on Morthorst et al.
In Germany, the main electricity support scheme is represented by a price-driven incentive, the feed-in tariff.
The main features of the German support mechanism are stated in the Renewable Energy Source Act of 2000. The Act establishes that the feed-in tariffs are not dependent on the market price of energy but are defined in the law and that the feed-in tariff are different for wind, biomass, photovoltaic etc. Moreover, the feed-in tariffs are decreased over the years in order to take into account the technological learning curves.
For instance, the German tariff for wind on-shore is €83.6/MWh for at least 5 years, €52.8/MWh for further 15 years.
The United Kingdom was the first European country to pursue liberalization in the electricity market by the end of 1998. In UK, energy from renewable resources is supported by quantitative-driven strategies. Over the last decades, the scheme adopted by UK was the tender system, but, since 1999, the system in use is a quota obligation system with Tradable Green Certificates. The obligation (based in tradable green certificate) target increases during years, and electricity companies that do not comply with the obligation have to pay-out penalties. Considering wind power, electricity companies which do not comply with the obligation have to pay a buy-out penalty that was at €65.3/MWh in 2005.
In Denmark the support schemes are mainly related to the wind power sector. To implement renewable resources, the strategy adopted is price-driven, that is a premium feed-in tariff for on-shore wind, and fixed feed-in tariffs for the other renewable resources.
In France, the strategy adopted is mainly price-oriented; the electricity support schemes are feed-in tariffs plus tenders for large projects. The main support instrument for wind power is the feed-in tariff which states, for wind on-shore,

€82/MWh for 10 years and €28-82/MWh for the following 5 years, depending on the local wind conditions.

Italy has not a significance experience in producing energy from renewable resources. Several factors obstruct the development of renewables in Italy, as administrative constraints and high connection costs. During the 1990s, the energy sector in Italy was entirely restructured in order to introduce competition, as set by the EU Directive 96/02/EC (Lorenzoni, 2003). The promotion of electricity produced from renewables has taken place through support schemes as the quota obligation system and feed-in tariff. Concerning wind energy, in 2002 the Italian government abandoned the feed-in-tariff[6], introducing the quota obligation system with tradable green certificates (CVs).

Under this certificate system, electricity producers and importers are obliged to source an increasing proportion of their energy from renewable resources. Green certificates are used to fulfil this obligation. Italy has adopted a ministerial measure that balances supply and demand in order to tame speculative fluctuations on the value of green certificates[7]. Currently, Green Certificates are sold for 88,66 euro/MWh, providing a strong stimulus for market growth (GSE, 2009).

The mechanisms implemented by the Italian government has quite spurred the diffusion of renewables in the electricity sector; the trend of growth due to the measures to support renewable energy growth estimated in the late 1990s was close to real renewable energy penetration in the electricity sector, as it is shown in the following table.

Table 2.2: RES-E penetration in the Italian electricity sector

| Year | RES-E estimated share of electricity production in the late 1990s | RES-E share of electricity production |
|---|---|---|
| 2001 | 19.3% | 19.7% |
| 2002 | 18.8% | 17.2% |
| 2003 | 18.4% | 16.3% |
| 2004 | 18,0% | 18.4% |
| 2005 | 17.5% | 16.4% |
| 2006 | 17.1% | 16.6% |
| 2007 | 16.8% | 15.7% |
| 2008 | 16.4% | 18.6% |

Source: Autorità per l’energia elettrica e il gas, 2009; Lorenzoni, 2003

[6] Fixed feed-in-tariff is the support scheme currently in force for the Italian photovoltaic sector.

[7] The fixed reference price for green certificates is calculated as the difference between 180,00 €/CV and the market electricity price (GSE, 2009)

## 3. Policy analysis

I analyze three reasons why the government should implement the use of energy from renewable resources, that are the presence of polluting emissions, learning by doing and the big push.

### 3.1. Tax versus Subsidy

Polluting emissions create a damage to society; without a price system, firms see a price of zero for pollution and it leads to a wrong amount of pollution.

Since the right level of pollution will not emerge in a spontaneous way, the government must increase the cost of pollution by raising a tax, in order to reduce pollution generation. If pollution becomes more costly, the producer will produce less pollution.

If the tax is at the optimal level, it is called a Pigouvian tax. The optimal amount of pollution is the amount that minimizes total costs from producing one more unit of pollution and total damages from pollution. Thus, the condition that marginal cost (or marginal saving) equals to marginal damage leads to the generation of the right amount of emissions.

This is the main idea of the Pigouvian tax: “A Pigouvian fee is a fee paid by the polluter per unit of pollution exactly equal to the aggregate marginal damage caused by the pollution when evaluated at the efficient level of pollution. The fee is generally paid to the government” (Kolstad, 2000).

Note that the Pigouvian tax is also equal to the marginal cost from pollution generation at the optimal level of pollution.

The difficulty for the government to levy a Pigouvian fee is that there are reasons why it is not feasible. First of all, it is not easy to do a quantitative evaluation of the marginal damage. The number of activities and the number of people affected by pollution are so great that it is quite hard to estimate in money the damage from pollution.

Moreover, the optimal tax level on polluting emissions is not equal to the marginal net damage that the polluting activity generates initially, but to the damage it would cause if the level of the activity had been adjusted to its optimal level (Baumol and Oates, 1971).

If we are not at the optimum, the Pigouvian tax will be neither the marginal cost of pollution nor the marginal damage from pollution. Basically we can say that in a perfect environment, like an economy in which there is perfect information and no constraints on the government tax policy, only the Pigouvian tax is necessary to achieve efficiency.

If there are other distortions in the economy or limitation for the social planner, then other taxes and subsidies are needed to achieve efficiency.

### 3.2. Environmental policy for generating a big push

The other reason I consider for an environmental policy comes from the "big push" literature; here I consider the paper by Murphy et al (1989). They focus on the contribution of one firm to the market size, in a setting with imperfect competition and demand spillovers. Such spillovers might lead to multiple equilibria and the economy might be in a bad equilibrium (no industrialization) if coordination of investments among sectors does not occur. The 'big push' amounts to moving from the bad to the good equilibrium, even if no sector could break even industrializing alone.

One of the models presented in that paper takes into account investments in infrastructure. Let us consider a large infrastructure project such as the building of a railroad, which is particularly important for industrialization because it lowers significantly production costs. The externalities from building the railroad are not captured by firms, but with coordination of investments we can move to the 'good' equilibrium', that is, the big push takes place. The authors assume that the railroad builder is a monopolist. There are mainly two reasons why the monopolist might decide not to build it. First, if he can't price discriminate among users, then he can't extract all the surplus generated by the railroad. Moreover, there is uncertainty about industrialization even if the railroad is built, and the monopolist might be afraid of ending up with a "white elephant".

The link between the model presented by Murphy et al. and environmental policy may be understood if one thinks of "building a railroad" as "achieving a level of investment in wind power that will make green energy as competitive as fossil fuel due to investment and learning-by-doing spillovers."

In the renewable energy sector, and more specifically in wind power as we will see in my model, every firm benefits both from its own investment and from the spillovers that come from the industry. These spillovers will lead to a reduction of costs and it is expected that green energy will be competitive with fossil fuel in the long run. Because of the uncertainty within the energy industry about the level of investment in renewables made by the firms themselves, it is possible that no one invests in the production of energy from renewable resources.

With coordination of investment by the government, such as taxes and subsidies, it is possible to reach the 'good equilibrium' that is, to achieve an environmental big push through the large-scale adoption of energy from renewable resources.

With respect to externalities, the model I present can be seen as a 'shorcut' when compared to Murphy et al. In the latter, resources invested by a firm go to the monopolist, who might build the railroad and then lower production costs for other firms; in the former, resources go directly to other firms. This means that the problem of no price discrimination is exacerbated (no pricing at all), while the 'white elephant' risk is not relevant: once investment takes place among all the firms in the green energy industry, production cost is lowered and every firm can take advantage of it even without coordination. Note that if the other firms in the industry do nothing, the investing firm ends up with a 'white elephant'. Even with such a 'shortcut', the baseline of our model is precisely the same: "an industrializing sector essentially has the effect of reducing the total production costs of other sectors" (Murphy et al, 1989). Then we might think of taxes and subsidies as a tool box governments can employ to internalize environmental externalities, achieve coordination and reach the big push in energy industry.

### 3.3. Learning by doing

The last motivation I analyze for an environmental policy for the development of energy from renewable resources is represented by the experience curve.
The future growth of the economics of energy from renewable resources is shown by the trend of the experience gained; the learning curve relates the cumulative quantitative development of a product to the development of the specific costs.

The following table shows the estimated learning rates across some energy technologies assuming that cost reductions are a function of the cumulative production (McDonald et al., 2001)

Table 3.1: Estimated learning rates

| Technology | Country | Time Period | Estimated learning rate (%) |
|---|---|---|---|
| Retail gasoline production | US | 1919-1969 | 20 |
| Coal for electricity production | US | 1948-1970 | 26 |
| Solar PV | EU | 1985-1995 | 35 |
| Wind Power | US | 1985-1994 | 32 |
| Wind Power | EU | 1980-1995 | 18 |
| Electricity from biomass | EU | 1980-1995 | 15 |
| Ethanol | Brazil | 1978-1995 | 22 |

Source: IEA, 2000 and McDonald et al., 2001

On the existing literature on learning by doing, the paper by Petrakis et al. (1997) is an interesting work to study the effects of learning by doing in a competitive industry. Basically they show that learning by doing is compatible with perfect competition if the industry presents increasing marginal costs, and that the equilibrium outcome is socially efficient.
More specifically, the point of departure of our study that explain the reasons for a policy in presence of learning by doing is the model proposed by Bläsi et al. (2007) focusing on the right subsidies in the presence of learning by doing in a competitive market.
They develop a two-period model in which there are two types of electricity producers that are: producers of energy from fossil fuel generating polluting emissions, and producers from wind power. In this framework, the energy market is competitive, and also the market for wind turbine is competitive. The wind-

turbine operators are heterogeneous because their productivity depends mainly on the location of the turbine; they buy turbines from turbine producers and these latter firms incur decreasing costs in the second period of production through learning.
In the paper there is a distinction between pure private learning and learning spillovers; pure private learning means that costs in the second period are lower thanks to the quantity of energy produced by the firms themselves, while learning spillovers means that firms benefit also from the quantity produced by all the firms in the industry.
They focus their analysis mainly on the wind turbine producers. Total learning that occurs in the upstream sector is the sum of private learning that comes from the turbines produced, and the spillovers from the quantity of turbines produced in the industry.
Note that in this study, they relate learning only to the quantity of turbines produced.
The cost function of a firm that produce wind turbine depends on his own output and, in the second period, on total learning or experience. The cost function has positive and increasing marginal cost in output in each period and experience by the firm or by the industry will reduce marginal cost in the second period.
Concerning a producer of energy from wind power, he faces a cost function that depends on the output and on a firm specific parameter that can be interpreted as the location of the turbine. We have that the cost function has positive and increasing marginal costs in output and in the location parameter.
The total output in the electricity market comes from both fossil fuel and wind power.
They first investigate the case in which economic incentives are given to the turbine's producers, so that the profit function of a typical turbine producer has an entry premium and an output subsidy.
In this setting, the authors find out that in a decentralized economy the optimal policy of the regulator in order to implement the first best consists in three instruments: a Pigouvian tax (equal to the marginal damage), an output subsidy per turbine and an entry premium for turbine producers.
Both subsidies depend on the spillover coefficient. If there are no learning spillovers, the regulator should internalize externalities from polluting emissions by setting a Pigouvian tax; no subsidies are needed.
In reality, as we have seen before, it is hard to set taxes at Pigouvian level and in addition in several countries is not allowed to subsidy wind turbine producers.
For these reasons, the authors study the second-best optimal subsidies when Pigouvian taxes and subsidies to turbine producers are ruled out.
Subsidies are paid to the producers of energy from wind power; the economic intuition is that higher demand for wind turbines stimulate and accelerate learning by doing in the wind turbine industry, so that costs will be lower as learning proceeds.

With only private learning among turbine producers, the authors eliminate subsidies from the turbine's producer profit and they consider an output subsidy on wind power.
In this scenario, the interesting results are that, first, if the subsidy or the tax rate is raised in one period, the amount of energy produced from fossil fuel decrease in both periods; the quantity of wind power and the number of firm that produce wind energy increase in both periods.
Moreover, while the price of electricity is unchanged because of the competitive market, an increase in the subsidy or in the tax rate leads to a higher price of wind turbines in the first period, and to a reduction of the price itself in the second period.
This is because the higher demand of turbines can be satisfied at higher prices in the first period since turbine producers incur in increasing marginal costs. At the same time, higher demand stimulates learning and we will have both lower costs and lower prices in the second period.
When learning is private, the second-best optimal subsidy rate takes into account the marginal damage from polluting emissions from fossil fuel and the sub-optimal emission tax rate. They find out that the subsidy paid to firms that produce energy from wind power should be higher in the first period with respect to the second one. This is because increasing output in the wind industry today accelerates learning by doing and then decrease costs curve in the future.
Moreover, they find out that if marginal damage is constant, the quantity of energy generated by fossil fuel is higher than the one in the first best, and then environmental damage is higher than optimal, while the output of energy from wind power is equal to the first-best level.
In the presence of learning spillovers the authors obtain a subsidy that is equal to the marginal damage plus a term that comes from the externality generated by learning spillovers. In this case there is ambiguity in the paper since the authors don't know the sign of the term due to spillovers and so they can't sign the subsidy itself.
The paper by Bläsi et al. basically shows that the regulator has to take into account the learning effect to implement the first-best policy. In particular, when learning occurs, the regulator should tax polluting emissions and subsidize the production of turbines. There is some ambiguity on the sign of the subsidy to production of wind energy, but the paper is interesting and it is the point of departure of our work.

## 4. The model

An arbitrarily large number of firms $i$ $(i=1,2,\ldots,n)$ operate in the energy market. They produce energy both from wind power and from non renewable resources.
Let $q_i$ be the total quantity of energy produced in period $t$ from wind power. Each firm produces also a quantity $Q_i$ of energy from non renewable resources.
I assume a one-to-one relation between the level of energy produced from non renewable resources and the polluting emission caused by $Q_i$, that is $e_i=Q_i$.

Let $d$ be the constant damage to environment caused by one unit of emission.
I want to study the learning by doing effects in the cost function of producing wind power. For doing so, I assume that the energy market is competitive with a fixed price $p_0$.
I am going to consider two models that differ in the manner I introduce learning.
In the first model (4.1), total learning that occurs for firm $i$ is described as followed: $L_i = I_i + k\sum_{j\neq i} I_j$, where $L_i$, the total learning, is the sum of the private level of investment in research $I_i$ made by the firm itself, and the spillovers $k\sum_{j\neq i} I_j$ that comes from the levels of investment in research $I_j$ made by the other firms of the industry.
The spillover coefficient is denoted by $k$, where $k$ with $0 \leq k < 1$. For $k = 0$ I have only private learning. I do not allow for $k = 1$ because in this case I have complete spillovers, and only the levels of investment in research $\sum_{j\neq i} I_j$ made by the other firms of the industry matter.

In the second model (4.2), total learning for firm $i$ is $L_i = q_i + k\sum_{j\neq i} q_j$; it means that I do not model the research activity in the wind power production, and total learning comes from the quantity of wind energy produced by the firm itself, and spillovers that come from the quantity of wind energy produced by the others in the industry.

In both models, the firm's cost function for the wind energy production is a function of the quantity of wind energy produced by the firm itself and of the total learning: $c^i(q,L)$.
I assume that the cost function satisfies the following properties: $c_q > 0$ and $c_{qq} > 0$, it means that costs are increasing with the production of wind energy. In addition, $c_L < 0$, $c_{LL} > 0$, i.e. the marginal effect of learning is decreasing, and $c_{qL} < 0$, that is, experience decreases production costs in the future.

For computations, I will sometimes use the particular form $c^i(q,L) = \frac{q_i^2}{\theta_i L_i}$,

I denote by $\theta_i$ the index of productivity of the wind turbine that produce wind power; this parameter can be viewed as the efficiency of the wind turbine, e.g. the location.

The cost function to produce energy from non renewable resources is $C^i(Q) = aQ_i + \frac{Q_i^2}{2}$ and I assume that $a < p_0 - d$, so that production from non renewable resources is socially valuable.
In order to answer the question if we should subsidize wind power and which is the best strategy, I am going to determine the optimal instruments in the two different models and I will compare the results.

**4.1. Government's policy under learning by doing from investments in research**

In the first model I consider, the learning function is $L_i = I_i + k\sum_{j \neq i} I_j$.

The welfare W is defined by:

$$W = p_0 \sum_i (q_i + Q_i) - \sum_i C^i(Q_i) - \sum_i c^i(q_i, L_i) - \sum_i I_i - d\sum_i Q_i$$

(1)

Let us first compute the optimum.

The social planner maximizes welfare W with respect to the quantity $q_i$ of energy produced from wind power, the quantity $Q_i$ of energy that comes from non renewable resources, and total learning $L_i$. The first-order conditions are:

$$p_0 = c_q^i(q_i, L_i)$$

(2)

$$p_0 = C_Q^i(Q_i) + d$$

(3)

$$1 + c_L^i(q_i, L_i) + k\sum_{j \neq l} c_L^j = 0$$

(4)

The FOCs shows that within the energy industry there are to two externalities. The first one is represented by the damage *d* to environment caused by one unit of emission, and it is created by the production of energy from non renewable resources.
The other externality is $k\sum_{j \neq l} c_L^j$ that express spillovers from the marginal cost of learning of the other firms of the industry.
The policy instruments at government's disposal to implement the first best allocations are Pigouvian tax $t$ on $Q_i$, a subsidy $\sigma$ on $I_i$ and a subsidy $s$ on the production of wind energy $q_i$. The appropriate instrument will depend on which variables are observable.

*4.1.1. Optimal allocation if investments in research are observable*

If the levels of investment in research are observable within the industry, the profit of a representative firm that produces energy both from wind power and non renewable resources is:

$$\pi = (s + p_0)q_i + (p_0 - t)Q_i - C^i(Q_i) - c^i(q_i, L_i) - I_i + \sigma_i I_i \qquad (5)$$

The profit maximization problem yields the following results:

$$s + p_0 = c_q^i(q_i, L_i), \qquad (6)$$

that compared with the condition for the social optimum $W_{q_i}$ leads to $s = 0$, which means no subsidy on the quantity of wind energy produced;

$$p_o - t = C_Q^i(Q_i), \qquad (7)$$

that compared with $W_{Q_i}$ leads to $t = d$, that is, the tax paid by the firm per unit of polluting emissions equals to the damage caused by the pollution;

$$1 + c_L^i(q_i, L_i) - \sigma_i, \qquad (8)$$

and comparing this equation with the condition for the social optimum $W_{L_i}$, I obtain that the level of subsidy in research activities is $\sigma_i = -k(\sum_{j \neq i} c_L^j)$. Note that $\sigma_i$ is positive since the spillover coefficient is $0 \leq k < 1$ and $c_L^j < 0$ by assumption.

As usual, we have two instruments to correct two externalities.

*4.1.2. Best policy if investments in research are not observable*

Things become more interesting if I instead assume that the levels of investment in research are not observable. Then, the social planner cannot use the subsidy on research anymore.

The social planner maximization problem becomes:

$$\begin{cases} \underset{Q_i, q_i, L_i}{Max}\; W = p_o \sum_i (q_i + Q_i) - \sum_i C^i(Q_i) - \sum_i c^i(q_i, L_i) - \sum_i I_i - d \sum_i Q_i \\ \text{s.t. } c_L^i + 1 = 0, \ \forall_i . \end{cases} \qquad (9)$$

The constraints originate from the firms' behavior when they choose their investment in research.

Let $\lambda^i$ be the lagrangian multiplier associated to these constraints.
The first order conditions for the welfare maximization problem with respect to $Q_i, q_i$ and $L_i$ are given by the following equations:

$$p_o = C_Q^i(Q_i) + d \,, \qquad (10)$$

that from the comparison to $W_{Q_i}$ in order to implement the first best, lead to the standard result $t = d$ that is tax equal to marginal damage;

$$p_0 - c_q^i(q_i, L_i) = \lambda^i c_{Lq}^i \,, \qquad (11)$$

that compared with $W_{q_i}$ leads to the equation $s = -\lambda^i c_{Lq}^i$ >0, which means that there is a subsidy on the quantity of energy from wind power produced. To demonstrate that the right-hand side is positive, I will work on the following FOC with respect to the total learning *L*;

$$1 + c_L^i + k\sum_{j \neq i} c_L^j + \lambda_i c_{LL}^i + k\sum_{j \neq i} \lambda_j c_{LL}^j = 0 \,, \ \forall_i \qquad (12)$$

that I develop to study the sign of $\lambda_i$. The equation can be rewritten as:

$$k\sum_{j \neq i} c_L^j - kc_L^i + \lambda^i c_{LL}^i + k\sum_{j \neq i} \lambda^j c_{LL}^j - k\lambda^i c_{LL}^i = 0$$

Summing on *i*, I get $\lambda^i c_{LL}^i (1-k) = k\left[ c_L^i - \frac{\sum_{j \neq i} c_L^j}{(n-1)k+1} \right]$ .

The multiplier $\lambda^i$ is positive since all the terms within the equation are positive, including the term in brackets: $c_L^i > \frac{\sum_{j \neq i} c_L^j}{(n-1)k+1}$ (solving the latter inequality I get $\sum_i c_L^i (n-1)(k-1) > 0$ ).

Writing explicitly and rearranging, I achieve

$$\lambda^i = \frac{1}{c_{LL}^i} \frac{k(n-1)}{(n-1)k+1} > 0 \qquad (13)$$

Moreover, I obtain an important result by substituting the value from (13) into equation (11).

Since $c_q^i = p_i$, that is the marginal cost of producing energy from wind power equals to the price $p_i$ paid to firm *i* for energy from wind power, I can rewrite equation (11) as $p_0 - c_q^i(q_i, L_i) = \lambda^i c_{Lq}^i \Leftrightarrow p_i = p_0 - \lambda^i c_{Lq}^i$

By substituting the value of $\lambda^i$ into the latter equation, I get:

$$p_i = p_0 - \frac{c_{Lq}^i}{c_{LL}^i}\frac{k(n-1)}{(n-1)k+1}. \qquad (14)$$

Recall that $\frac{k(n-1)}{(n-1)k+1} = \beta > 0$ that does not depend on $i$. In order to calculate the fraction $\frac{c_{Lq}^i}{c_{LL}^i}$, I work on the form of the cost function I have assumed at the beginning of the model, that is $c^i(q, L) = \frac{q^2}{\theta L}$.

I have $c_L = -\frac{q^2}{\theta L^2} = -1 \Rightarrow \frac{L}{q} = \frac{1}{\sqrt{\theta}}$, $c_{Lq} = -\frac{2q}{\theta L^2}$, $c_{LL} = \frac{2q^2}{\theta L^3}$ and then $\frac{c_{Lq}^i}{c_{LL}^i} = -\frac{1}{\sqrt{\theta_i}}$.

Substituting the results found so far, equation (14) becomes:

$$p_i = p_0 + \frac{1}{\sqrt{\theta_i}}\beta \qquad (15)$$

This result is very interesting, because it means that the price $p_i$ paid to firm *i* for the energy produced from wind power is heterogeneous, and varies among the firms that produce energy from wind power, according to the index of productivity $\theta_i$ of the firm itself.

I can summarize the results obtained as follows:

If the levels of investment in research are observable, the socially optimal allocation can be reached by taxing at the Pigouvian level the energy produced from non renewable resources, and by subsidizing the investment in research.

If the levels of investment in research are not observable, the best policy consists in taxing at the Pigouvian level the energy produced from non renewable resources, and at the same time subsidizing the quantity of energy produced from wind power. Then the price paid to firm $i$ for the quantity of energy produced by wind power depends on the index of productivity $\theta_i$ of the firm itself.

*4.1.3. The effects on subsidies by setting a sub-optimal tax*

Suppose moreover that the tax is set at a sub-optimal level, that is $0 \leq t < d$ . The subsidy $s$ is not affected, and so the social planner's policy does not change.

The policy would have changed if the consumer surplus $S$ were $S\left(\sum_i q_i + Q_i\right)$ and/or the cost function for producing energy from both the wind power and non renewable resources were not separable, that is $C\left(q_i, Q_i, L_i\right)$ .

### 4.2. Government's policy under learning by doing from investments in quantity of energy from wind power

In this second model, the basic assumption is that total learning for the representative firm $i$ is given by the sum of the quantity of wind energy produced by the firm itself, and spillovers that come from the quantity of wind energy produced by the other firms of the industry, that is $L_i = q_i + k\sum_{j\neq i} q_j$ . This assumption means that there is no research in the sector of wind energy.

Welfare is defined by:

$$W = p_0\sum_i (q_i + Q_i) - \sum_i C^i(Q_i) - \sum_i c^i(q_i, L_i) - d\sum_i Q_i$$

The social planner maximizes welfare with respect to the quantities of energy produced respectively from wind power, $q_i$ and non renewable resources, $Q_i$.
The maximization problem leads to:

$$p_0 - c_q^i(q_i, L_i) - c_L^i(q_i, L_i) - k\sum_{j\neq i} c_L^j = 0$$

$$p_0 - d = C_Q^i(Q_i)$$

The welfare maximization problem shows that there are two externalities: the first one is represented by the marginal cost of total learning for the firms within the industry, that is $\left[-c_L^i(q_i, L_i) - k\sum_{j\neq i} c_L^j\right]$ .

The other externality is represented by the damage $d$ caused from pollution; the firm produce energy both from wind power that is a clean energy, and non renewable resources that pollute the environment creating a damage to society.

The profit of a representative firm under the assumptions of this model will be:

$$\pi = (p_0 + s)q_i + (p_0 - t)Q_i - C^i(Q_i) - c^i(q_i, L_i)$$

The first order conditions are given by the following equations:

$$p_0 + s = c_q^i(q_i, L_i)\ ,$$

and the comparison of his equation to $W_{q_i}$ gives us the optimal level of subsidy to the quantity of wind energy in order to implement the first best, that is $s = -\left( c_L^i + k\sum_{j \neq i} c_q^j \right) > 0$ ;

$$p_0 - t = C_Q^i(Q_i)\ ,$$

and comparing this equation with the condition for the social optimum $W_{Q_i}$ , the optimal tax is given by charging a Pigouvian tax equal to marginal damage, $t = d$ .

Summarizing the results above, the socially optimal allocation can be reached by charging a Pigouvian tax equal to marginal damage, and paying a subsidy on the quantity of energy from wind power produced.

## 5. Conclusion

This study has explored the learning by doing effects from the production costs of wind power as a justification to the observed environmental policies.

When investments and production of wind energy generates learning externalities that help reduce costs of future production, the regulator should subsidize wind power to make it competitive in the energy industry.

Firstly, I have analyzed the policies of the European Union to implement the use of wind power among EU member states and I have seen that these strategies are mainly price-driven oriented.

I have analyzed three reasons why the government should enforce the use of energy from wind power, that are the presence of polluting emissions, learning by doing and the big push. In particular, since Pigouvian taxes are not feasible, the government has a tool box of instruments such as environmental taxes and subsidies to wind industry that would lead to Pareto-efficient levels of the polluting activities.

I have shown also that with coordination of investments that are taxes and subsidies, it might be possible to reach the ‘good equilibrium’ that is, to achieve an environmental big push through the large-scale adoption of energy from wind power and renewables in general.

The focus of the research has been to show the effects of learning by doing in the production costs of wind power. In doing so, I have developed two different models differing on the composition of total learning. In the first model learning

that occur for a firm comes from investment in research made by the firm itself and spillovers from investments in research made by the other firms of the industry. In the second one, total learning for a firm is made of the quantity of energy from wind power produced by the firm itself and production spillovers from the quantity of energy produced by the other ones.
In both settings I have found that the regulator has three instruments to correct the externalities in the market and to lead to the first best levels of the polluting activities.
Depending on the variables observable, the social planner can levy an environmental tax equal to the marginal damage; he can give respectively a subsidy to investments in research or a subsidy to the quantity of energy produced if I have learning from investment in research or learning from wind energy produced.
Moreover, the interesting result I have found is that, in the case of learning from investments in research, if the social planner cannot observe the level of investment of a firm in the wind power industry, the price paid to the firm for the quantity of energy produced by wind power is heterogeneous - it depends on the index of productivity of the firm itself.
The strategy I analyze, based on environmental tax and subsidies to investment in research or to the quantity of energy produced (depending on the variables observable), allow to reach the social optimal allocation. The policy discussed in this research differs from the EU policy, implying that the strategy adopted by the European Union does not seem optimal.
Further line of research could be the construction of a multiple equilibrium model in order to show that an environmental big push might be possible.

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ISSN 1825-0211

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